FEASIBILITY OF ARTIFICIAL RECHARGE
TO THE HIGH PLAINS AQUIFER,
NORTHWESTERN OKLAHOMA

By

HAROLD O. WHITE, JR.

Bachelor of Science

College of William and Mary

Williamsburg, Virginia

1980

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 1984

FEASIBILITY OF ARTIFICIAL RECHARGE
TO THE HIGH PLAINS AQUIFER,
NORTHWESTERN OKLAHOMA

Thesis Approved:

Wayne A Pettyjohn

Thesis Adviser

Douglas C. Kent

A Hounslow

Norman N. Durham

Dean of the Graduate College

PREFACE

Agricultural prosperity in northwestern Oklahoma is inextricably linked to irrigation with ground water pumped from the High Plains aquifer. Annual withdrawals far exceed natural recharge and, as a result, water levels have declined by more than 100 feet in many areas during the past 40 years. Continued pumping at current rates will deplete large areas of the aquifer and render irrigation economically unfeasible in the future. Artificial recharge, where feasible, offers a means to augment the supply of water in storage and reduce, or possibly even halt, the rate of water-level decline. Because the High Plains aquifer underlies about 7,500 square miles of northwestern Oklahoma, a vast amount of data, from a variety of sources, had to be collected and interpreted. Ultimately, these data were incorporated into the synoptic regional evaluation presented here.

This thesis marks the first comprehensive analysis of artificial recharge to the High Plains aquifer in Oklahoma. Much of the data contained within these pages, whether or not a direct result of this study, can be used as a foundation for future, site-specific studies. Potential users of the investigative results include state and federal agencies, municipalities, industries, ground-water management districts, and farmers and ranchers. To accomodate such a broad audience, the general tone of the thesis is non-technical.

I would like to express my sincere gratitude to my major adviser, Dr. Wayne A. Pettyjohn, for granting me the opportunity to continue my education. Further, without his sage advice, and his support and trust, my tenure at Oklahoma State University would have been far less rewarding.

I am thankful to Dr. Douglas C. Kent for teaching me the fundamentals of computer modeling and for his invaluable assistance with the modeling portion of my thesis.

I am also thankful to Dr. Arthur Hounslow for teaching me organic and inorganic geochemistry, and for offering excellent suggestions for the improvement of my thesis.

Additional thanks are due Kelly Goff, School of Geology, and Brad Huffman, computer programmer, for their patient assistance in extracting meaningful data from obstinate microchips.

Special recognition, and appreciation, are accorded to Dr. William T. Back, of the U.S. Geological Survey, for his longstanding friendship and scholarly council.

I am also thankful to the U.S. Office of Water Policy for their generosity in funding this important research. Without their foresight and understanding this project might never have been undertaken. I am also indebted to the University Center for Water Research at Oklahoma State

University for awarding me a Presidential Fellowship for this investigation.

Finally, I would like to dedicate this work to my mother and father whose life-long support and guidance I truly revere.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

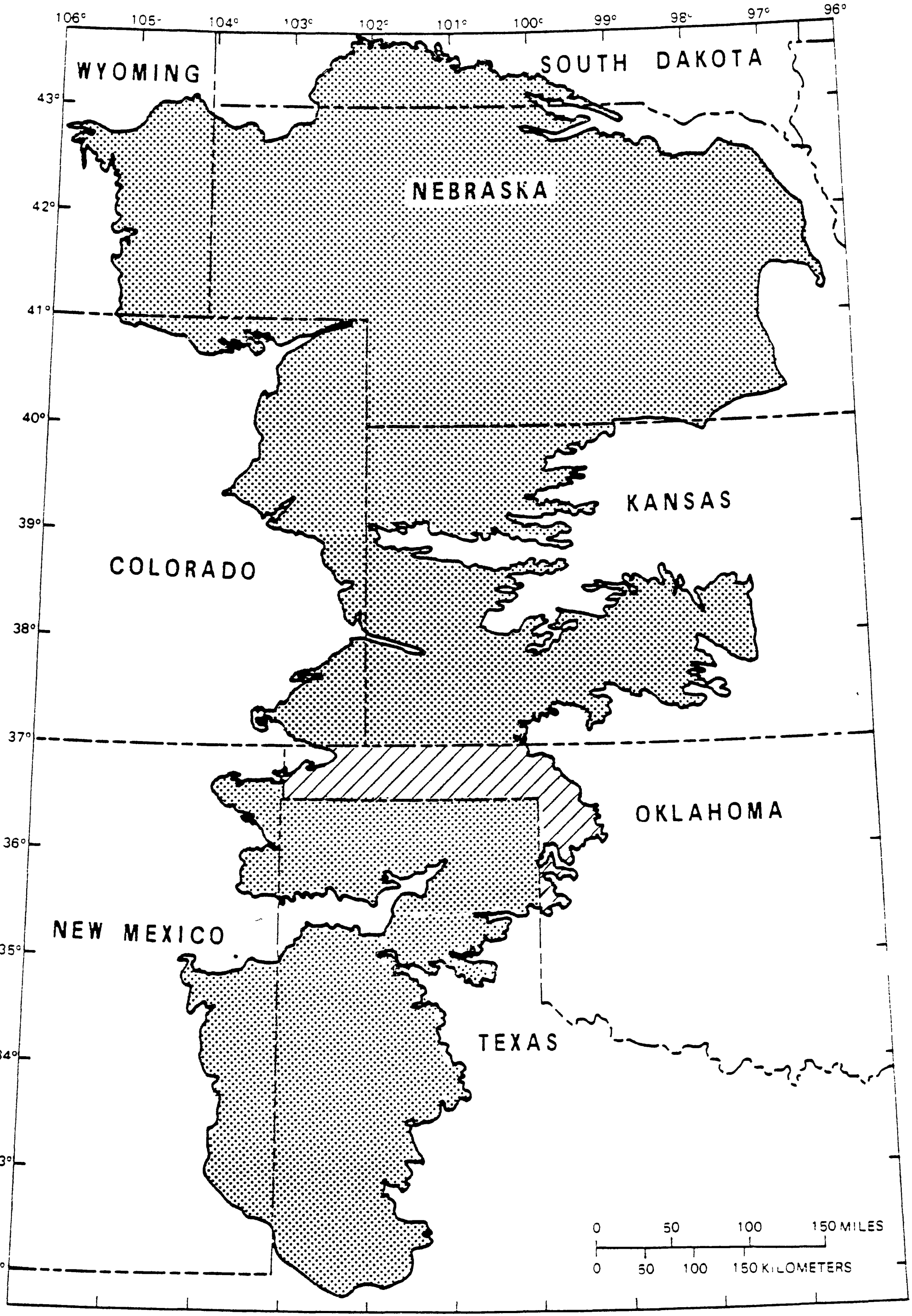
INTRODUCTION

General Overview

The High Plains aquifer is a vast underground reservoir that extends from South Dakota to Texas and underlies areas of eight states including much of northwestern Oklahoma (Figure 1). Parts of eight Oklahoma counties overlie the aquifer and constitute the study area (Figure 2).

The High Plains aquifer is comprised of the Ogallala Formation (Tertiary) and Quaternary alluvium and terrace deposits, and dune sand. This aquifer is the principal source of supply of ground water in northwestern Oklahoma as well as the Southern High Plains of Texas, western Kansas, and most of Nebraska.

Before widespread exploitation of the High Plains aquifer began in the 1940's, a dynamic equilibrium existed between the rates of natural recharge and discharge. As a result, water levels in the aquifer remained relatively stable. After World War II the number of irrigation wells tapping the High Plains aquifer began to increase steadily. This increase was spawned by the seemingly inexhaustible supply of good quality water, abundant and inexpensive reserves of locally occuring natural gas, and the appealing



Source: Havens and Christenson (1984).

Figure 1. Location of the High Plains Aquifer (shaded) and Study Area (hachured)

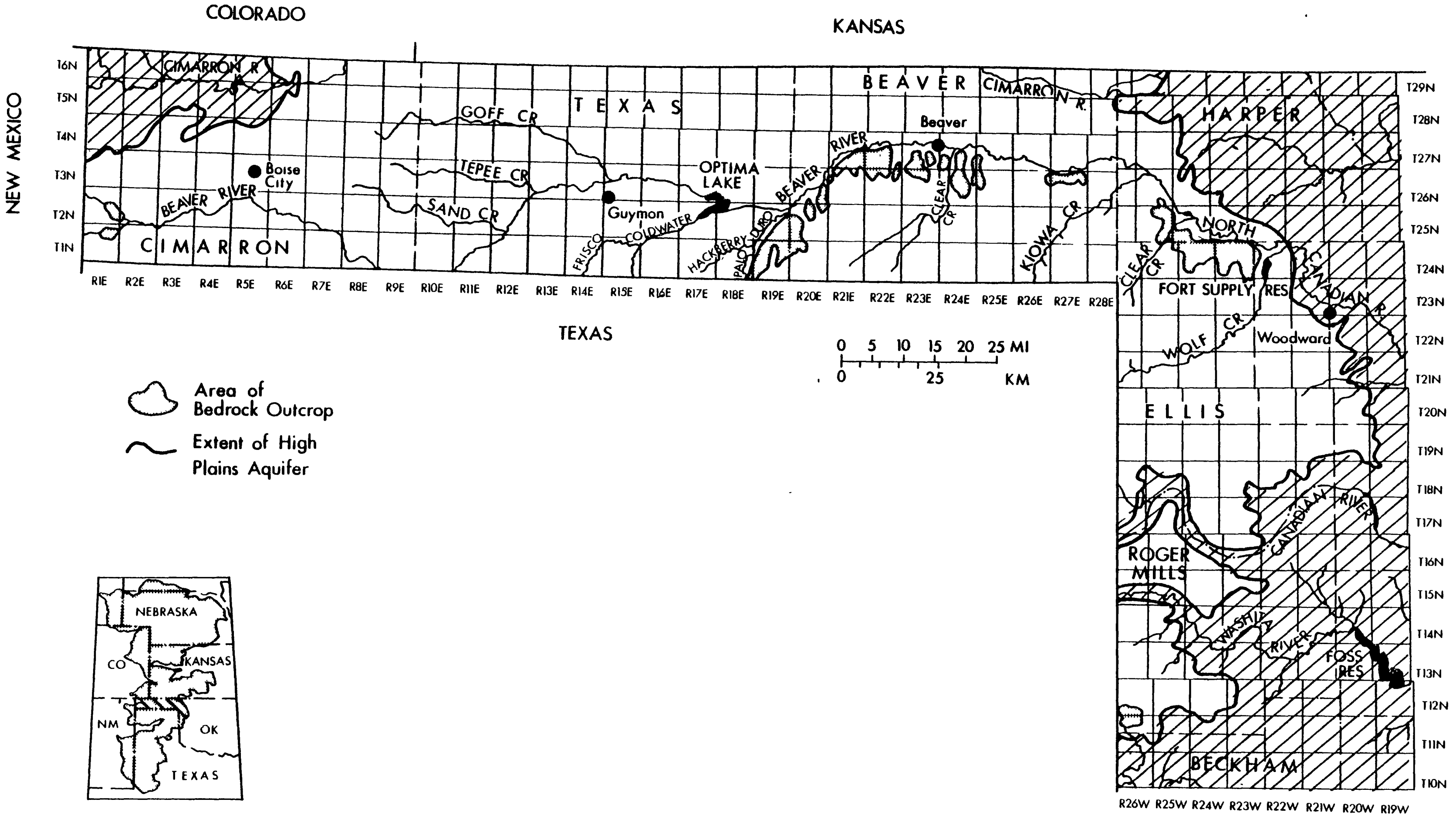


Figure 2. Extent of the High Plains Aquifer in Northwestern Oklahoma

economic returns from irrigated crops. The early 1960's saw the introduction of center pivot irrigation systems. As the use of these systems became more widespread, the rate at which new wells were drilled increased rapidly (Figure 3).

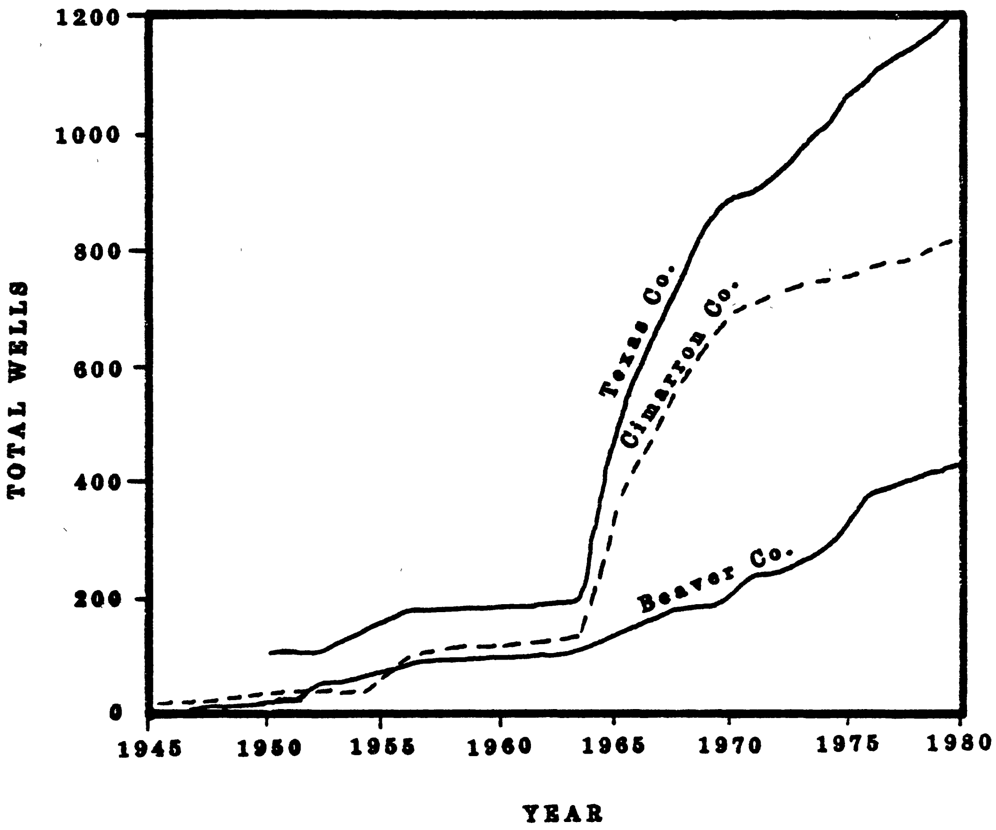
Much of the region underlain by this aquifer now supports extensive agriculture through intensive irrigation. Although the High Plains aquifer underlies less than 10 percent of the total area of Oklahoma, this region yields a significant portion of the wheat, grain sorghum, and corn produced within the State. Seventy-five percent of the State's total irrigated wheat, 85 percent of the total irrigated sorghum, and 76 percent of the total feed corn are harvested in northwestern Oklahoma (O.W.R.B., 1983).

Statement of the Problem

The study area receives an average of 18 inches of precipitation per year. Average annual evapotranspiration over the area is almost exactly the same, which effectively reduces the potential for ground-water recharge. Natural recharge to the High Plains aquifer is estimated to be less than 0.2 inch per year (Pettyjohn, White, and Dunn, 1983).

Over 2,000 high capacity irrigation wells tap the Oklahoma portion of the High Plains aquifer. Combined discharges from these wells far exceed the volume of annual recharge. Consequently, ground-water levels are declining at an alarming rate in many areas.

Declining water levels result in increased pumping



Source: O.W.R.B. (1980).

Figure 3. High Capacity Well Development in the Panhandle Counties

costs, decreased well yields, and shortened aquifer life. In many areas of northwestern Oklahoma the current depth to water exceeds 150 feet as compared to 100 feet in the 1940's (Schoff, 1943). As the depth to water increases, more energy is required to extract the water. This increase is reflected in higher costs per acre-foot of water extracted. Declining water levels imply that the saturated thickness is decreasing and, therefore, that the amount of water available for pumping is also reduced. In order to pump the same quantity of water a well must be pumped for longer periods, or pumped in conjunction with other wells. When an aquifer can no longer supply water to wells, its life has physically ended. The economic life of an aquifer is exhausted when the cost of pumping exceeds the benefits provided by the water. Escalating energy costs, coupled with decreasing saturated thickness and increasing depth to water, will render continued irrigation of a large portion of the study area economically unfeasible in the future. This would force reversion to dryland farming and severely reduce production. Agricultural production from northwestern Oklahoma represents a significant portion of the State's total production. The adverse economic impact created by reduced agricultural production would be felt not only within the State or the High Plains region, but possibly throughout the Nation (O.W.R.B., 1983).

Purpose and Objectives

The purpose of this study is to determine if it is feasible to reduce, or halt, the rate of water-level decline by artificial ground-water recharge. Artificial recharge refers to techniques that serve to augment the quantity of water in underground storage by increasing the rate at which water infiltrates into the aquifer. Factors affecting the feasibility of artificial recharge include; (1) a source of water available for recharge, (2) proximity of the recharge site to the source of water, (3) favorable topographic relief and attitude of the adjacent land, (4) reasonably high permeability of near-surface materials at the site, (5) acceptable quality of the source, and (6) land availability.

The objectives of this study are fourfold; (1) the identification of those areas in northwestern Oklahoma where significant water-level declines have either already caused problems or will in the foreseeable future, (2) the identification of those areas where artificial recharge is potentially feasible, (3) to design potential artificial recharge systems, and (4) to develop a computer simulation of the effects of artificial recharge at selected sites.

Methods of Investigation

To determine the feasibility of artificial recharge to the High Plains aquifer in northwestern Oklahoma, existing reports and data concerning the geologic, hydrologic, climatic, and agronomic characteristics of the region were studied. Then, using the amassed data base, potential recharge sites were identified and recharge system designs developed. Finally, a computer model was developed to evaluate the effectiveness of artificial recharge at two specific sites. It is assumed that the inputs to the model could be modified according to the specific characteristics of any potential recharge site either within the study area, or the High Plains region as a whole.

CHAPTER II

PREVIOUS RESEARCH

Tertiary deposits near the town of Ogallala in Keith County, Nebraska, were named the Ogallala Formation by Darton in 1899. He considered the "Tertiary Grit", "Mortar Beds", and "Magnesia" of Kansas and southward to be part of his Ogallala.

Gould (1905) conducted one of the earliest geologic investigations in northwestern Oklahoma as part of his statewide survey of water resources. Thompson (1921) conducted a cursory evaluation of the irrigation potential of aquifers near Gage, Oklahoma. He did not, in fact, even recognize that the Tertiary formations, which supplied much of the ground water in the area, were represented by the Ogallala Formation as described by Darton (1899).

Schoff (1939, 1943) conducted detailed studies of the "Geology and Ground Water Resources" in Texas County (1939), and Cimarron County (1943). A later map by Schoff (1955) showing the major aquifers of Oklahoma and an accompanying text was published by the Oklahoma Geological Survey. Marine and Schoff (1962) later co-authored "Ground Water Resources of Beaver County, Oklahoma".

At least a half dozen hydrologic atlases have been published that cover a portion of northwestern Oklahoma that is underlain by the High Plains Ogallala aquifer. Wood and Hart (1967) surveyed the availability of ground water in Texas County. Two ground water reconnaissance studies were completed in the early 1970's. The first, by Sapik and Goemaat (1973), surveyed Cimarron County, and the second, (Morton and Goemaat, 1973) appraised Beaver County. Morton (1973) published another atlas that evaluated the occurrence of ground water underlying the Panhandle from formations other than the High Plains Ogallala aquifer. Reconnaissance studies were conducted on the water resources in the Clinton and Woodward quadrangles by Carr and Bergman (1976), and by Morton (1980). Loo (1972) completed a Master's thesis from Oklahoma State University which examined the influence of vertical variations in Ogallala formation lithology on a mathematical computer model. DeVries and Kent (1973) also considered the influence of vertical variations in Ogallala lithology in Texas county, Oklahoma. They concluded that future computer models should account for vertical variations in lithology. Pettyjohn, White, and Dunn (1983) prepared an atlas that described the water resources of Oklahoma including the High Plains aquifer.

The United States Congress passed a law in 1976 authorizing the "Six-State High Plains-Ogallala Aquifer Area Study". The purpose of this law was essentially to analyse the water supply needs of the High Plains on a regional and state level, and develop management alternatives to promote the economic vitality of the region. These management alternatives were intended to insure that the region continued to produce a majority of the Nation's food supply. The Economic Development Administration was charged with supervising the study. The results of this study were published both on a regional scale (High Plains Assoc., 1982) and at the state level (O.W.R.B., 1983).

In 1978 the U.S. Geological Survey initiated a 5-year study of the High Plains regional aquifer system. The purpose of the study was to gather and generate hydrologic data for the evaluation of the long-term development of the aquifer. A finite-difference computer model (based on Trescott, Pinder, and Larson, 1976) was used to predict the response of the aquifer to alternative changes in ground-water management strategies (Havens and Christenson, 1984). Numerous publications have since resulted from this 5-year study. Many of the reports have been regional overviews and several are listed in the selected references.

Detailed studies conducted by the U.S. Geological Survey within Oklahoma have resulted in a wealth of published reports. Morton (1980) utilized the digital-model to project saturated thickness and recoverable water in Texas County. Havens (1982a, b, c, and d) produced a suite of hydrologic maps for the High Plains aquifer, which included a structural contour map on the base of the aquifer, altitude of the 1980 water table, altitude of the predevelopment water table, and the 1980 saturated thickness of the aquifer. Havens (1983) later completed a map depicting water-level changes in the aquifer from predevelopment to 1980. Krothe and Oliver (1982) studied sulfur isotopic composition and water chemistry of the aquifer and found that concentration of dissolved solids increases from west to east (the direction of regional ground-water flow). Havens and Christenson (1984) used the computer model to predict water levels and volume of water in storage for the years 1993 and 2020. Hart, Hoffman and Goemaat (1976) conducted a comprehensive study of the hydrogeology of the Oklahoma Panhandle, which included the Permian and Mesozoic units.

Though Theis (1937) calculated that the amount of natural recharge over the southern High Plains was only a fraction of an inch and intimated that increased pumpage would eventually lead to ground water depletion, there have been no scientific artificial recharge experiments conducted in northwestern Oklahoma. The need for such studies, however, has been recognized since 1949. In that year, M. B. Cunningham, then Superintendent and Engineer with the Oklahoma City Water Department, noted that there were "a number of locations in the State where a thorough investigation should be made for possible beneficial use [of artificially recharged fresh water]" (1949, p.51). Cochran (1981) briefly summarized the only artificial recharge attempts to date in Oklahoma. These were conducted by the Southwest Soil and Water Conservation District from 1967-

1970. Thirty-seven wells were drilled into the Dog Creek Shale and Blaine Gypsum Formations to allow irrigation runoff to flow back into the aquifers. Though these efforts met with some success, questions arose about possible contamination of the aquifers.

Artificial recharge experiments in other areas of the High Plains have been conducted since the late 1940's, particularly in the Southern High Plains of Texas (Myers, 1964; Hauser and Lotspeich, 1967; Dvoracek and Wheaton, 1968; Dvoracek and Peterson, 1971; Jones and Schneider, 1972; and Pool, 1977). The Texas High Plains Underground Water Conservation District No. 1 has conducted numerous hydrologic studies within their jurisdiction, including artificial recharge and methods to improve irrigation efficiency. Since mid-1981 this agency has focused attention on a new method to extend the life of the High Plains aquifer called "Secondary Recovery". This method calls for air to be injected into the aquifer, which causes the release of capillary water to the water table. Results of three major field experiments were published in 1982.

The U.S. Geological Survey has evaluated recharge in most of the states that overlie the High Plains aquifer. In Texas (Keys and Brown, 1971; Brown and Signor, 1973; Bassett et. al., 1978), New Mexico (Havens, 1966), Colorado (Boettcher, 1966), Nebraska (Lichtler, Stannard, and Kouma, 1980), Kansas (Gillespie and Slagle, 1972), and South Dakota (Kolm and Case, 1983).

Artificial recharge has been used throughout the world for over 200 years for a variety of purposes, including ground-water management, waste-water rejuvenation, reduction of land subsidence, increased well yields, inhibition of saline water intrusion, and secondary recovery of oil (Pettyjohn, 1981). Countless symposia and conferences have been dedicated to the broad topic of artificial recharge. Among the more well known are the Symposium of Haifa (UNESCO, 1967), Water Reuse Symposium I and II (Am. Wat. Works Assoc. Res. Found., Pomona, CA, 1979; Wash., D.C., 1981), and the Ogallala Aquifer Symposium, 1970 (Lubbock, Texas).

CHAPTER III

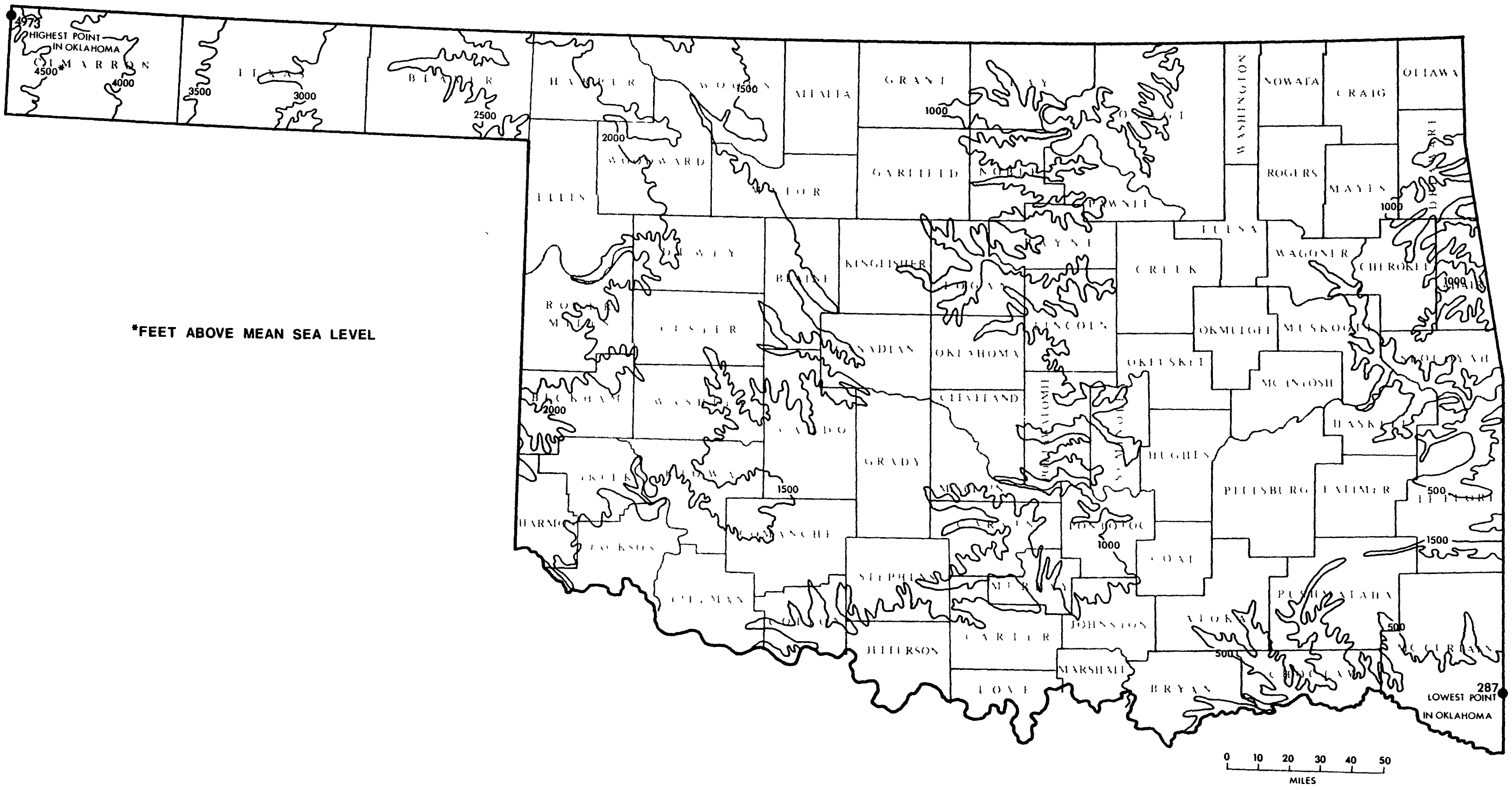
GENERAL FEATURES OF NORTHWESTERN OLKAHOMA

Topography

The Oklahoma portion of the High Plains/Ogallala aquifer underlies an area of approximately 7,000 square miles in the northwestern part of the State, which includes nearly the entire Panhandle. The Panhandle lies in the Great Plains physiographic province while the eastern part of the study area lies in the Osage Plains section of the Central Lowlands province (Havens and Christenson, 1984). The generally flat land surface slopes from west to east at a rate of about 15 feet per mile. Elevations range from roughly 4,800 feet in the west to 2,000 feet in the east (Figure 4). Major drainages, the Beaver/North Canadian River and numerous tributaries, have dissected the otherwise featureless plain. Relief is typically less than 50 feet, but locally can be as high as 200 feet where streams are deeply incised.

Climate

The climate ranges from semi-arid in the Panhandle to sub-humid toward the eastern margin of the study area (O.W.R.B., 1980). Precipitation, which increases from less



Source - OSU Cartography Service (1979)

Figure 4. Generalized Topography of Oklahoma

than 16 inches in the west to about 24 inches along the eastern margin of the High Plains aquifer, averages about 18 inches (Figure 5). Graphs of mean monthly precipitation for Boise City, Beaver, and Laverne indicate that the greastest amount of rainfall occurs from May through August (Figure 6). Evapotranspiration isopleths closely mirror those of precipitation both in distribution and value (Figure 7), which reduces the ground-water recharge potential of the rainfall. Annual snowfall on the other hand averages over 20 inches in the west and decreases to less than 8 inches in the east (Figure 8).

Agriculture

Northwestern Oklahoma supports the most extensive agricultural activities in the State due largely to intensive irrigation with water from the High Plains aquifer (O.W.R.B., 1980). The numbers of irrigated acres in this region has historically increased and parallels the rise in construction of irrigation wells. Since the late 1960's a yearly average of more than 200,000 acres are irrigated in the three Panhandle counties alone (O.W.R.B.). Despite the fact that the High Plains aquifer underlies less than 10 percent of Oklahoma, the overlying lands produce a large majority of the wheat, sorghum and corn harvested in the State (O.W.R.B., 1983). Three-quarters of both the total irrigated wheat, and feed corn are raised on these lands. Eighty-five percent of the total irrigated sorghum is also

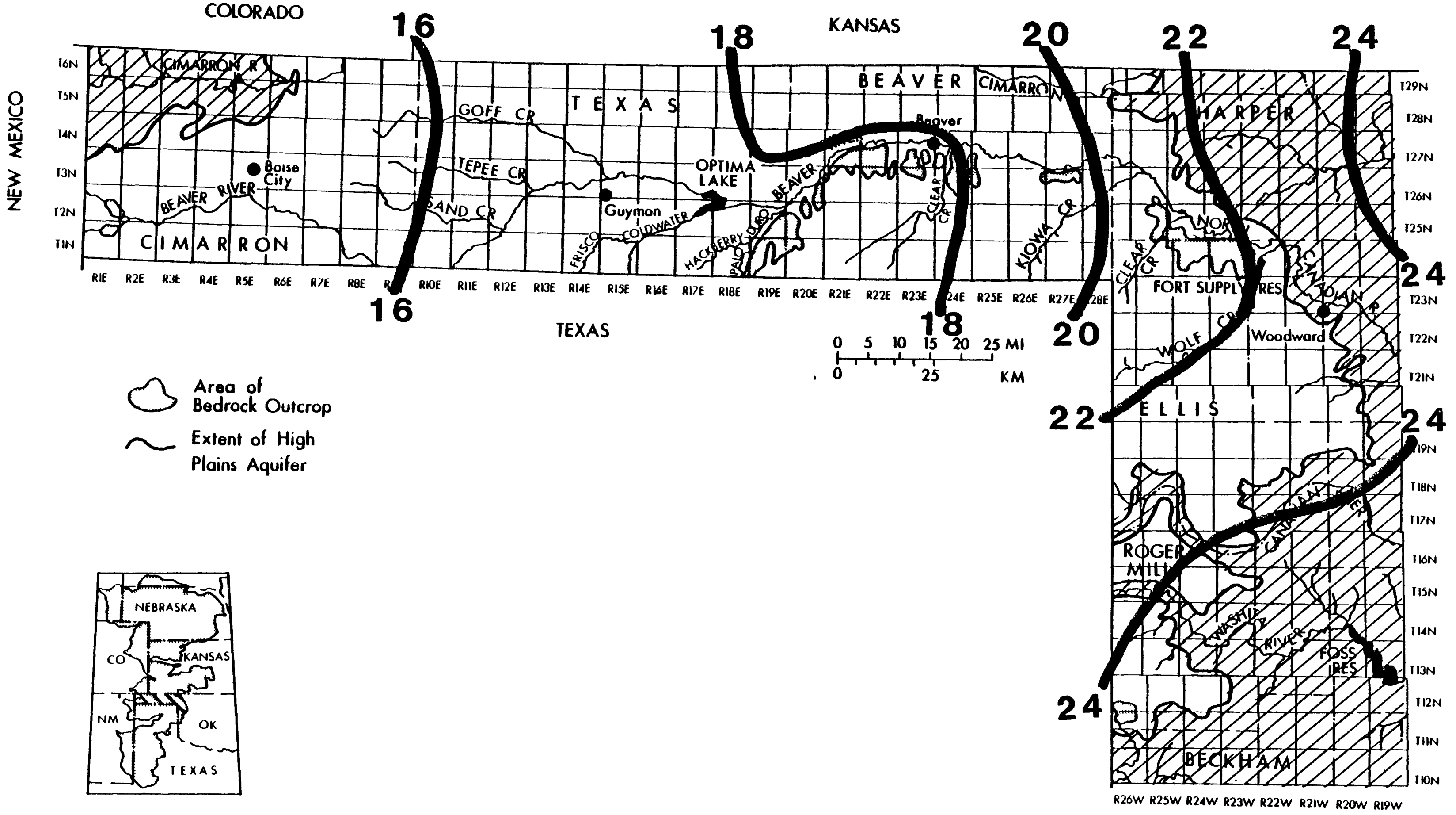
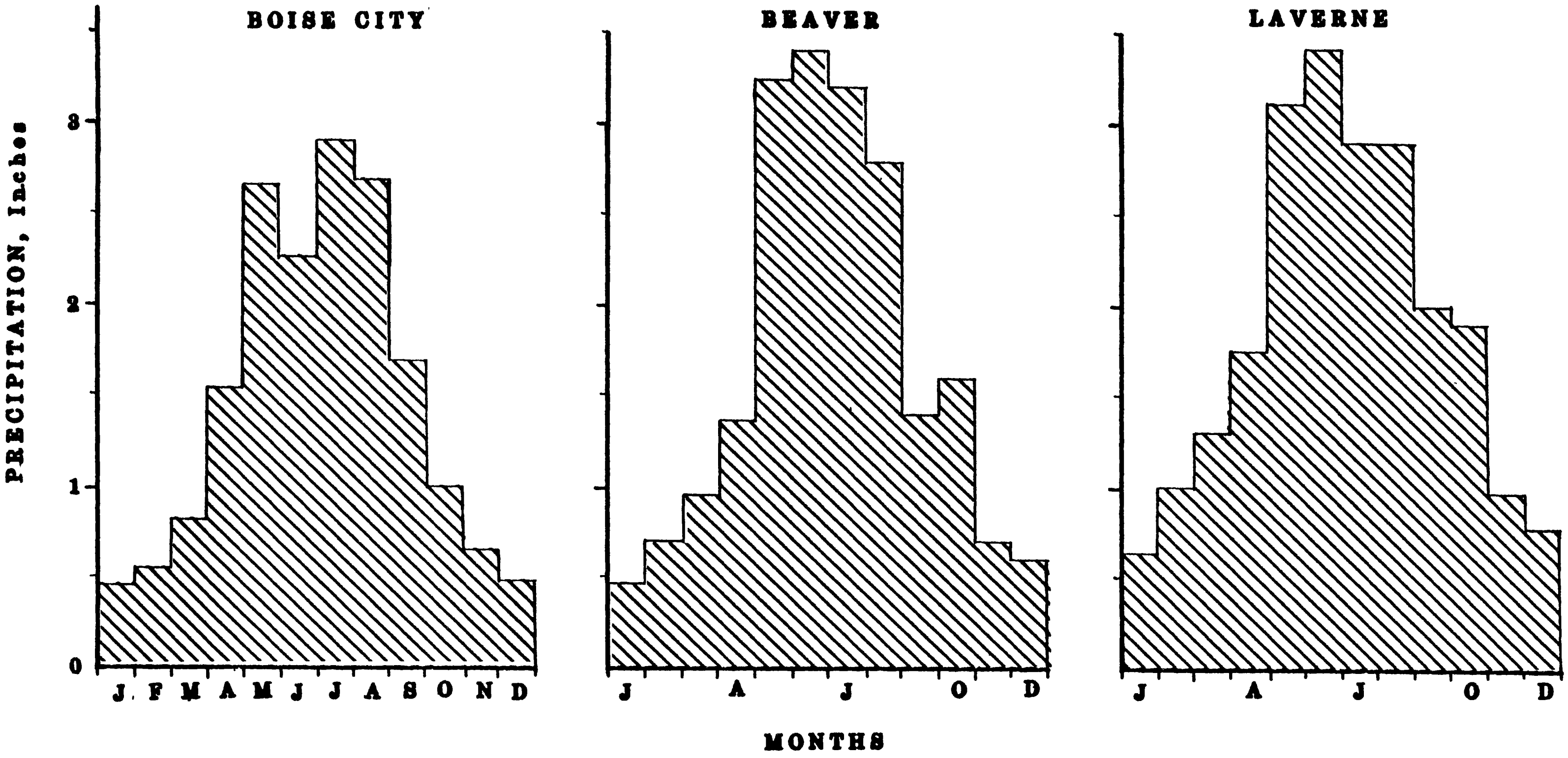


Figure 5. Average Annual Precipitation in Northwestern Oklahoma



Data: N.O.A.A.

Figure 6. Normal Mean Monthly Precipitation for Boise City, Beaver, and Laverne

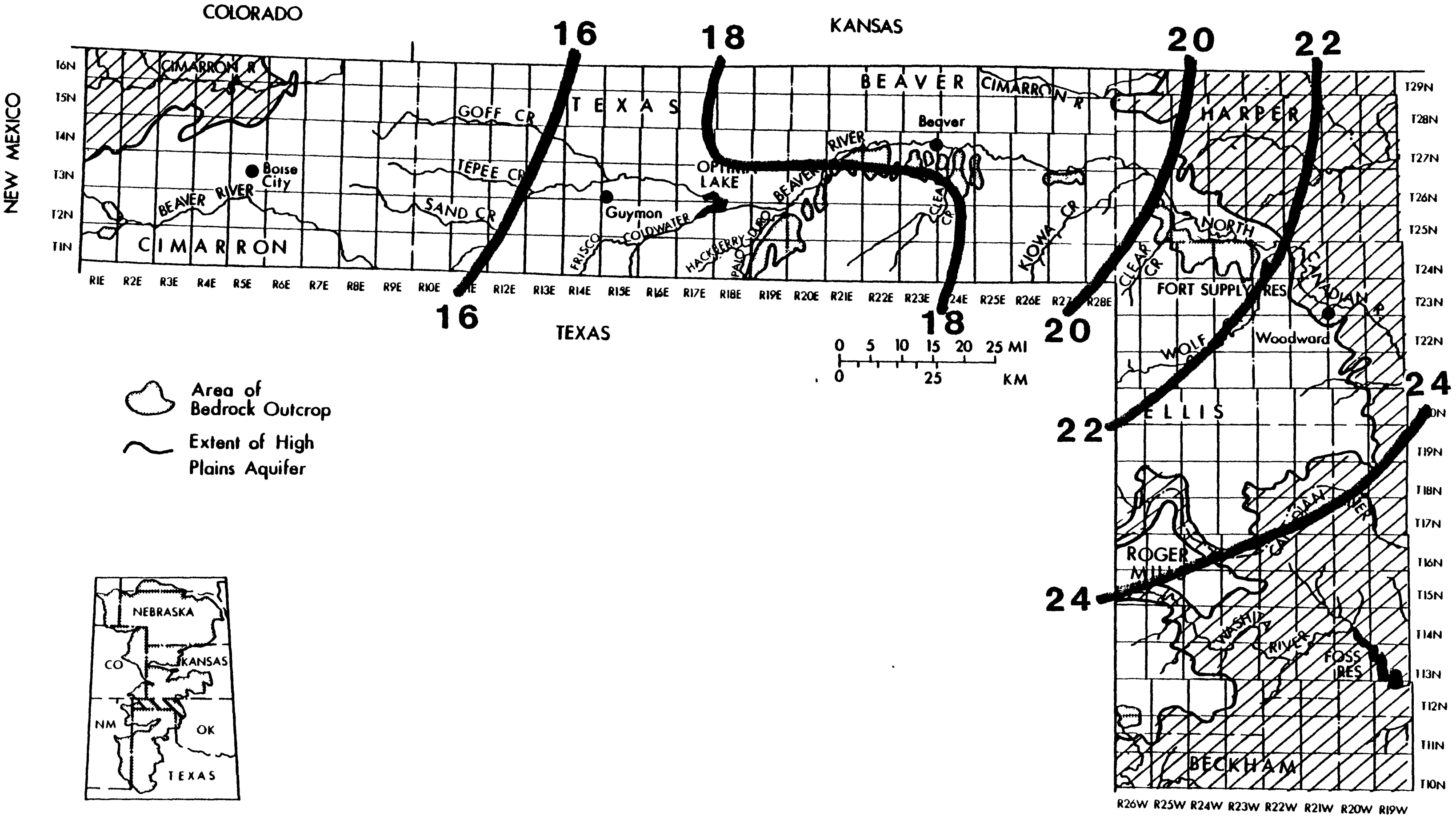


Figure 7. Average Annual Evapotranspiration in Northwestern Oklahoma

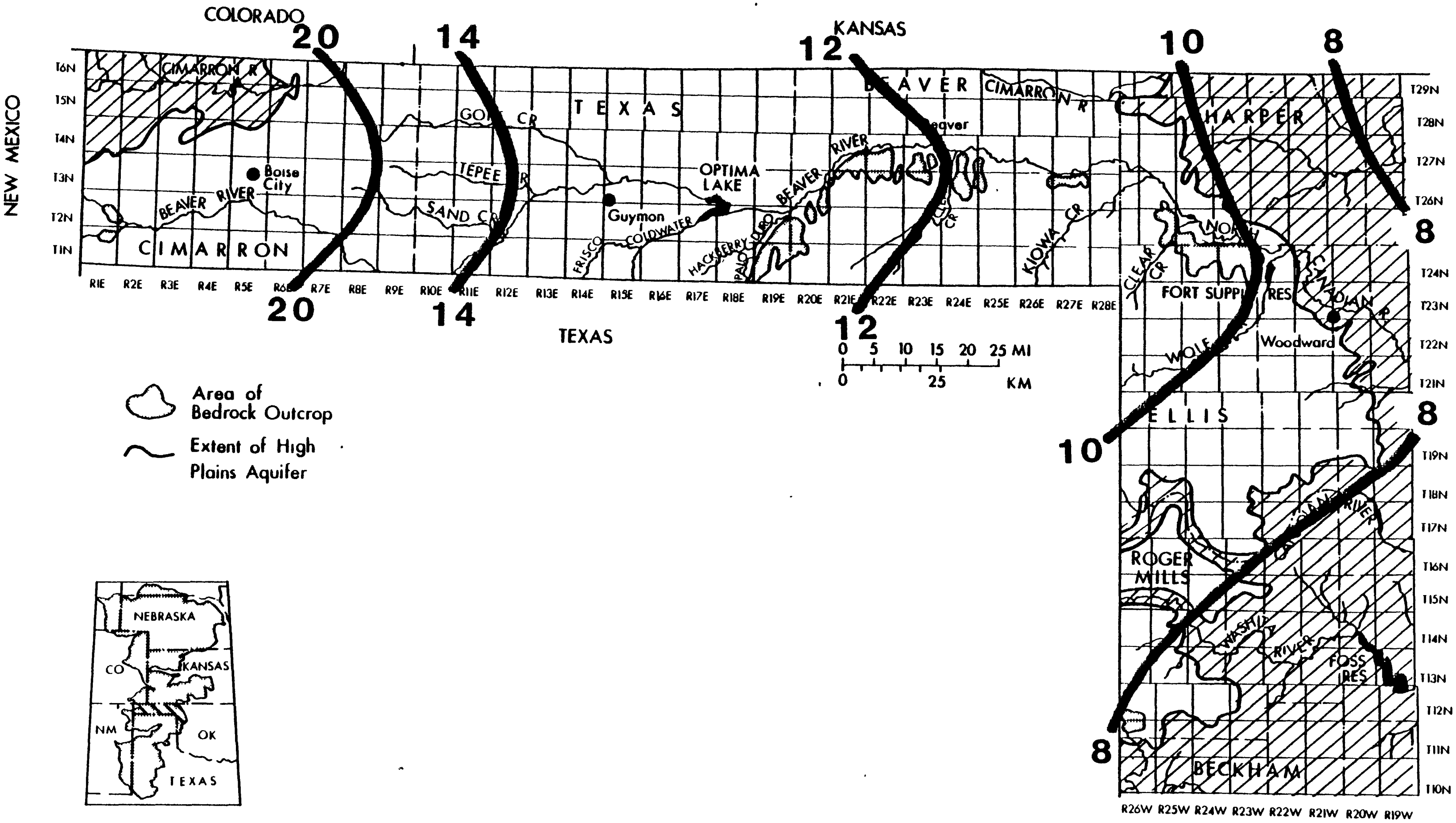


Figure 8. Average Annual Distribution of Snowfall in Northwestern Oklahoma

produced here (O.W.R.B., 1983). These feed crops plus irrigated alfalfa support a thriving fed-cattle industry.

Geology

Gould (1905) conducted one of the earliest geologic investigations in northwestern Oklahoma as part of his statewide survey of water resources. Subsequently, the geology of the three Panhandle counties has been studied in detail; Rothrock (1925), and Schoff (1943) examined Cimarron County, Gould and Lonsdale (1926a), and Schoff (1939) analyzed Texas County, and Gould and Lonsdale (1926b) surveyed Beaver County. The eastern part of the area has not been as extensively studied because of significantly less ground-water development. The geologic units that occur in northwestern Oklahoma are summarized in Table 1.

Surficial Units

Rocks of Permian age are the oldest units that crop out in the study area. The Lower Cretaceous Dakota Sandstone crops out in limited exposures in southwestern Cimarron County. The Ogallala Formation (Tertiary) is the principal surficial geologic unit in northwestern Oklahoma, covering an area of approximately 7,000 square miles (Havens and Christenson, 1984).

The first reference to the Ogallala Formation was made by Darton in 1899 as he described Tertiary deposits near the town of Ogallala in Keith County, Nebraska. He recognized

TABLE I

GENERALIZED STRATIGRAPHIC SECTION OF GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES

System	Series	Stratigraphic unit		Thickness (feet)	Physical character	Water supply
Quaternary	Holocene and Pleistocene		Dune sand	0-50±	Light-brown, fine to medium sand with lesser amounts of clay, silt, and coarse sand formed into small hills and mounds by wind.	Lies above the water table and does not yield water to wells The dunes have a high infiltration rate and are important areas of ground-water recharge
			Alluvium and terrace deposits	0-100±	Light-brown or gray, silt, clay, sand, and gravel along the major streams and valleys and in some adjacent uplands Material is moderately permeable	Deposits usually provide adequate water for stock and domestic use and, where sufficiently saturated, yield water for irrigation.
Tertiary	Pliocene		Basalt	0-85±	Dark, dense, poorly conductive vesicular rock forming cap rock of Black Mesa.	Yields no water to wells
			Ogallala Formation	0-650±	Brown to light-gray but may include red, pink, yellow, black and white interfingering lenses of gravel, sand, silt, clay, limestone, and mixtures of these In some places consolidated by lime cement, but mostly unconsolidated	The Ogallala Formation is the principal water-bearing deposit in the Panhandle and yields as much as 2,500 gal/min
Cretaceous	Upper Cretaceous	Colorado Group	Greenhorne Limestone	0-200±	Gray, fossiliferous limestone and calcareous shale. Limestone is poorly conductive	Not known to yield water to wells
			Graneros Shale		Gray shale Shale is poorly conductive	
	Lower Cretaceous		Dakota Sandstone	0-200±	Buff to light-brown, fine to medium grained, thin to massive bedded sandstone with interbedded shale, Unit is moderately to highly conductive	Adequate for stock and domestic and where sufficiently saturated yields as much as 150 gal/min.
Cretaceous	Lower Cretaceous	Purgatoire Formation	Kiowa Shale Member	0-65±	Gray to black, fossiliferous shale with sandstone in the upper part Shale is poorly conductive	Not known to yield water to wells
			Cheyenne Sandstone Member	0-125±	White to buff, massive fine to medium-grained sandstone, containing some conglomerate in the lower part Sandstone is moderately to highly conductive	Locally yields as much as 500 gal/min Usually through multiple screen wells that also obtain water from the overlying Ogallala.
Jurassic	Upper Jurassic		Morrison Formation	0-470±	Varicolored shale, fine to very coarse-grained sandstone, limestone, dolomite, and conglomerate Formation is poorly conductive except for isolated lenses of sandstone	Sandstone units provide water for stock and domestic wells
			Exeter Sandstone[1]	0-50±	Massive, white to buff, fine to medium-grained sandstone Sandstone poorly to moderately conductive	Sandstone may yield as much as 20 gal/min.
Triassic	Upper Triassic	Dockum Group	Upper sandstone	0-450±	Varicolored siltstone or claystone, conglomerate, fine-grained sandstone, and limestone Original conductivity low but fractures and solution openings provide some conductivity	Adequate for stock and domestic supplies
			Lower sandstone	0-200±	Varicolored, fine to medium-grained sandstone with some clay and interbedded shale Conductivity ranges from poor to moderate.	Provides water to stock and domestic wells and also to some irrigation wells where sufficient saturated sandstone exists.
Permian	Upper permian		Undifferentiated red beds	1,000±	Shale, siltstone, sandstone, dolomite, and anhydrite, local limestones and salt.	Supplies small quantities to stock wells, but will not supply enough for for irrigation wells

[1] Equivalent to Entrada Sandstone of some geologists

SOURCE: Adapted from D.L. Hart, Jr. et.al., USGS WRI 25-75, 1976.

that the "Mortar Beds", "Tertiary Grit", or "Magnesia" of Kansas and southward, and a calcareous formation "extending from Kansas and Colorado far into Nebraska" belonged to the same formation. He applied the "distinctive name Ogallala formation" to these sedimentary deposits (Darton, 1899 p.734). Darton described the unit as an

> . . .impure calcareous grit, or sand cemented with carbonate of lime. At its base there are often beds of conglomerate with pebbles, consisting mainly of gray sandstone or limestone. Throughout its mass there are scattered pebbles of crystalline rocks from the Rocky Mountains, streaks of pebbly sand, and thin ledges of sandstone. The harder calcareous beds are of white or cream color, and outcrop in irregular cliffs along the slopes of depressions. Some softer intercalated beds of sandy character are of light-pinkish color (p. 741).

It has since been described by numerous authors as consisting of interbedded sand, siltstone, clay, lenses of gravel, thin limestone, and a caliche caprock. Within the study area the thickness of the Ogallala ranges from 0 to more than 600 feet, which is primarily due to the irregularity of the pre-Ogallala surface (Havens and Christenson, 1984). The contact between the Ogallala and underlying Permian and Mesozoic strata represents an unconformity.

There has been much debate about subdivisions within the Ogallala. It is generally agreed that the formation consists of three sub-units; Valentine, Ash Hollow, and Kimball. Early workers based their divisions on occurrence of vertebrate fossils. More recent research (Merriam, 1955) indicates that fossil seeds are much more useful, and reliable, for differentiating zones within the Ogallala.

Various workers have referred to these units as formations within the "Ogallala Group" (Lugn, 1939), as members (Merriam and Frye, 1954), and as floral zones (Frye and Leonard, 1959).

The poorly consolidated, heterogeneous alluvial deposits that comprise the Ogallala were derived from erosion of the ancestral Rocky Mountains (Havens and Christenson, 1984). Detrital material washed down into valleys, eventually filling them. As the deposits accumulated, alluvial fans were formed. Gradually, the intervalley plains were covered by coalescence of these fans into a broad alluvial plain (Frye, 1970). Deposition slowed as the Rockies wore down and the climate became drier. Erosion assumed prominance and the Ogallala was cut off from its source area. Ogallala sediments have been continually reworked by streams and wind, which has locally imparted considerable relief to the High Plains surface (Camp Dresser and McKee, Inc. et al., 1982).

Pleistocene and Recent deposits of alluvium, dune sand, and/or terrace deposits locally unconformably overlie the Ogallala. Alluvium and terrace deposits are more extensively developed along the north banks of the major drainages. This is probably due to the southerly migration of the streams down the regional dip of the underlying Permian rocks and to the influence of the prevailing southerly winds (Davis and Christenson, 1981).

For the most part there are no continuous zones of lower permeability between these materials and the Ogallala and they can be considered to be more or less hydrologically connected. It has, in fact, been recognized for years that a high amount of recharge to the Ogallala occurs in regions of extensive dune deposits (Theis, 1937; Schoff, 1939, 1943; Marine and Schoff, 1962; Marine, 1963; Cronin, 1964).

Subsurface Units

Red beds of Permian age underlie the entire study area. With the exception of the area west of Guymon in Texas County, they form the base upon which the Ogallala was deposited. Permian strata consist primarily of reddish-brown sandstone, siltstone, shale and sandy shales. Sandstones are generally fine to very-fine grained. Halite, gypsum, and silt are common accessory constituents. Thin lenses of limestone and dolomite are locally present (Hart, Hoffman, and Goemaat, 1976).

Triassic age sedimentary rocks of the Dockum Group subcrop throughout most of Cimarron County and in west-central Texas County. The Ogallala directly overlies these units across much of this area. The upper Dockum is predominantly a shale with beds of fine-grained shaly sandstone and siltstone. The lower Dockum is comprised mainly of slightly micaceous fine- to medium-grained sandstone. These rocks have a limited outcrop in northwestern Cimarron County and in central Texas County (Hart et al., 1976).

Rocks of Jurassic age include the Exeter Sandstone and the Morrison Formation. These rocks crop out in the northwestern corner of Cimarron County near Black Mesa, and overlie the Dockum in western Cimarron County. The Exeter is a fine- to medium-grained sandstone, which contains some gravel and lenses of clay. The Morrison Formation contains beds of shale, clay, marl, sandstone, conglomerate, limestone, dolomite, and some quartzite (Hart et al., 1976).

The Cretaceous System is represented, in ascending order, by the Purgatoire Formation, the Dakota Sandstone, and the Colorado Group, all of which are almost exclusively limited in outcrop to the northwestern corner of Cimarron County. The Purgatoire crops out in limited exposures in southwestern Cimarron County as well. Two distinct members comprise the Purgatoire Formation; the lower Kiowa Shale and the upper Cheyenne Sandstone. The Kiowa Shale is mostly a dark, clayey shale with local beds of sandstone. Thin dense limestone also occurs locally within the unit. The Cheyenne is a fine- to medium-grained massive sandstone. It is typically loosely consolidated and exhibits some cross-bedding. The Dakota Sandstone occurs in roughly the same localities as the Purgatoire Formation but is a much more resistant unit. Many of the buttes and canyon rimrocks are formed of the generally fine- to medium-grained Dakota Sandstone. The Colorado Group consists of two formations; the lower Graneros Shale and the upper Greenhorn Limestone. These units are composed of interbedded shale, marl, limestone, and bentonite. Distinguishing between these two units is difficult in Cimarron County. They are limited in their extent to the western half of the county and crop out only in the northwestern corner (Hart et al., 1976).

Tertiary basalts occur as cap rock in the extreme northwestern corner of Cimarron County. They occur outside the study area and have no hydrogeologic significance.

Hydrology

Surface Water

The major drainages in northwestern Oklahoma include the North Canadian (Beaver), Cimarron, and Washita Rivers. Larger tributaries include Sand, Tepee, Goff, Coldwater, Hackberry, Palo Duro, Kiowa, Clear , and Wolf Creeks. Typically these streams enter the study area from the west or southwest and flow eastward. Average annual runoff ranges from 0.2 inches in the Panhandle to less than 0.5 inches along the eastern boundary of the study area (Figure 9). Two major reservoirs, Optima and Fort Supply, are contained within the study area. Fort Supply lake was completed in 1942 and supplies water to the City of Fort Supply. Though construction of Optima Reservoir began in 1966 and was completed in 1978, it is still in the early filling stages (O.W.R.B., 1980).

Within the study area the U.S. Geological Survey maintains nine continuous-record surface-water stations (Figure 10). Two gaging stations are located on the Cimarron River (1545 and 1569), four along Beaver River (2325, 2332.10,

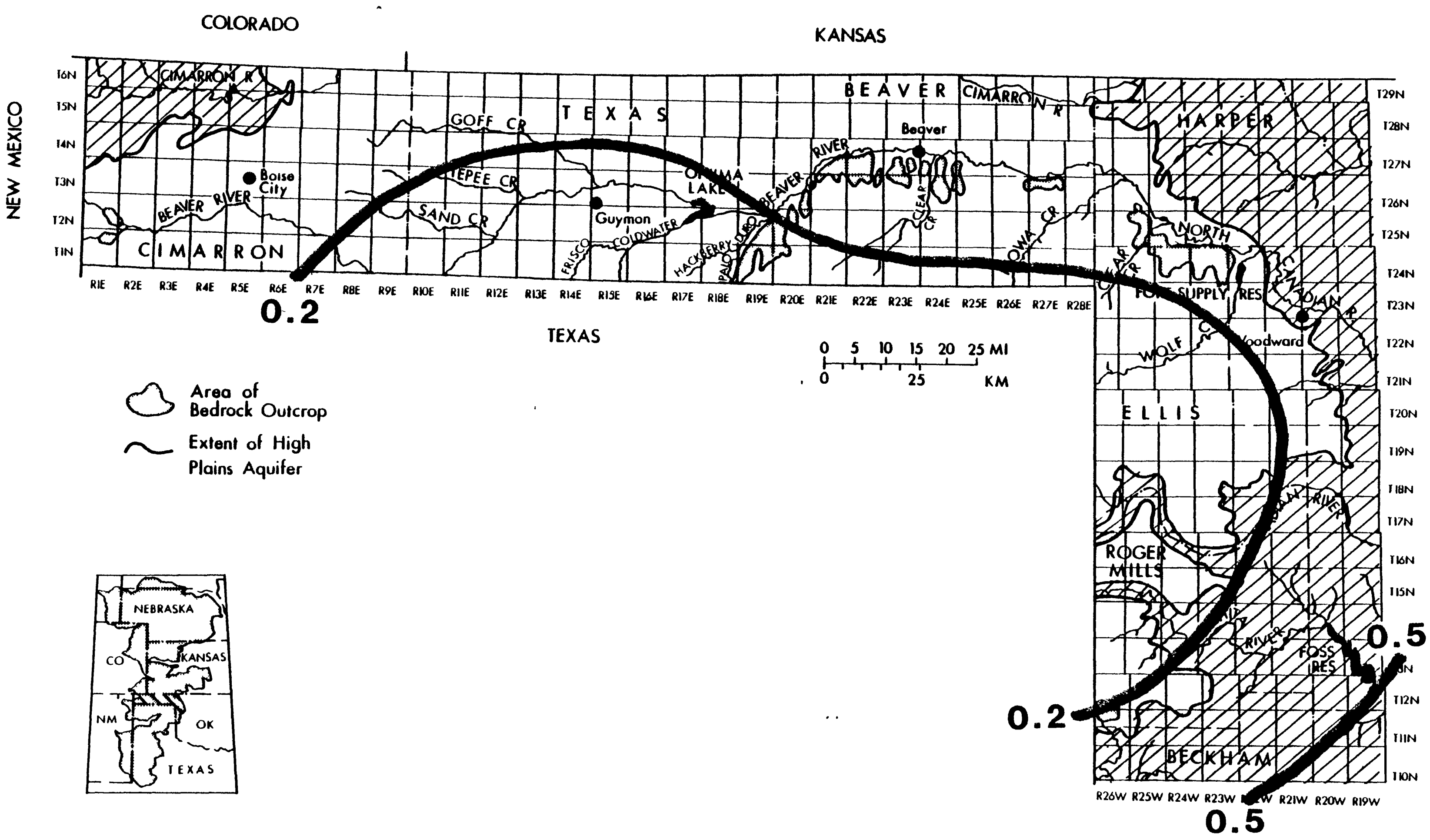
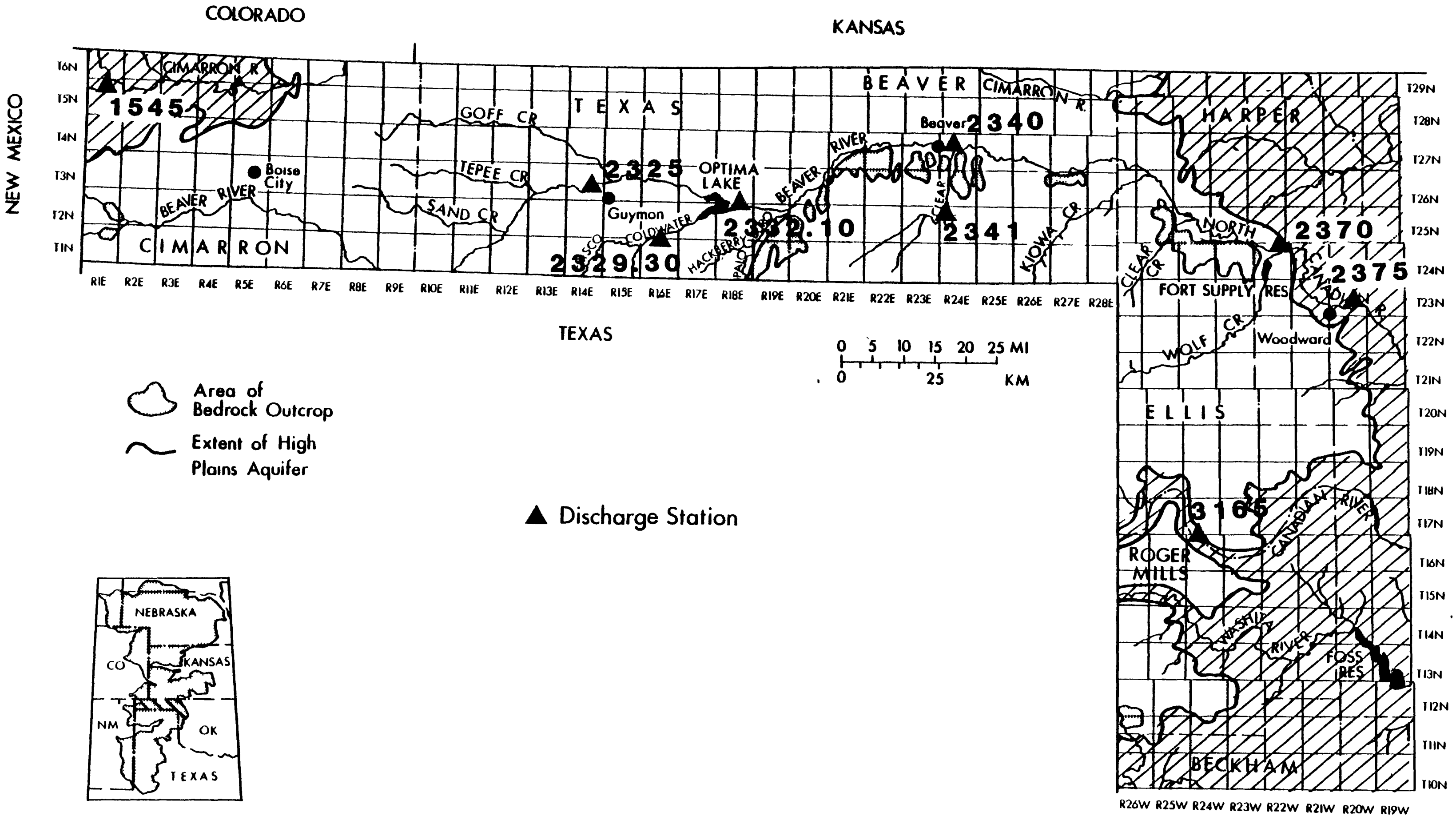


Figure 9. Average Annual Runoff in Northwestern Oklahoma

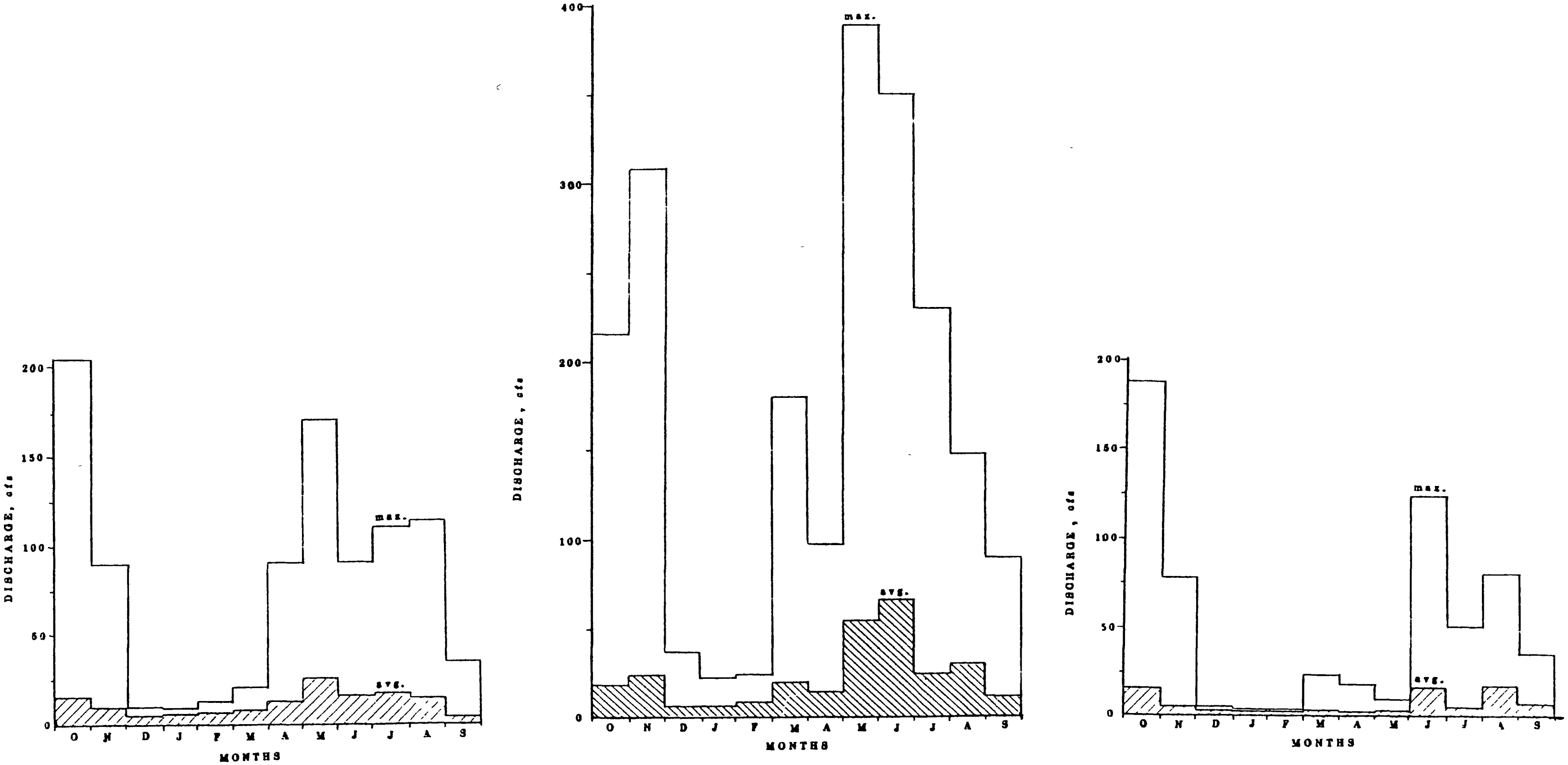


Source: U.S. Geological Survey

Figure 10. Locations of U.S. Geological Survey Stream Gaging Stations in Northwestern Oklahoma

2340, and 2370), two on major tributaries (2329.80 on Coldwater Creek, and 2341 on Clear Creek), and one on the Washita River (3165). Streamflow in all of these drainages is highly variable from month to month and from one year to the next. All of these streams are flashy: baseflow is generally low, commonly there are periods of no flow, but there are short periods of extremely high discharge. The hydrographs of stations 2325, 2340, and 2341 (Figure 11) illustrate this point. From these hydrographs it can be seen that the highest flows occur in the summer and fall. High summer streamflows are primarily the result of intense thunderstorms which are the dominant precipitation events.

The U.S. Geological Survey also conducts water-quality investigations on samples collected from various points in the study area (Figure 12). Based on water-quality data through 1979 (Table 2) a general trend of downstream deteriorating quality is evident for Beaver River. At all points sampled, the water is very hard (hardness in excess of 180 mg/L). Chloride concentrations also increase downstream but the water is suitable for public supply from the New Mexico state line eastward to Optima Reservoir. A major quality deterioration in Beaver River occurs between Guymon and Beaver. This is probably due to the influx of water from Palo Duro Creek, which receives mineralized groundwater discharge from underlying Permian rocks (O.W.R.B., 1980). Beaver River is unsuitable for public supply at Beaver and Woodward owing to the high chloride and sulfate



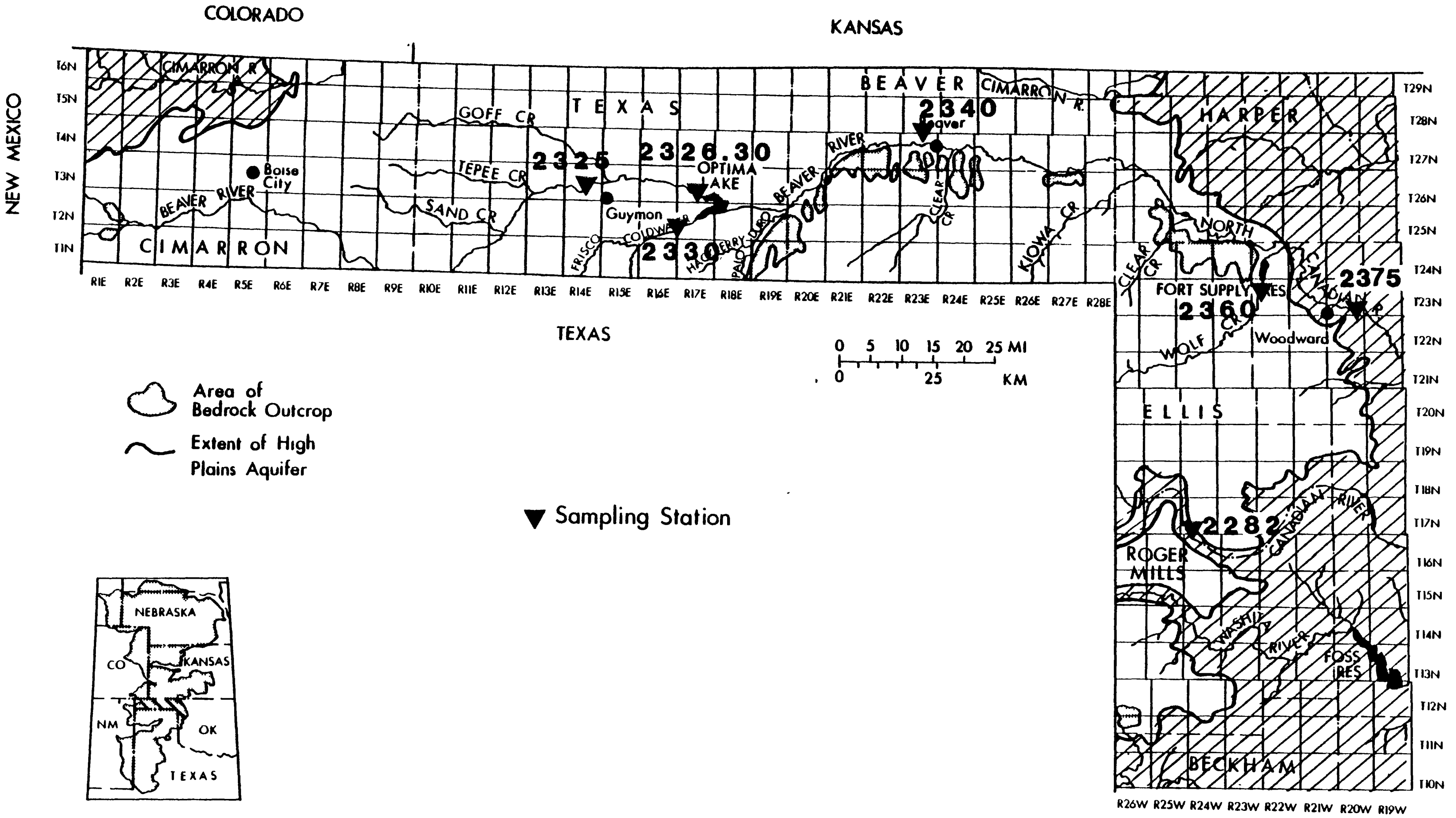
Station 2325--Beaver River at Guymon

Station 2340--Beaver River at Beaver

Station 2341--Clear Creek near Elmwood

Data: U.S. Geological Survey

Figure 11. Hydrographs of Mean Monthly Discharge for Stations 2325, 2340, and 2341



Source: Stoner (1981)

Figure 12. Water Quality Sampling Sites in Northwestern Oklahoma

TABLE II

ANALYSES OF WATER FROM SELECTED SURFACE-WATER SAMPLING SITES

Station	Average Hardness mg/L	Average Chloride mg/L	Average Sulfate mg/L	Salinity Hazard	Sodium Hazard (SAR)	Suitable Public Supply
2325 Beaver R. (Guymon)	220	16	52	Medium	Low (0.9)	Yes
2326.30	277	28	161	High	Low (1.4)	Yes
2330 Coldwater Creek	333	39	176	High	Low (1.3)	Yes
2340 Beaver R. (Beaver)	622	712	398	Very High	High (7.7)	No
2360 Wolf Creek	244	121	64	High	Low (2.2)	Yes
2375 Beaver R. (Woodward)	509	307	344	High	Low (4.4)	No
2282 Washita R.	445	343	296	High	Low (4.4)	No

Source: Stoner (1981)

concentrations. It is interesting to note that average concentrations of hardness, chloride, and sulfate decrease from a maximum level at Beaver downstream toward Woodward. This is probably due to dilution of Beaver River water by an influx of less mineralized water from major tributaries--Clear, Kiowa, and Wolf Creeks--of the Beaver along this lower reach.

Recharge

Numerous depressions, called Playas, dot the landscape in eastern Cimarron and western and northern Texas counties. Playas are natural surface runoff collection points from which water then either infiltrates or evaporates. Until recently it was believed that most of the playa water simply evaporated. Wood and Osterkamp (1984) presented strong evidence that most of the recharge to the High Plains aquifer in the Texas High Plains occurs through the annulus surrounding playa bottoms and not from sand dune areas.

Using a computerized stream hydrograph separation technique developed by Pettyjohn and Henning (1979), Pettyjohn, White, and Dunn (1983) calculated the effective regional ground-water recharge rate over the study area to be less than two-tenths of an inch per year (Figure 13).

Groundwater

Because of the similarity in the hydrologic properties of the Tertiary and younger units they are grouped together

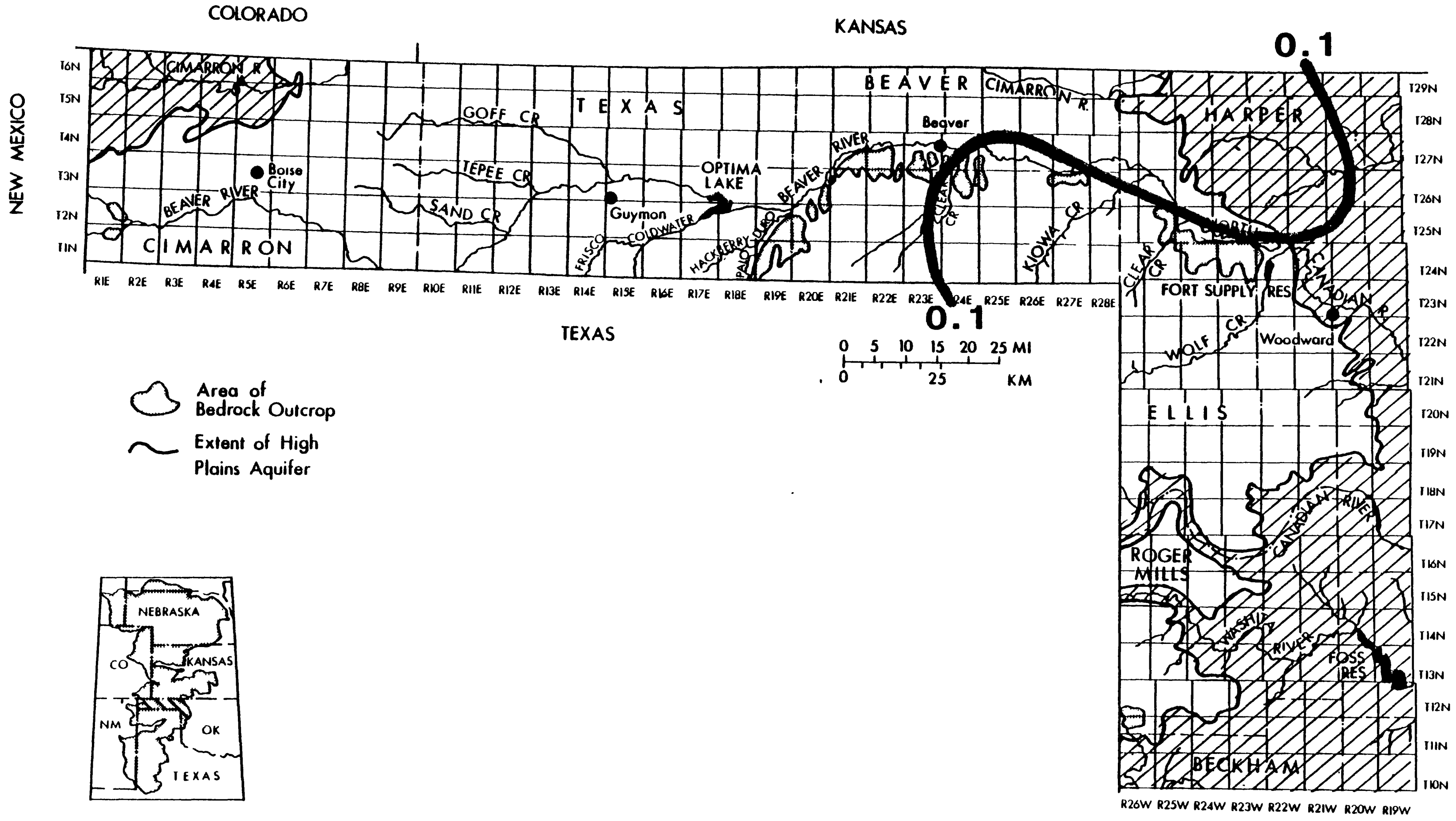


Figure 13. Effective Regional Ground-Water Recharge Rates in Northwestern Oklahoma

as a single hydrologic unit referred to as the High Plains aquifer. These units include the alluvium, terrace, and dune deposits of Quaternary age and the Ogallala Formation. From Guymon eastward, alluvial deposits yield up to 700 gpm. Except during periods of low streamflow the water from these deposits is suitable for most uses (O.W.R.B., 1980).

Water in the High Plains aquifer predominantly occurs under water-table (unconfined) conditions. For the most part, units underlying the Ogallala are significantly less permeable and act as a lower confining bed (Bassett and others, 1981). In eastern and southeastern Texas County, water of poor quality is being induced upward from Permian rocks into the Ogallala, due to heavy pumping (O.W.R.B., 1983). Except in the lowest layers of the High Plains aquifer, water is of good quality and suitable for most uses though it is typically classified as hard to very hard.

The ground water that occurs within the underlying Permian and Mesozoic formations is typically saline. Wells completed in these rocks of low permeability generally yield 1-20 gpm. Locally the Dockum Group and the Cheyenne Sandstone may yield up to 500 gpm of acceptable quality water. The Dakota Sandstone yields as much as 150 gpm of good quality water throughout much of its extent and provides water to many supplemental irrigation wells (Hart, Hoffman, and Goemaat, 1976).

Water Usage

Based on 1980 water use estimates in the study area (Table 3.) ground water provides 100 percent of the water used for municipal supply, and over 95 percent of the water used for irrigation and industry. The High Plains aquifer provides the majority of this water. The withdrawals for 1980 in the three Panhandle counties alone total more than 412,000 acre-feet (O.W.R.B., 1980).

Water Level Changes

The amount of recharge from precipitation over the entire Panhandle is estimated to equal approximately 60,000 ac-ft. Even if irrigation return flow ,estimated to be as high as 20 percent of water applied, is accounted for (81,000 ac-ft), there remains a net reduction of 272,000 ac-ft of water in storage per year. Assuming an even distribution of withdrawal over the Panhandle and a porosity of 10 percent, the volume of water removed is equal to about 10 inches of water table decline. Because irrigation wells are not evenly distributed and some areas are being irrigated with surface water, water levels are declining in some areas and increasing in others. In general, the volume of recharge is far less than the volume of discharge and, as a result, water levels in some areas of northwestern Oklahoma have declined by more than 100 feet during the past 40 years. It has been predicted that if ground-water withdrawals continue at their current rate and no source of

TABLE III

1980 REPORTED WATER USE IN NORTHWESTERN OKLAHOMA

	WATER USE (ac-ft)			
	Ground Water		Surface Water	
County	Irrig.	Munic./Ind.	Irrig.	Munic./Ind.
Beaver	48,020	1141	306	0
Cimarron	82,644	805	203	0
Dewey	4,940	1	0	0
Ellis	21,715	1,622	120	0
Harper	16,241	4,272	6,000	0
Roger Mills	9,406	148	1,056	0
Texas	273,789	6,224	691	0
Woodward	985	9,732	374	0

Source: O.W.R.B. (1983)

augmentation is developed, the entire region will have to revert to dry-land farming before the end of this century. Such a measure would severely reduce productivity in the region and cause widespread economic turmoil throughout not only the State, but the region, and the nation as well.

To maintain a balance in the hydrologic system, withdrawals of ground water must be offset by equal volumes of recharge. Recharge can occur naturally through two principal mechanisms; (1) direct infiltration of precipitation and excess irrigation water, and (2) leakage from streams, ponds, and playas. The recharge potential of these mechanisms is diminshed by evapotranspiration and adhesion of the water molecules to soil particles in the unsaturated zone. Average annual precipitation over northwestern Oklahoma is almost exactly equal to the average annual evapotranspiration, thereby negating its recharge potential. In order for water to percolate downward and reach the water-table, the moisture content of the soil must exceed field capacity. The depth to water (thickness of the unsaturated zone) averages over 100 feet in northwestern Oklahoma. Regionally, a tremendous volume of water would be required for the unsaturated zone to reach field capacity. Such a volume of water is rarely, if ever, naturally available in this arid region.

Declining water levels have three primary impacts; (1) the costs of pumping water out of the ground increase, (2) well yields decrease, and (3) the usable life of the aquifer decreases. Extraction of water from the ground requires a certain amount of energy for a given lift. As the lift increases so does the amount of energy required to extract the water. This increase in required energy is reflected in higher cost for each acre-foot extracted. The amount of water that can be pumped from a well is dependent upon, among other factors, aquifer transmissivity--the product of the permeability of the aquifer and its saturated thickness. A declining water table implies a reduction in the saturated thickness and, therefore, a decrease in the amount of water an aquifer can transmit to wells. The result is increased drawdown and reduced well yield. All aquifers have a finite thickness that, in the absence of recharge, represents the lowest point from which water may be extracted. As the water level approaches the bottom of the aquifer a point is reached where it is no longer feasible, or economically viable, to continue extracting water. At this stage the usable life of the aquifer is at an end and some alternate supply of water must be found. In most of northwestern Oklahoma no other alternative supply of water is available at this time.

A fourth potential result of declining water levels is reversal of the head differential between aquifers causing flow between them to be reversed. In certain cases this situation would be desirable because water from the lower aquifer could be induced to recharge the upper aquifer. The High Plains aquifer is currently in equilibrium with underlying Permian and Mesozic formations in most areas. If the head potential between the High Plains aquifer and the underlying materials were reversed, then saline water would leak upward into the High Plains aquifer and possibly severely degrade the quality of the aquifer. This situation already exists in eastern and southeastern Texas county (O.W.R.B., 1983).

Management Alternatives

To halt the rate of water level decline and thereby increase the life of the High Plains aquifer, the hydrologic balance between discharge and recharge must be regained. This can be accomplished by; (1) reducing discharge, (2) increasing recharge, or (3) a combination of both. Given the historical trend for yearly increases in total number of acres irrigated and volume of water extracted, it would seem optimistic to assume that ground-water withdrawals will continue only at current rates. Increasing withdrawals of groundwater will certainly speed the dewatering of the High Plains aquifer.

In recognition of the problem of declining water levels several management alternatives have been proposed. Among these proposals are; (1) allow unrestricted use of groundwater, essentially non-management, (2) supplement the water in the region by either weather modification or water importation, (3) conserve the remaining water by restricting pumpage, and/or employment of more efficient soil and water-management practices, and (4) augment the amount of water in storage by artificial recharge. Non-management will surely lead to more rapid depletion of water in the aquifer and hasten economic hardship to the region. Weather modification involves complex legal questions and is not considered a viable alternative (Camp Dresser & McKee et al., 1982). Oklahoma is currently giving serious consideration to plans for an intrastate water conveyance system. This system would transport water from the humid eastern half of the State to the arid western half. While such a system is theoretically and technologically feasible, the costs of construction, operation, and maintenance are astronomical. The conveyance system is, therefore, not a realistic alternative at this time.

A partial solution to the problem is more efficient use of the available ground water. Through the use of water-conserving irrigation systems, revised irrigation schedules, and improved plowing/tilling techniques the usable life of the aquifer can be extended.

The Texas High Plains Water Conservation District No. 1 has been enthusiastically investigating the feasibility of secondary recovery of capillary water from the unsaturated zone. While secondary recovery does cause the release of water held in capillary storage and a consequent rise in water levels, it also intensifies the soil moisture deficiency. The effect is then to permit even less water to infiltrate through the unsaturated zone and recharge the aquifer. Should a source of recharge water ultimately be found, a much greater percentage of this water would then be required to resaturate the soil to allow recharge to occur.

The only potentially viable means of augmenting the volume of water in storage in the High Plains aquifer is by increasing recharge through techniques known collectively as "Artificial Recharge".

CHAPTER IV

FUNDAMENTALS OF ARTIFICIAL RECHARGE

Purpose

The purpose of artificial ground-water recharge is to increase both the rate at which water infiltrates into the ground, and the total volume of water added to storage in the aquifer. Artificial recharge techniques have been practiced throughout the world for more than 200 years (Pettyjohn, 1981). Artificial recharge technology is broad enough to allow implementation over a wide range of geologic and economic considerations for a variety of different purposes.

Some of the purposes for which artificial recharge techniques have been intentionally employed are:

1. Ground-water management
2. Reduction in the rate of land subsidence
3. Renovation of wastewater
4. Improvement of ground-water quality
5. Reduction of flood flows
6. Increased well yields
7. Prevention of salt water intrusion
8. Increase streamflow
9. Secondary recovery of oil
10. Disposal of liquid waste

There are also many examples of unintentional ground-water recharge. A large quantity of water and wastewater is inadvertantly introduced into the ground water from excess irrigation returnflow, excavations, waste disposal lagoons, leaky sewer pipes, septic tanks, and holding ponds (Pettyjohn, 1981). For the most part, unintentional recharge is rarely desirable or beneficial.

Criteria

Over the study area, artificial recharge represents a potential partial solution to the problem of declining water levels. The feasibility of artificial recharge, and the design of appropriate recharge systems, is dependent on several site specific criteria:

1. Areas where a problem exist
2. Source of recharge water
3. Proximity to source
4. Topography
5. Permeability of near-surface materials
6. Quality of source
7. Quality of water in the aquifer
8. Availability of source

Given the inherently slow velocity of ground water, it is important to locate artificial recharge structures as close to the problem area as possible. Even in highly permeable materials it may take water months or years to move from a recharge site to an extraction site.

Once the problem areas have been identified, a source of recharge water must be located. Typical sources of recharge water include excess stream flow, industrial cooling water, treated waste water, irrigation runoff, and impounded precipitation.

Selection of the recharge site is also coincidentally dependent on the location of the source of recharge water.

An ideal situation would be where the source of recharge water is directly upgradient, and close to, the recharge site, particularly if the site will permit gravity flow of water to the recharge facility. Unfortunately this is not usually the case and water must be somehow diverted from the source and conveyed to the recharge site.

Diversion of recharge water can be as simple as excavating a trench or pit, or as complex as construction of multiple recharge basins. Topography is the deciding factor as to whether or not the water will flow into the structures under the force of gravity. If the water must be pumped, the complexity of the system is significantly increased as are the construction , operational, and maintenance costs.

In order for the water to infiltrate and recharge the aquifer, the permeability of near-surface materials must be relatively high. Low permeability materials can cause the water to pond at the surface, or inhibit its movement toward areas where it is needed. Commonly it is necessary to excavate through the uppermost layers of low permeability materials, if present, and backfill with high permeability materials, such as gravel.

Quality of the recharge water is a critical factor, especially if the water is ultimately to be used for potable supply. Contamination of the entire aquifer can occur if undesirable, or toxic, constituents are present in the recharge water. Permeability of the aquifer can be adversely affected if turbid waters are recharged, since suspended particles can accumulate and plug pore spaces. Similar problems are related to the growth of algae and bacterial slime buildup.

When ground water is recharged, the resultant mixture is usually different in composition than the native water. In some instances the quality of the ground water is improved and in others it is degraded. The ultimate use of the ground water dictates whether or not a particular source is acceptable for recharge. Another possible consequence of mixing is chemical interaction between the two waters, or between the resultant mixture and the aquifer material. Some of the potential reactions are increased concentrations of solutes caused by dissolution of the aquifer, increased mobility of certain chemical species, increased (or decreased) biologic activity, or precipitation of certain mineral such as calcium carbonate. Whether the effects are beneficial or harmful depends on the specific situation.

Finally, the ultimate factor in determining the feasibility of artificial recharge at a specific site is the availability of a source of recharge water. Is the water available for recharge, or has it been fully appropriated? If it has been appropriated, is purchase of the water rights economically feasible? Another closely related consideration is the availability of the land where the recharge structure is to be constructed.

Methods

Artificial recharge techniques fall into two broad categories; (1) water spreading, and (2) deep systems.

Water spreading refers to inundation of large land areas, construction of infiltration basins, excavation of ditches or furrows, modification of existing stream channels, and irrigation (Pettyjohn, 1981). Factors controlling the amount of water recharged are water contact time, surface area flooded, and permeability of underlying materials (Pettyjohn, 1981). Water contact time is influenced by the surface topography and ambient climatic conditions. If the slope of the land surface is less than about 3 degrees, the water tends to pond near the dispersal site and the available surface area is only partially inundated (A.R.S., 1970). Conversely, if the slope is too great, the water tends to run off instead of infiltrate, and levees or ditches are necessary to confine and redivert the water. Weather and season can be major factors influencing the efficiency of water spreading. High summer temperatures and steady breezes evaporate tremendous volumes of water. Low temperatures increase the viscosity of water and reduce its capacity for infiltration.

The larger the wetted surface area, the greater the opportunity for infiltration. Permeability of the soil and near-surface materials is the single most important factor that governs infiltration. Higher permeability materials will pass equal amounts of water in shorter periods of time than low permeability materials. High permeability can compensate to some extent for insufficiencies of the other factors--topography, weather, and surface area. Land slopes can, therefore, be steeper, ambient temperature can be warmer (or colder), and smaller wetted surface area is required. Depending on the permeability of the materials underlying the particular spreading site, coarser materials may be introduced to enhance the infiltration rate.

Flooding of large land areas is achieved by diverting water to relatively flat areas where it is allowed to infiltrate. Water is diverted to the recharge area by simple trenches, or an elaborate system of supply and diversion ditches. It is desirable to keep velocities to a minimum to prevent erosion and maximize contact time.

When large land areas are not available for flooding, smaller recharge basins can be utilized. These basins are usually excavated, but can be formed by construction of levees to impound water. When flood flows are the primary source of recharge water, basins are commonly operated in series to allow suspended silt and clay to settle out. These fine materials can plug the bottom of the basins and reduce the infiltration rate. Even with a series of settling and recharge basins, silt and clay may have to be periodically removed. Schneider and Jones (1984) compared the rates of infiltration from a simple basin, a furrowed-bottom basin, and a basin lined with an organic mat. Their results showed that significantly less cleaning was required to maintain a high infiltration rate with furrowed- or lined-bottom basins. Lehr (personal communication, 1984) conducted laboratory experiments on the rate of infiltration from flat-bottomed and V-bottomed basins. He concluded that V-bottomed basins were more conducive to infiltration than flat-bottomed ones.

Ditches and furrows require less land area than recharge basins and can be adapted to irregularly shaped areas. These systems utilize relatively narrow, flat-bottomed excavations to disperse water through the recharge area. Based on the geometry of the ditches and furrows, three general types of systems are common: (1) contoured--the ditches parallel topography, (2) dendritic--the main feeder canal branches into smaller canals or ditches, and (3) lateral--smaller canals diverge laterally from the feeder canal (A.R.S., 1970). Where slopes are steep, checks are required to minimize erosion, increase contact time, and maximize wetted area. Because of the large ratio of wetted area to total surface area, these systems can recharge as much water as a basin covering a much greater surface area (A.R.S., 1970).

Channel modifications fall into three general categories: (1) those that increase the time of water contact, (2) those that increase the wetted area, and (3) those that increase the permeability of the streambed. Low head dams are a popular structure to check the rate of flow, impound water, and increase contact time. These structures must be carefully designed and constructed so as not to create a hazard in times of flooding (A.R.S., 1970). Stream channels can be widened to make a larger surface area available for wetting and reduce the rate of stream flow. A series of baffles could be constructed to reduce stream velocities and increase contact time. Reduced stream velocity results in settling of the suspended load, which can result in silt build up and reduced permeability of the streambed. Periodic scouring or dredging might then be necessary to restore permeability. If the stream bottom is composed of fine sediments, coarser materials may be introduced to increase permeability and enhance the infiltration rate.

Irrigation can provide large volumes of water to underground storage, particularly if water is applied during the non-growing season. Industrial waste-water and sewage effluent are attracitve sources of recharge water because the soil and unsaturated aquifer material can filter out much of the suspended organic matter (Pettyjohn, 1981). Depending on the nature of the suspended material, the soil may actually benefit from this "fertilization", and water that is normally discarded is available for reuse.

Deep systems include large, relatively shallow pits, shafts, and screened wells. These structures provide direct access to the aquifer and are particularly suited to areas where permeability of near-surface materials is low, or depth to water is relatively great (Pettyjohn, 1981).

Abandoned gravel pits or quarries are economically attractive as recharge pits because they require no excavation and are typically situated above permeable material. Many quarries and pits have been used as landfills and liquid waste disposal sites, which can cause inadvertant contamination of the aquifer. Even if the bulk of the waste has been removed, use of such pits can further degrade the aquifer.

Recharge shafts are used when a layer of low permeability material lies near the surface. A hole is drilled, bored, or excavated through the low permeability layer to allow water to pass into the aquifer. The hole may be uncased, cased, open, or back-filled with coarse material. Shafts are commonly constructed within pits, basins, or stream channels to facilitate recharge (Pettyjohn, 1981). Use of turbid water presents a special problem with small diameter shafts because the removal of silt-laden material is difficult. If flood waters are the primary source of recharge, it may be desirable to construct settling ponds in order to use less silty water, or filter the water prior to reaching the site (A.R.S., 1970).

Screened wells are used to recharge deep aquifers, or in areas where land is not available for any other recharge method. They are usually constructed in a manner similar to supply wells, but water is pumped into, rather than out of, the aquifer. These wells are expensive to construct and to maintain (Pettyjohn, 1981). Because of the relatively small zone of recharge provided by injection wells, several wells must be operated in an area. Recharge wells are also subject to clogging and bacterial incrustation. Water quality is a critical consideration when using wells for recharge (Pettyjohn, 1981). In addition to directly recharging an aquifer, injection wells have been used to establish a fresh-water barrier to salt water-intrusion (A.R.S., 1970), secondary recovery of oil, and disposal of liquid waste (Pettyjohn, 1981).

A variation on well system recharge is the technique of "Induced Infiltration". Instead of being used as a conduit for direct flow into the aquifer, the well serves to establish a hydraulic gradient that "induces" water to infiltrate from a water course into the adjacent streamside aquifer. The well, or wells, are constructed adjacent to the stream, pond, or lake that is to serve as the source of recharge water. Pumping of the well(s) creates a cone of depression that draws water into the aquifer. The quality of the source is an important consideration because a significant proportion of the water that is subsequently pumped from the aquifer originated in the surface source and will be of the same quality (Pettyjohn, 1981).

It is readily evident that many techniques have proven feasible for artificial recharge. Each potential artificial recharge site is unique, however, and any particular design must conform to the existing conditions. Furthermore, an important factor in design is imagination coupled with ingenuity. These characteristics can permit one to develop a system that may consist of a number of techniques that are combined to best suit the specific field conditions.

CHAPTER V

FEASIBILITY OF ARTIFICIAL RECHARGE IN NORTHWESTERN OKLAHOMA

Identification of Problem Areas

Identification of ground-water problem areas initially requires definition of the factors that designate a problem. These factors depend on the perspective from which the ground-water situation is appraised. This study is concerned with identification of problem areas from two perspectives: (1) that of the ground-water user, and (2) that of the artificial recharge specialist.

The ground-water user is primarily concerned with (1) the current depth to water, (2) the rate at which water levels are declining, and (3) the quality of the ground water. From this perspective, problem areas exist where the depth to water is excessive, where the rate of water level decline is rapid, or where the quality of water is poor. Presently, the average depth to water over the study area is in excess of 150 feet below land surface (Figure 14). Since the mid-1940's, water levels in some areas have declined by as much as 150 feet (Figure 15)--an average of over 3 feet per year. Dewatering during the past 40 years ranges from 25 to about 150 feet (Havens, 1983). For

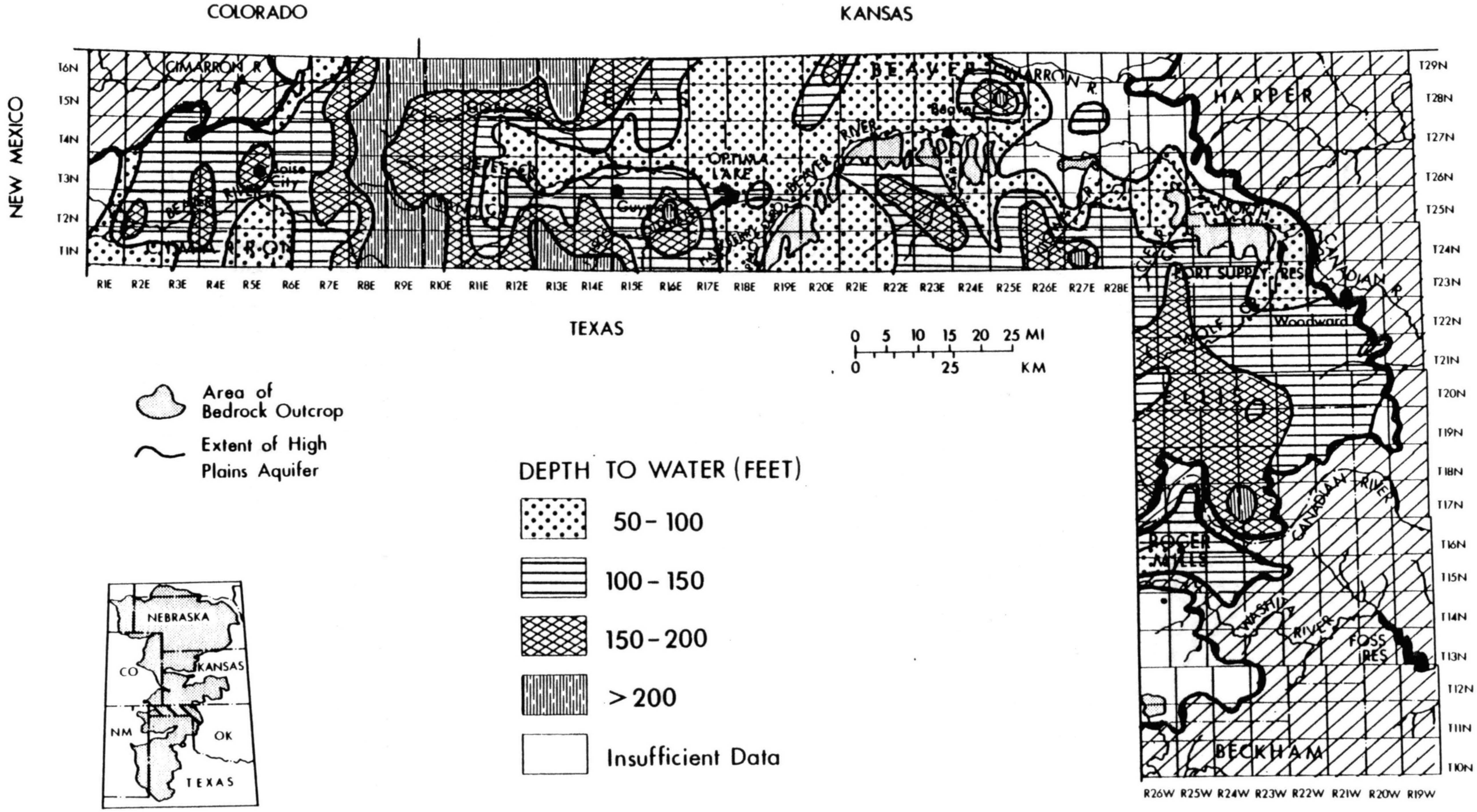
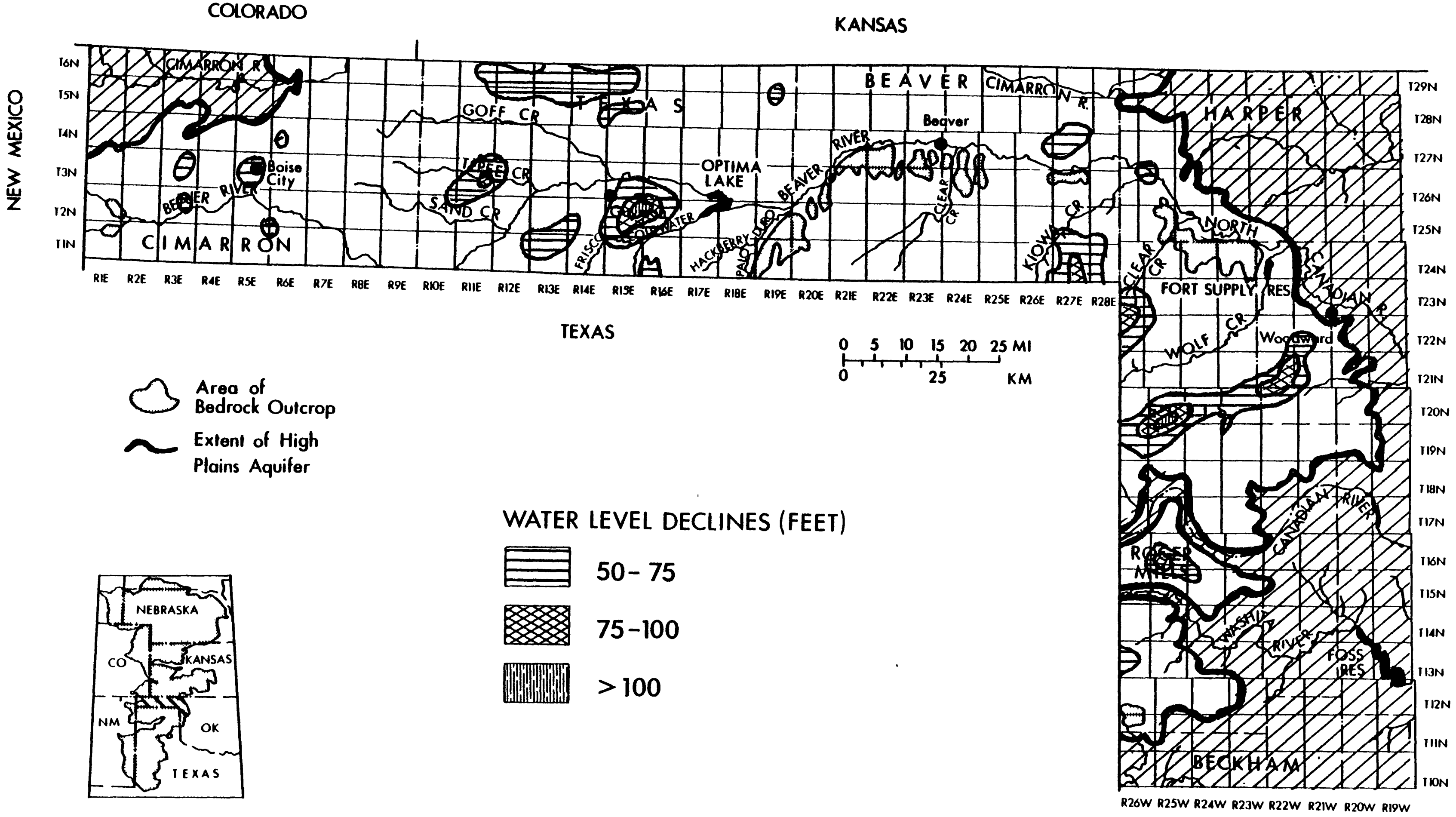


Figure 14. Generalized Depth to Water in the High Plains Aquifer, Northwestern Oklahoma



Source: Havens (1983).

Figure 15. Water-Level Declines, 1940-80, in the High Plains Aquifer, Northwestern Oklahoma

purposes of this study, problem areas have been designated based on three criteria: (1) where the current depth to water exceeds 200 feet below land surface, that is, 50 feet or more below the average depth, (2) where water-levels have declined by more than 50 feet, and (3) where ground water is of poor quality. Figure 16 represents a composite of these designated problem areas.

Mineralized water has leaked into the High Plains aquifer from underlying Permian rocks in southern and southeastern Texas County, but the areal extent of the problem is ill-defined. Water of Palo Duro Creek exhibits similar mineralization, therefore, its drainage basin within Oklahoma is designated as a problem area due to poor ground-water quality.

The recharge specialist defines a problem area as one where (1) no source of recharge water is available, (2) quality of the available source is unacceptable, (3) depth to the aquifer is excessive, or (4) permeability of near-surface materials is low.

Source of Recharge Water

Sources of recharge water in northwestern Oklahoma are limited to precipitation, snow melt, sewage effluent, irrigation return flow, and streamflow. Precipitation provides little water for recharge because of high evapotranspiration rates coupled with the fact that most rainfall occurs during the growing season. Snowmelt is

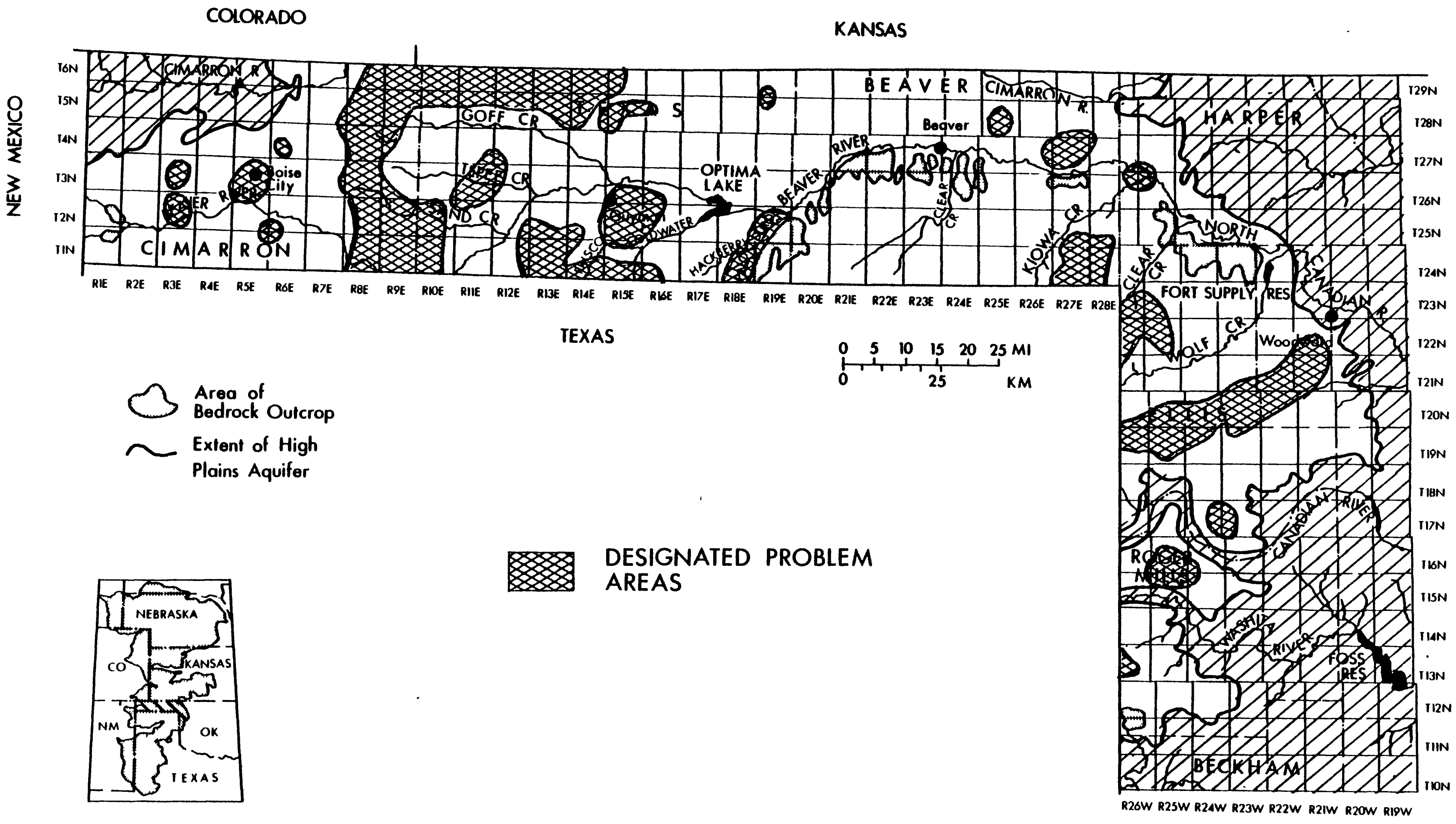


Figure 16. Designated Ground-Water Problem Areas in Northwestern Oklahoma

another potential source, which is both seasonally limited and minimally contributing. Northwestern Oklahoma is sparsely populated and the yearly volume of municipal sewage effluent totals much less than 1 percent of the ground water that is pumped for irrigation. Irrigation return flow is estimated to be as high as 20 percent of the water applied. While this is a significant volume of recharge, there remains a net loss of 80 percent of the total water pumped. Although streamflow is intermittant and frequently of poor quality over much of the area, it represents the only viable source of recharge water in the area.

Proximity to Recharge Source

With streamflow as the primary source of recharge water, only those areas in relatively close proximity to streams that exhibit suitable quality, have potential as recharge sites. Water can be diverted from streams to recharge sites either through ditches, furrows, or canals, or pipes. Distance from the stream is limited principally by the economics of construction. Most of the problem areas lie at distances of greater than one mile from a major stream (Figure 16). The cost of constructing and maintaining diversion structures of such lengths would be substantial.

A limited amount of precipitation collects in local playas. This water is subject to intensive evaporation and much of it is lost. Playas modified to enhance infiltration could potentially recharge a significant amount of water on a local scale.

Topography

Unfortunately, over most of the area, stream beds occur in steep gullies and flooding of large surface areas would not generally be feasible. There are, however, vast areas that are naturally subject to flooding that would be topographically ideal for construction of recharge basins. These structures could be simple and inexpensive, such as excavated pits. Because flood events occur infrequently and most of the flood waters inflitrate anyway, construction of these basins would probably be of limited value.

Permeability of Near-Surface Materials

One of the characteristic features of the High Plains aquifer is the presence of caliche, which occurs near the top of the Ogallala Formation. This layer is typically more resistant than underlying material and forms the caprock that is evident in many stream cuts and arroyos. The caliche attains a maximum thickness of about 50 feet and ranges from soft and friable to hard and compact. Locally, the indurated caliche may impede infiltration of water, but for the most part solution openings are common and provide access for recharge. Most of the recharge basins constructed near Lubbock, Texas are excavated down to the caliche layer because it is more permeable than the overlying soil (Schneider and Jones, 1984).

Soil moisture deficiency may be a far more significant problem than presence of caliche. A dry, permeable soil will absorb large amounts of water but until the field capacity of the soil is exceeded, the water is unable to percolate through the unsaturated zone and recharge the aquifer. Tremendous volumes of water would be required to saturate the zone above the water table even in areas where depth to water is only 50 feet. Such a volume of water is rarely, if ever, available in this arid region.

Quality of Recharge Source

Water in Beaver River from the New Mexico state line to Optima Reservoir is generally of acceptable quality, as is the water in Coldwater Creek. Downstream from Optima, at the confluence with Palo Duro Creek, and extending to Ft. Supply Reservoir, Beaver River water becomes too mineralized even for irrigation, because of the discharge of highly mineralized ground water (Table 2).

Quality of Water in the Aquifer

Water pumped form the High Plains aquifer is typically hard, but suitable for most purposes. Ground-water provides all the water used for municipal supply in the three Panhandle counties. Only in the area drained by Palo Duro Creek is Ogallala water highly mineralized. Hart and others (1976) reported that several deep wells in this area contained dissolved solids in excess of 5000 mg/L.

Concentrations of chloride and sulfate are commonly greater than 1000 mg/L. This is probably the result of leakage of saline water from Permian formations.

Availability of Recharge Source

In general all surface water in northwestern Oklahoma is fully appropriated. In fact, appropriations exceed the normal reliable supply of the streams. Although Optima Reservoir has been filling for the past 6 years, it contains only a small quantity of water. The Oklahoma Water Resources Board has received more applications for water allocations from Optima than the reservoir is expected to yield (O.W.R.B., 1983).

Availability of Recharge Site Acreage

A large percentage of land in northwestern Oklahoma is undeveloped. Though large areas of range and grassland are grazed by cattle, land is available for construction of recharge structures.

CHAPTER VI

DESIGN OF RECHARGE SYSTEMS

Due to the reconnaissance nature of this study and the regional scale, recharge structure designs are generalized to allow application for any number of locations where the requisite hydrogeologic conditions are satisfied.

Low Head Dams

Low head dams (2 to 3 feet high, depending on topography) could be constructed so as to extend across perennial, intermittant, and ephemeral stream channels. They would serve to reduce velocity, impound runoff, and increase retention time, but they would not be intended to act as flood control structures. Structures such as these could allow more water to infiltrate; water that normally would flow into streams and out of the area. Another purpose of low head dams would be to divert water from the channel to nearby recharge ditches, basins, pits, or shafts. Despite the fact that a majority of the tributaries and major drainages in the area are dry most of the year, low head dams could be constructed at modest cost and at least provide an opportunity for recharge to occur.

Pits and Basins

Recharge pits and basins could be constructed along the floodplains of major drainages adjacent to irrigated fields. These could be relatively shallow and of moderate size. Shafts, filled with coarse material could be constructed within the excavation to facilitate recharge (Figure 17). Unfortunately, few of the designated problem areas are adjacent to floodplains of the major drainages. Recharged water provided by these structures could be used for future development in areas where there is no current development. In some instances it may even be possible to abandon irrigation of lands at greater distances from these recharge sites, and begin cultivation adjacent to these sites.

Induced Infiltration

Irrigation along perennial streams, such as the Coldwater or the Palo Duro, could initiate induced infiltration and result in either a decrease in the rate of water-level decline, or possibly a rise in the water level. In fact, water levels have shown a rise along the Palo Duro, which indicates that irrigation with surface water is occurring despite the fact that the quality of the water is typically not good. A potential solution to this problem may be to induce infiltration of lesser quality water, and then irrigate with the better quality mixture of waters. On the other hand, this could potentially create problems since all water used for municipal supply in the Panhandle

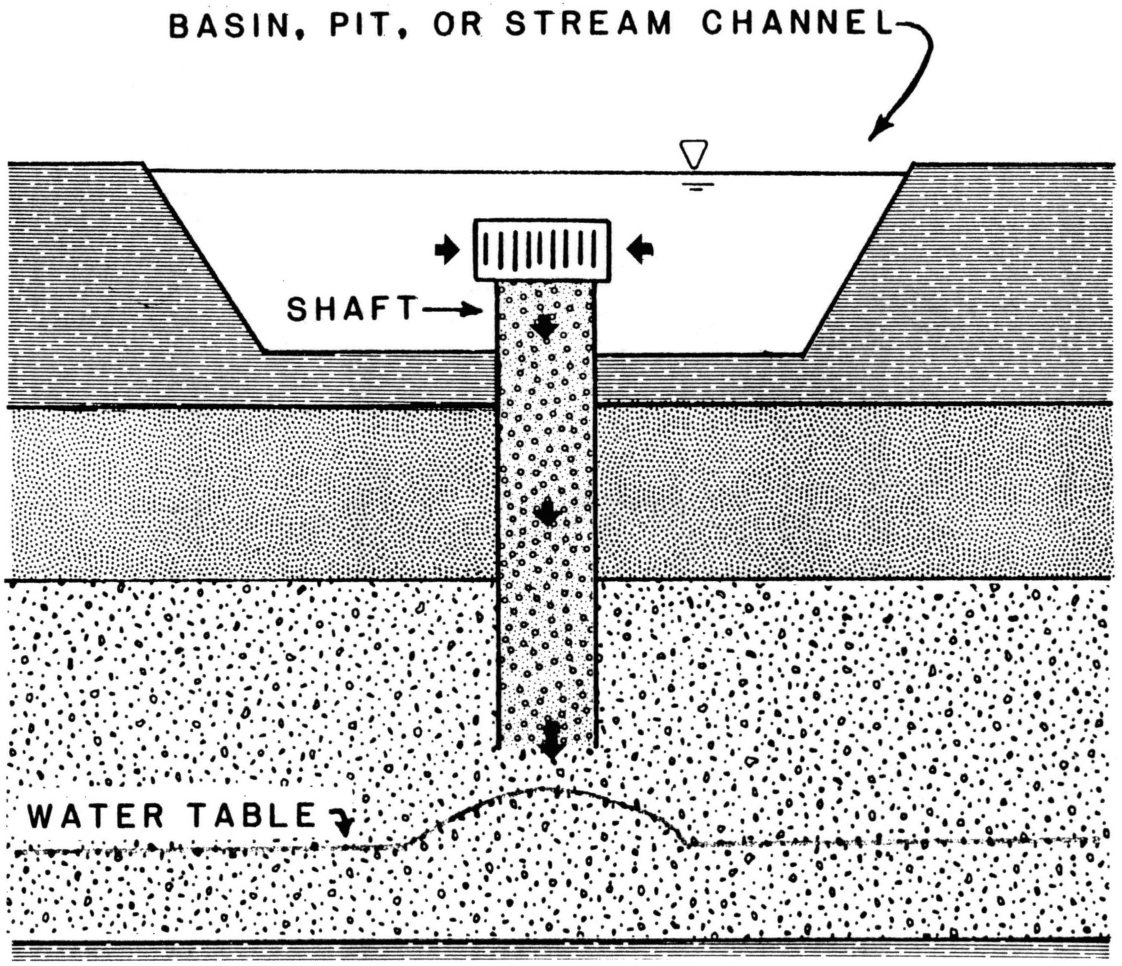


Figure 17. Combination Recharge Basin and Shaft

is ground water. Evaluation of the impacts of this type of recharge would have to be conducted on a site by site basis.

Underdrains

Underdrain systems consist of gravel-filled ditches and perforated tiles, tubes, or pipes enclosed in shallow, gravel-lined trenches to intercept infiltrating water near land surface. They can be constructed across stream channels, beneath surface holding ponds, along the perimeter of irrigated fields, in the bottom of excavations, or beneath natural depressions (such as playas). Because they are located relatively near the surface, underdrains are effective in collecting a relatively large amount of water. Ordinarily this water would evaporate, escape as runoff, or disperse in the unsaturated zone with minimal benefit. After collection the intercepted water could be diverted to a central collection tank for recharge through a pit, shaft, or well.

Collector Wells

Collector wells were first developed at Canton, Ohio in the late 1940's (Pettyjohn, 1981). These systems consist of very large diameter casings--called caissons--that are sunk into the ground and completed by extending perforated laterals into the aquifer. These laterals radiate from the central caisson and serve to disperse recharge water into the aquifer (Figure 18). Collector wells might be constructed

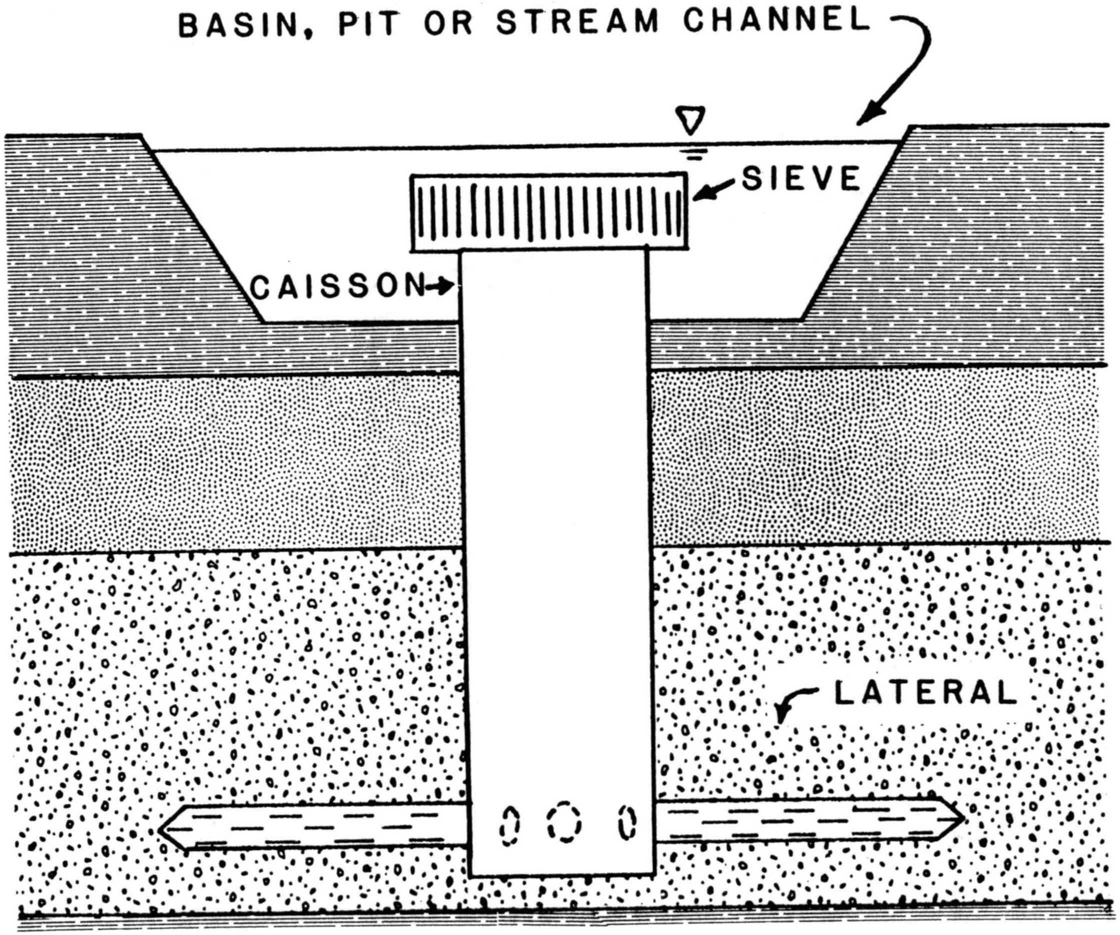


Figure 18. Collector Well System

within the channel of major drainages to intercept flood flows, or operated in conjunction with underdrains, low head dams, or basins. Not likely to be practical in the High Plains, collector wells are very expensive and, depending on depth and diameter, would require an investment that would probably exceed $200,000 per well.

CHAPTER VII

DEVELOPMENT OF COMPUTER MODEL

One of the objectives of this study is development of a mathematical computer model that simulates the hydrologic system of the High Plains/Ogallala aquifer at two selected sites. Development of a model requires input data that are representative of the aquifer parameters. Since a model is a simplified conceptual version of reality, the validity of the simulation depends on the accuracy of the input; the more accurate the input, the more valid the simulation (Wang and Anderson, 1982). Calibrated models allow simulation of future aquifer response to changes in the hydrologic system.

Feasibility of artificial recharge to the High Plains aquifer depends not only on the suitability of the physical setting, but also on the economic impact of the anticipated effects. Computer models provide both an inexpensive and informative means to predict the consequences of various ground-water management alternatives.

Two sites were selected for the computer simulations; the first, southeast of Guymon (Figure 19), and the second, southwest of Woodward (Figure 20). These sites were chosen for several reasons: (1) both sites are located in designated problem areas, (2) the Guymon site is representative of the western High Plains aquifer environment--thick aquifer deposits, distant boundaries, and minimal recharge, and (3) the Woodward site is representative of the eastern High Plains environment--thinner aquifer deposits, close proximity to the aquifer margin, and greater amount of recharge.

Five simulations were conducted on each site. The first was a calibration run, which simulated the response of the aquifer to "steady-state" conditions. The second run was a five-year simulation based on the results of the first calibration run. Once the model was assumed to be accurately calibrated for static conditions, the model was stressed to simulate the response of the aquifer to 40 years of pumping. Two specific management alternatives were then simulated to project the effects to the year 2000: (1) future withdrawals of ground water restricted to 1980 usage, and (2) restricted withdrawals coupled with artificial recharge efforts.

Fundamentals of P*L*A*S*M

Ground-water flow is mathematically described by a set of partial differential equations that have no general solutions. These equations can, however, be approximated using numerical methods. One such approach is the finite-difference method. The aquifer to be modeled is divided into units of finite dimension represented by nodes. Each node has a set of discrete parameters that approximate the actual aquifer parameters. Differentials in the equation governing ground-water flow are substitued by these sets of discrete elements that are assumed to be equivalent to the differentials. Ground-water flow through each node is governed by a unique discretized equation. These equations are then solved simultaneously for head values. Numerical methods are particularly amenable for solution with the aid of a digital computer because of the complexity and large number of equations that must be solved.

The model selected for this study is called P*L*A*S*M, which is an acronym for "Prickett-Lonnquist Aquifer Simulation Model". P*L*A*S*M was originally developed by T.A. Prickett and C.G. Lonnquist for the Illinois State Water Survey in 1968 (Prickett and Lonnquist, 1971). This model was chosen for four reasons; (1) it is well known and well documented, (2) it has been proven to be accurate when correctly calibrated, (3) the model was translated from FORTRAN to BASIC and extensively revised at Oklahoma State University in order to run on microcomputers, and (4) this particular revision has been modified to account for dewatering of the aquifer.

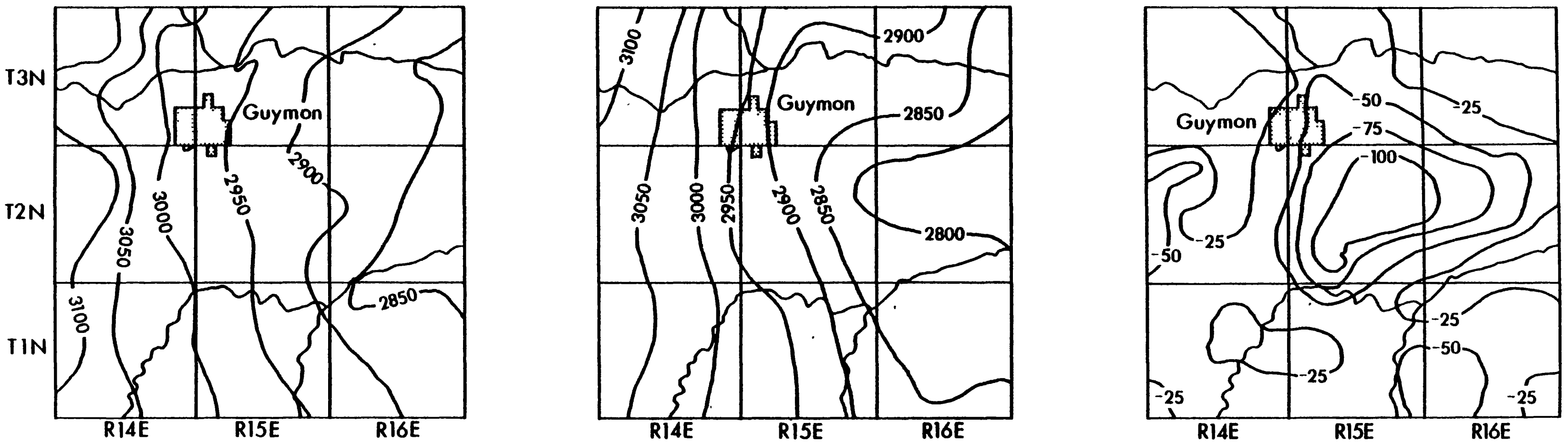
Calibration of Models

Model Inputs

The first step in constructing the model is to superpose a grid over the area. This divides the aquifer into nodes and defines the areal extent of the model. Nodes along the perimeter are conventionally defined by parameters that approximate the boundary conditions of the aquifer. When natural boundaries, such as streams, ground-water divides, or low permeability strata occur close to the margins they should represent the boundary conditions. Commonly, no natural boundaries occur within the area and the grid is simply made large enough so that computational inaccuracies at these nodes do not effect internal nodes (Wang and Anderson, 1982). Values of transmissivity, storativity, discharge, head, recharge, permeability and elevation of aquifer base are required for each node.

The grids are composed of nodes that represent one mile on a side (a section). The total dimension of the grid is 18 x 18 nodes (or 18 miles by 18 miles), thus the site represents nine-townships. A one node wide boundary surrounding the entire grid was used to simulate the assumed boundary conditions at each site. To test the influence of the boundary conditions on the model, a simulation was run with first a constant-head boundary and then a no flow boundary. Differences between heads at internal nodes would then indicate that boundary conditions were critical. Substitution of these boundary conditions produced no significant effect on the mean of the absolute values of the difference between computed and measured heads.

Initial head conditions, saturated thickness, and elevation of the base of the aquifer were derived from reports published by the U.S. Geological Survey (Havens and



WATER TABLE ELEVATIONS
1940

(A)

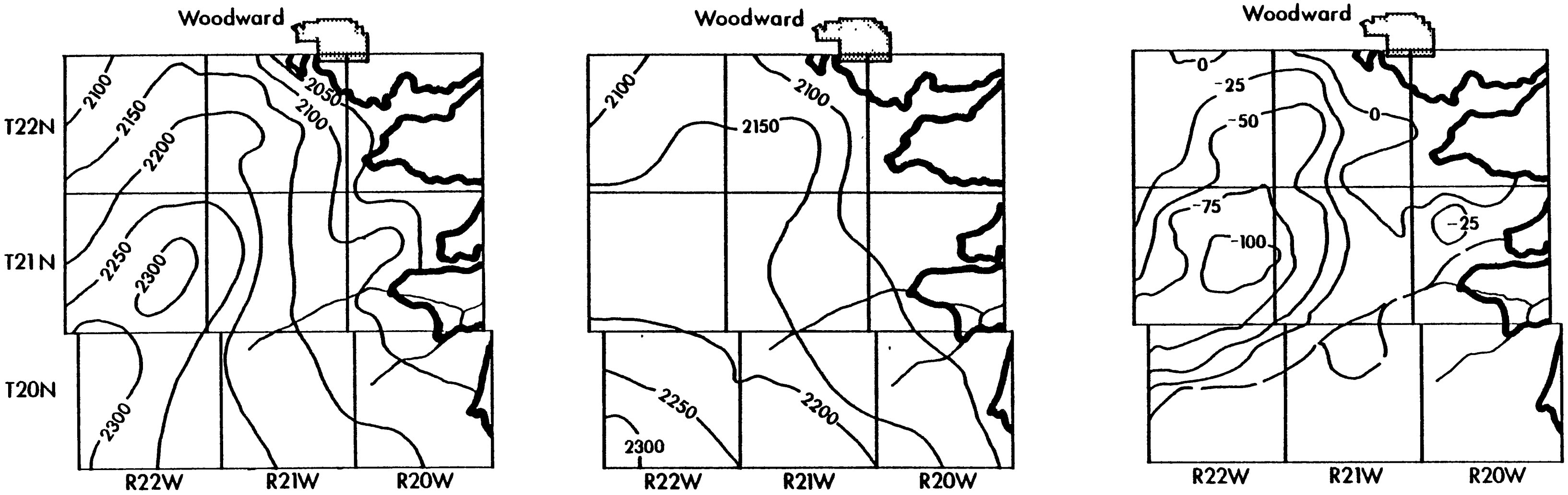
WATER TABLE ELEVATIONS
1980

(B)

WATER LEVEL DECLINES
1940-1980

(C)

Figure 19. Guymon Modeling Site



WATER TABLE ELEVATIONS 1940

(A)

WATER TABLE ELEVATIONS 1980

(B)

WATER LEVEL DECLINES 1940-1980

(C)

Figure 20. Woodward Modeling Site

Christenson, 1984; Havens, 1982a,b,c,d,and 1983), as were the aquifer permeability (250 gpd/sq.ft) and storativity (0.1). Input data are presented in Appendix A.

Calibration Techniques

The generally accepted method of calibration involves first simulating the steady-state conditions of the aquifer. These data are then used as the initial conditions for simulation of transient conditions (Wang and Anderson, 1982). Ideally, data that accurately define the hydrologic system at some later time are available. The model is then run for a similar period of time and the computed head values compared against the actual values. Calibration is performed by simply adjusting input data and running the simulation until computed heads match the actual ones. Commonly, the simulation will have to be run many times before the mean of the absolute values of the differences in head is minimized. When the mean is finally minimized, the model is assumed to be calibrated. Wang and Anderson (1982) caution, however, that there "is no guarantee that the combination of parameters found by trial and error is unique" (p.110). As a measure of the accuracy of the model, the mean of the absolute values of the differences between computed and observed heads should be minimized. Because "differences in head can be both positive and negative, it is possible to have a very small average difference in heads while having large differences at individual nodes" (Havens and Christenson, 1984, p.17). For their most recent effort, Havens and Christenson (1984) calibrated their model to an accuracy in which the mean of the absolute value of the differences in head was 50 feet per node.

Each of the models were subjected to a 1000-year "steady-state" simulation period. Such a period was assumed to be sufficiently long for hydrolgic conditions to stabilize. During this simulation period, total discharge from stream nodes was approximately equal to the total volume of recharge. Thus, any change in the distribution of heads was assumed to be due to natural hydrogeologic influences. When differences between input heads and simulated heads were minimized, it was further assumed that the aquifer parameters had been accurately modeled. For both sites, significant changes in head occurred only during the initial 40-year time-step. These changes are attributable to the precision of the computer-model computation of head for each individual node. Only a few of the nodes within each model site had a "known" head value. All other nodes were assigned a head value based on linear-interpolation between the closest nodes with known head values. Because finite-difference equations account for aquifer parameters in computing heads at each node, model interpolations of head between nodes are not linear. When the model is run, the effect is to smooth out irregularities in the input data and more accurately represent ground-water flow.

Using the aquifer parameters from the steady-state simulation, transient (or dynamic) conditions were calibrated. Water-level elevations at the end of a 5-year simulation were used as "initial conditions" for subsequent simulations. The model was then stressed for a 40-year simulation period and the heads compared to those assumed to be "actual". Calibration was achieved by shifting the locations of the pumping nodes and increasing or decreasing the rate of withdrawal. All other parameters were held constant for two reasons; (1) so that if new and better well data should become available the model can be easily adjusted to more accurately reflect the hydrogeologic situation, and (2) to allow comparison of model results with previous modeling studies of the area (i.e. Havens and Christenson, 1984). Calibrated results and their "actual" counterparts are presented in matrix form in Appendix B. Accuracy of this calibration is limited by the lack of accurate information on well locations and pumping rates.

Guymon Site. The mean of the absolute values of the difference between input heads (actual) and those resulting from the 5-year simulation is 9 feet. Mean difference between heads resulting from the 1000-year simulation and heads resulting from the 5-year simulation is 11 feet per node. Based on this relatively small difference, the model was assumed to be correctly calibrated and accurately reflect the hydrologic conditions at the site.

The second phase of calibration involved pumping an arbitrary number of nodes using variable pumping rates for a simulated 40-year period. Estimation of the pumping rates for the years between 1940 and 1980 required extrapolation backward from the known 1980 volume of ground-water usage and the reported numbers of wells in Texas county. Pumping was assumed to be constant over a 5-year period, thus, the simulation required 8 time-steps of 5 years each. A total of 21 wells were simulated, which resulted in contours of computed-water level declines closely approximating contours of observed drawdowns. Comparison of the actual 1980 water-table elevations at the site with the simulated elevations revealed a mean of the absolute values of the difference between heads of approximately 11 feet per node.

Woodward Site. The mean of the absolute values of the difference between input heads (actual) and those resulting from the 5-year simulation is 8 feet. Mean difference between heads resulting from the 1000-year simulation and heads resulting from the 5-year simulation is 17 feet per node. Using these calibrated results, the model was then run to calibrate transient conditions. This simulation was run for two 20-year time-steps because the eastern half of the aquifer was not heavily exploited until the early 1960's, and pumping for the period 1940 to 1960 was assumed to be zero. From 1960 to 1980 a total of 7 model wells were pumped to achieve a close approximation of the observed distribution of heads. The mean of the absolute value of the difference between these computed heads and actual heads is 18 feet.

Model Projections

With current withdrawals already vastly exceeding the rate of natural recharge, continued pumping obviously can be expected to cause additional water-level declines. The calibrated models of each of the two sites allow for quantification of the anticipated additional declines. Two simulations representing aquifer response from 1980 to the year 2000 were run for each site. In the first simulation, pumping rates were held constant at 1980 levels. The second projection simulated the effects of an artificial recharge system. Three injection nodes were simulated at each site and operated continuously for the 20-year period. Recharge volumes were constant for each well and totaled nearly 1500 gpm (2510 ac-ft/year).

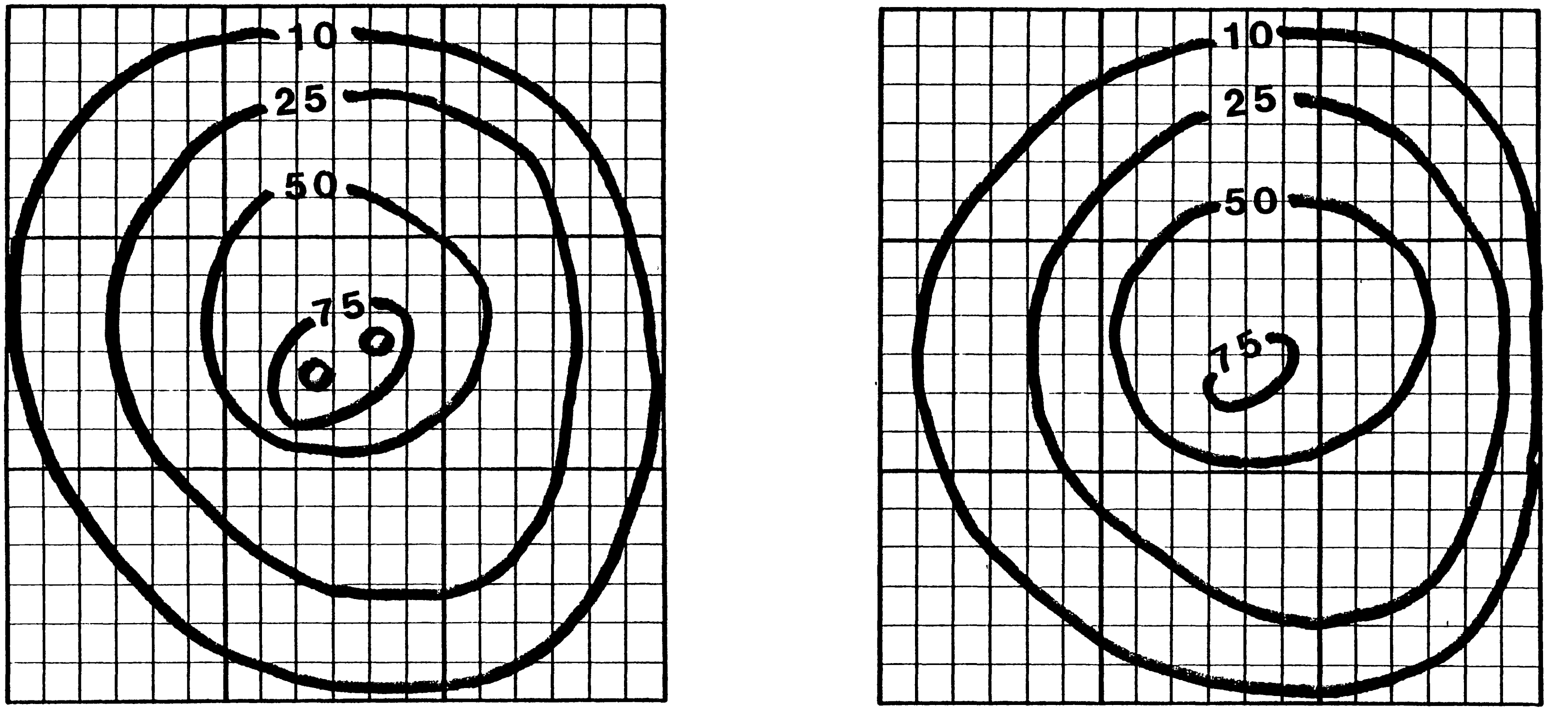
The volume of water added to storage by the simulated recharge systems is unrealistically large in terms of water that is available for recharge and recharge site acreage. For the Guymon site, 1500 gpm represents a significant percentage of the average flow of Beaver River at Guymon. Beaver River water in this reach is already fully appropriated and not available for artificial recharge. Precipitation at the Guymon site averages about 17 inches per year. If 100 percent of the rainfall falling on a recharge basin could be recharged to the aquifer, the basin would have to occupy an area of almost 3 square miles.

The Woodward site presents a similar situation. Instead of stream water being fully appropriated, there are no "major" streams in the area from which water could be continuously diverted. Intermittant flows could be diverted but, the streams do not flow across the areas where recharge is needed most. Precipitation, which averages about 20 inches per year in this region, provides the only potential source of recharge water. A recharge basin that was 100 percent efficient in inducing infiltration of precipitation would have to cover more than 2 square miles to recharge the volume of water simulated.

Guymon Site

Figure 21A shows contours of additional decline in water levels from 1980 to 2000 if pumping continues only at 1980 rates and no recharge program is initiated. From this simulation water levels can be expected to decline by as much as 100 feet in the next 20 years.

Figure 21B shows the contours of decline if a three-point recharge system that adds nearly 1500 gpm of water to storage is implemented. The central area of greatest decline now shows a maximum of slightly more than 90 feet. Though nodes up to 5 miles distant from the recharge nodes show some recharge influence, for the most part this system has an insignificant impact on reducing the rate of water level decline (Figure 22).



(A) No Artificial Recharge

(B) With Artificial Recharge

Figure 21. Guymon Site--Projected Water Level Declines,1980-2000, due to Continued Pumping at 1980 Rates of Withdrawal

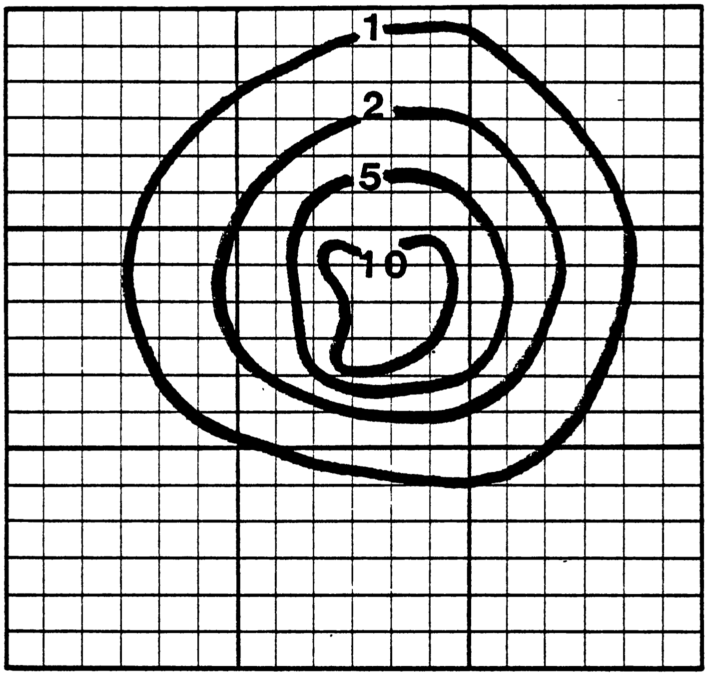


Figure 22. Contours of Reduced Water Level Declines due to the Effects of Artificial Recharge at the Guymon Site

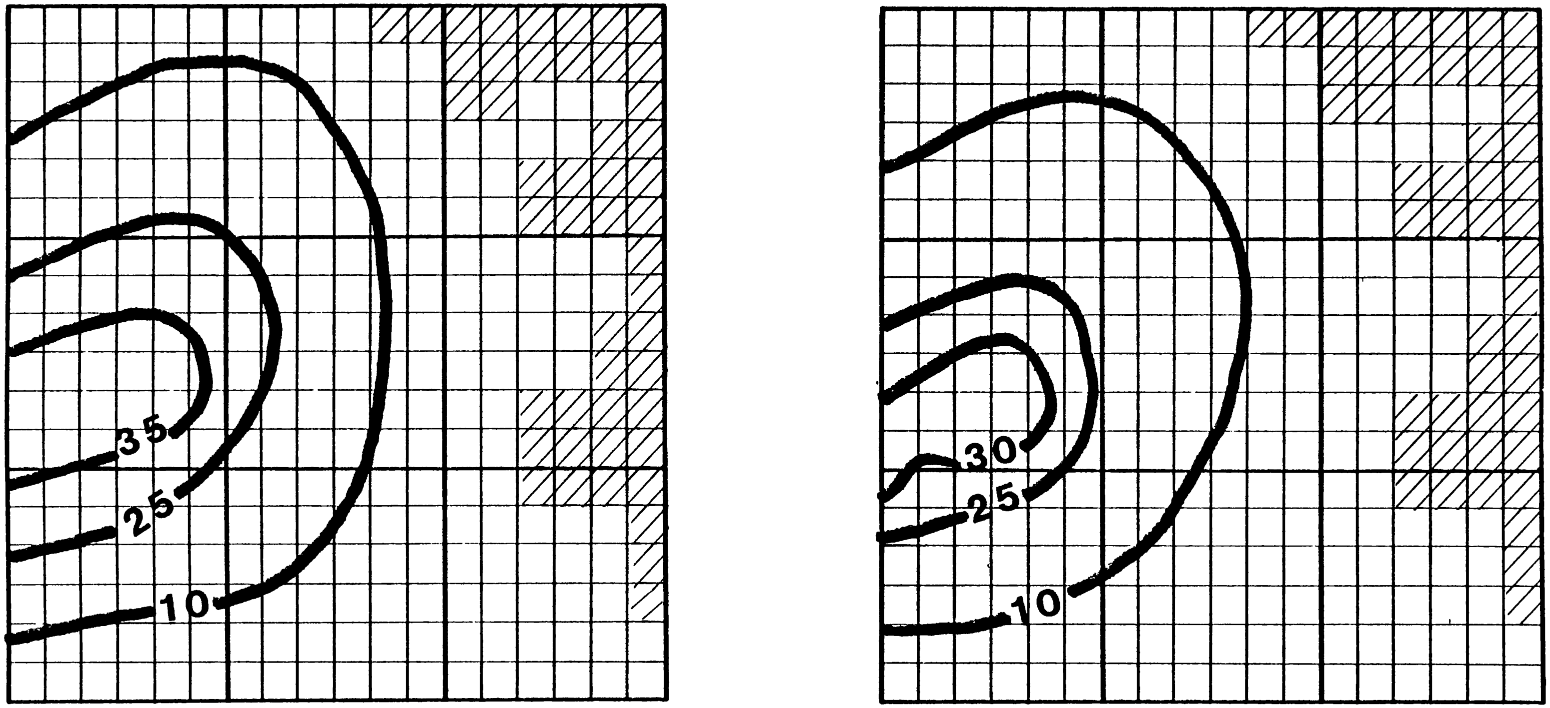
Woodward Site

In the absence of artificial recharge, water levels at this site can be expected to decline an additional 40 feet in the areas of highest pumping by the year 2000 (Figure 23A).

A recharge system similar to the one implemented at the Guymon site would only succeed in reducing the maximum amount of decline by 5 feet (Figure 23B). Nodes as near as five miles away show only slight effect of the artificial recharge system (Figure 24).

Model Implications

Clearly, tremendous volumes of water will be required to slow or halt the rate of water level decline to any significant degree at either site. For artificial recharge to be feasible in terms of a beneficial return on investment, more than one recharge system will probably have to be implemented, and additional sources of recharge water will have to be located.



(A) No Artificial Recharge (B) With Artificial Recharge

Figure 23. Woodward Site--Projected Water Level Declines,1980-2000, due to Continued Pumping at 1980 Rates of Withdrawal

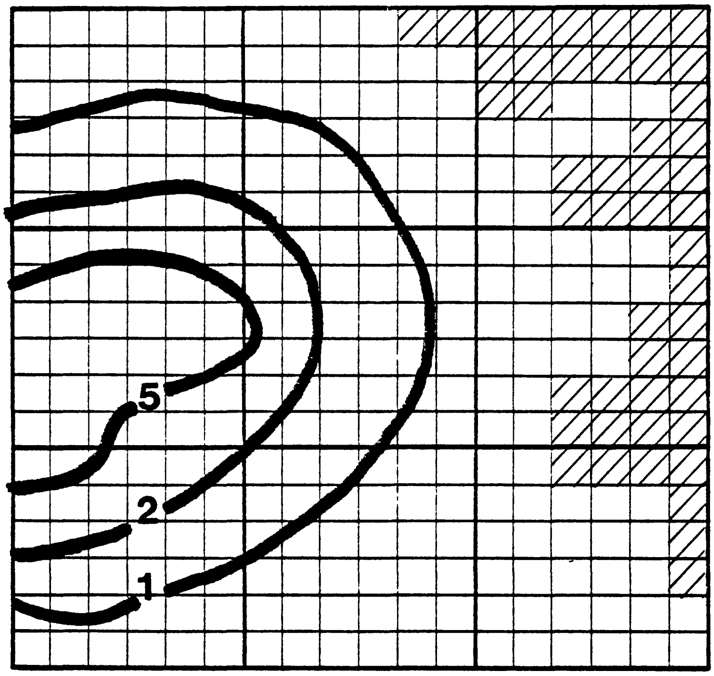


Figure 24. Contours of Reduced Water Level Declines due to the Effects of Artificial Recharge at the Woodward Site

CHAPTER VIII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The High Plains-Ogallala aquifer is the principal source of water in northwestern Oklahoma. Much of the area supports extensive agriculture through intensive irrigation. Precipitation annually provides only 0.2 inch of recharge to the aquifer. Because the yearly volume of water removed from storage in the aquifer exceeds the volume of recharge to the aquifer, water levels in many areas have declined significantly during the past 40 years. Even at current pumping rates, water levels will continue to decline. Yearly withdrawals of water have historically increased and the trend is expected to continue. Increased withdrawals will expedite dewatering of the aquifer over much of the region, which is predicted to make continued irrigation economically unfeasible in the future. In the absence of irrigation, crop productivity would be severely reduced. The adverse consequences of such a reduction would be felt not only within the region or the State, but throughout the Nation. To slow, or halt, the rate of water-level decline a variety of water management alternatives have been suggested. Of these, only decreased well yield and artificial recharge appear promising from a practical and economic point of view. Computer-model simulations of the effects of artificial recharge systems are less than optimistic. A source of recharge water that is large enough to offset the huge volume of irrigation withdrawals is simply not available on a regional scale.

Conclusions

Based on the results of the study, the following conclusions can be made:

1. precipitation is so slight that structures to intercept rainfall would, at best, be only locally effective
2. caliche does not appear to be the ubiquitous barrier to recharge that it was once believed to be--its permeability is highly variable and whether it would hinder, or benefit, recharge would have to be determined on a site to site basis
3. low head dams constructed across drainages--whether ephemeral, intermittant, or perennial--would result in more infiltration (and possibly recharge) than currently occurs. If operated in conjunction with basins, pits, or shafts, the amount of recharge could be increased substantially
4. most of the larger designated problem areas are too far from major drainages to receive benefit from flood flows regardless of the type of recharge

structure

5. most of the drainages in the region are intermittant--a continuous source of recharge water is not available
6. the quality of the water in the only perennial reach in the region (Palo Duro Creek and along Beaver River from the confluence with the Palo Duro eastward to Woodward) is unsuitable for most purposes
7. all surface water in the region that is of suitable quality is fully appropriated
8. computer model projections indicate that artificial recharge systems which recharge only a fraction of the total amount of water withdrawn for irrigation will have an insignificant effect on the rate of water level decline
9. artificial recharge is not feasible on a regional scale in northwestern Oklahoma
10. artificial recharge may well serve as a viable option for small, local problem areas, but each area would require a specific site analysis and recharge system design

To summarize, the factors that preclude artificial recharge on a regional scale are (1) poor quality of water available for recharge, (2) general unavailability of water of suitable quality, because of prior appropriations or minimal annual supply, and (3) the long distances that typically separate the source from the problem area.

Recommendations

Artificial recharge is regionally desirable and does appear to be viable locally. Each of the problem areas designated by this study should be examined on a site-by-site basis to determine; (1) availability and quality of potential recharge water, (2) locations of nearby pumping wells and quantities of water withdrawn, (3) thickness of, and depth to, the caliche and its permeability, (4) thickness of the unsaturated zone, (5) thickness and permeability of the saturated material, and (6) the particular type of recharge structure that would be most effective.

SELECTED REFERENCES

Agricultural Research Service, 1970, Ground-Water Recharge Hydrology: U.S. Dept. of Agriculture, ARS 41-161, 62p.

American Water Works Association Research Foundation, 1981, Water Reuse in the Future: Proc. Water Reuse Symp.II, Wash., D.C., Aug. 23-28, 1981.

American Water Works Association Research Foundation, 1979, Water Reuse, From Research to Application: Proc. Water Reuse Symp. Vol. 1, Wash., D.C., Mar. 25-30, 1979.

Bassett, R.L., E.P. Weeks, M.L. Ceazan, S.G. Perkins, D.C. Signor, D.L. Redinger, R.L. Malcolm, G.R. Aiken, E.M. Thurman, P.A. Avery, W.W. Wood, G.M. Thompson, and G.K. Stiles, 1981, Preliminary Data from a Series of Artificial Recharge Experiments at Stanton, Texas: U.S. Geol. Survey Open-File Rept. 81-149, pp.13,15,21-22.

Boettcher, A.J, 1966, Ground-Water Development in the High Plains of Colorado: U.S. Geol. Survey Water-Supply Paper 1819-I, 22p.

Brown, R.F., and D.C. Signor, 1973, Artificial-Recharge Experiments on the Southern High Plains of Texas and New Mexico: U.S. Geol. Survey Water-Resources Invest. 10-73, 54p.

Camp Dresser and McKee Inc.,Black and Veatch, and Arthur D. Little, Inc., 1982, Six-State High Plains-Ogallala Aquifer Regional Resources Study Summary: A Report to the U.S. Dept. of Commerce and the High Plains Study Council.

Carr, J.E., and D.L. Bergman, 1976, Reconnaissance of the Water Resources of the Clinton Quadrangle, West-Central Oklahoma: OK. Geol. Survey Hydrol. Atlas 5, scale 1:250,000, 4 sheets.

Cochran, R., 1981, Artificial Recharge and its Potential for Oklahoma's Ogallala Aquifer: OK. Wat. Res. Board Tech. Rept., 14p.

Cronin, J.G., 1964, A Summary of the Occurrence and Development of Ground Water in the Southern High Plains of Texas: U.S. Geol. Survey Water-Supply Paper 1693, 88p.

Cunningham, M.B, 1949, Artificial Recharge of Ground Water Reservoirs: OK. Geol. Survey, The Hopper, Vol.9, No.6, pp.51-58.

Darton, N.H., 1899, Preliminary Report on the Geology and Water Resources of Nebraska West of the One Hundred and Third Meridian: U.S. Geol. Survey 19th Ann. Rept, Part IV-Hydrography, pp.727-767.

Darton, N.H., 1903, Preliminary Report on the Geology and Water Resources of Nebraska West of the One Hundred and Third Meridian: U.S. Geol. Survey Professional Paper 17, 69p.

Darton, N.H., 1905, Preliminary Report on the Geology and Underground Water Resources of the Central Great Plains: U.S. Geol. Survey Professional Paper 32, pp.21-23, 178-79, 190-94.

Davis, R.E., and S.C. Christenson, 1981, Geohydrology and Numerical Simulation of the Alluvium and Terrace Aquifer along the Beaver-North Canadian River from the Panhandle to Canton Lake, Northwestern Oklahoma: U.S. Geol. Survey Open-File Rept. 81-483, 42p.

DeVries, R.N., and D.C. Kent, 1973, Sensitivity of Groundwater Flow Models to Vertical Variability of Aquifer Constants: Water Resources Bull. Vol.9, No.5, pp.998-1005.

Diffendahl, R.F.Jr., 1982, Regional Implications of the Geology of the Ogallala Group (upper Tertiary) of Southwestern Morrill County, Nebraska and Adjacent Areas: Geol. Soc. Am. Bull. Vol. 93, pp.964-976.

Dvoracek, M.J., and R.Z. Wheaton, 1969, Development of Systems for Ground Water Recharge into the Ogallala Formation: Office Water Resources Research, 22p.

Dvoracek, M.J., and S.H. Peterson, 1971, Development of Systems for Ground Water Recharge into the Ogallala Formation: Office Water Resources Research, 34p.

Feder, G.L., and N.C. Krothe, 1981, Results of a Reconnaissance Water-Quality Sampling Program of the Ogallala Aquifer in Colorado, Kansas, Nebraska, Oklahoma, South Dakota, and Texas: U.S. Geol. Survey Water-Resources Invest. 81-65, 7p.

Frye, J.C., 1970, The Ogallala Formation--A Review: Proc. Ogallala Aquifer Symp., Lubbock, TX, 1970, pp.5-14.

Frye, J.C., and A.B. Leonard, 1959, Correlation of the Ogallala Formation (Neogene) in Western Texas with Type Localities in Nebraska: TX. Bur. Econ. Geol. Rept. Invest. No. 39, 46p.

Gillespie, J.B., and S.E. Slagle, 1972, Natural and Artificial Ground-Water Recharge Wet Walnut Creek, Central Kansas: KS. Water Resources Board Bull. 17, 94p.

Gould, C.N., 1905, Geology and Water Resources of Oklahoma: U.S. Geol. Survey Water-Supply Paper 148, 148p.

Gould, C.N., and J.T. Lonsdale, 1926a, Geology of Beaver County Oklahoma: OK. Geol. Survey Bull. 38, 71p.

Gould, C.N., and J.T. Lonsdale, 1926b, Geology of Texas County, Oklahoma. OK. Geol. Survey Bull. 37, 62p.

Gutentag, E.D., and J.B. Weeks, 1980, Water Table in the High Plains Aquifer in 1978 in parts of Colorado, Kansas, Nebraska, New Mexico, Okalhoma, South Dakota, and Wyoming: U.S. Geol. Survey Open-File Rept. 80-50, scale 1:2,500,000, 1 sheet.

Gutentag, E.D., and J.B. Weeks, 1980, Water Table in the High Plains Aquifer in 1978 in parts of Colorado, Kansas, Nebraska, New Mexico, Okalhoma, South Dakota, Texas, and Wyoming: U.S. Geol. Survey Hydrol. Invest. Atlas HA-642, scale 1:2,500,000, 1 sheet.

Hart, D.L.,Jr., G.L. Hoffman, and R.L. Goemaat, 1976, Geohydrology of the Oklahoma Panhandle, Beaver, Cimarron, and Texas Counties: U.S. Geol. Survey Water Resources Invest. 25-75, 62p.

Hauser, V.L., and F.B. Lotspeich, 1967, Artificial Ground-Water Recharge Through Wells: Jour. Soil Water Cons., Vol.22, No.1, pp.11-15.

Havens, J.S., 1966, Recharge Studies on the High Plains in Northern Lea County, New Mexico: U.S. Geol. Survey Water-Supply Paper 1819-F, 52p.

Havens, J.S., 1982a, Generalized Altitude and Configuration of the Base of the High Plains Regional Aquifer, Northwestern Oklahoma: U.S. Geol. Survey Water-Resources Invest. Open-File Rept. 81-1117, scale 1:250,000, 2 sheets.

Havens, J.S., 1982b, Altitude and Configuration of the 1980 Water Table in the High Plains Regional Aquifer, Northwestern Oklahoma: U.S. Geol. Survey Water-Resources Invest. Open-File Rept. 82-100, scale 1:250,000, 2 sheets.

Havens, J.S., 1982c, Altitude and Configuration of the Predevelopment Water Table in the High Plains Regional Aquifer, Northwestern Oklahoma: U.S. Geol. Survey Water-Resources Invest. Open-File Rept. 82-275, scale 1:250,000, 2 sheets.

Havens, J.S., 1982d, Saturated Thickness of the High Plains Regional Aquifer in 1980, Northwestern Oklahoma: U.S. Geol. Survey Water-Resources Invest. Open-File Rept. 82-760, scale 1:250,000, 2 sheets.

Havens, J.S, 1983, Water-Level Changes in the High Plains Regional Aquifer, Northwestern Oklahoma, Predevelopment to 1980: U.S. Geol. Survey Water-Resources Invest. Rept. 83-4073, scale 1:500,000, 1 sheet.

Havens, J.S., and S.C. Christenson, 1984, Numerical Simulation of the High Plains Regional Aquifer, Northwestern Oklahoma. U.S. Geol. Survey Water-Resources Invest. 83-4269.

Heimes, F.J., and R.D. Luckey, 1982, Method for Estimating Historical Irrigation Requirements from Ground Water in the High Plains in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geol. Survey Water-Resources Invest. 82-40, 64p.

High Plains Underground Water Conservation District No. 1, 1982, Investigation of Secondary Resovery of Ground Water From the Ogallala Formation, High Plains of Texas: TX. Dept. Water Resources, 61p.

Hoffman, G.L., and D.L. Hart, Jr., 1973, Records of Selected Water Wells and Test Holes in the Oklahoma Panhandle: U.S. Geol. Survey Open-File Rept., 59p.

International Association of Scientific Hydrology, 1967, Symposium of Haifa, March 19-26, Haifa, Belgium, 499p.

Irwin, J.H., and R.B. Morton, 1969, Hydrogeologic Information on the Glorieta Sandstone and Ogallala Formation in the Oklahoma Panhandle and Adjoining Areas as Related to Underground Waste Disposal: U.S. Geol. Survey Circular 630, 26p.

Jones, O.R., and A.D. Schneider, 1972, Groundwater Management on the Texas High Plains: Water Resources Bull. Vol.8, No.3, pp.516-522.

Keys, W.S., and R.F. Brown, 1971, The Use of Well Logging in Recharge Studies of the Ogallala Formation in West Texas: U.S. Geol. Survey Professional Paper 750-B, pp.270-277.

Kolm, K.E., and H.L. Case, III., 1983, A Two-Dimensional, Finite-Difference Model of the High Plains Aquifer in Southern South Dakota: U.S. Geol. Survey Water Resources Invest. 83-4175, 23p.

Krothe, N.C., and J.W. Oliver, 1982, Sulfur Isotopic Composition and Water Chemistry from the High Plains Aquifer Oklahoma Panhandle and Southwestern Kansas: U.S. Geol. Survey Water Resources Invest. 82-12, 28p.

Krothe, N.C., J.W. Oliver, and J.B. Weeks, 1982, Dissolved Solids and Sodium in Water from the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geol. Survey Hydrol. Invest. Atlas HA-658, scale 1:2,500,000, 2 sheets.

Leonard, A.R, 1963, Oklahoma, in The Role of Ground Water in the National Water Situation by C.L. McGuiness. U.S. Geol. Survey Water-Supply Paper 1800, pp.671-676.

Lichtler, W.F., D.I. Stannard, and E. Kouma, 1980, Investigation of Artificial Recharge of Aquifers in Nebraska: U.G. Geol. Survey Water-Resources Invest. 80-93, 112p.

Loo, W.W., 1972, The Influence of Vertical Variations in Lithology on a Mathematical Management Model for the Ogallala Aquifer, Texa County, Oklahoma. (unpublished Master's thesis, Oklahoma State University).

Luckey, R.R., E.D. Gutentag, and J.B. Weeks, 1981, Water-Level and Saturated Thickness Changes, Predevelopment to 1980, in the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geol. Survey Hydrol. Invest. Atlas HA-652, scale 1:2,500,000, 2 sheets.

Lugn, A.L., 1939, Classification of the Tertiary System in Nebraska: Geol. Soc. Am. Bull. v.50, pp.1245-1276.

Mapp, H.P., Jr., 1983, Analysis of Irrigation Pumping and Application Efficiency in the Central Ogallala Formation: OK. Water Resources Research Inst., OK. State Univ., Stillwater, 104p.

Marine, I.W., and S.L. Schoff, 1962, Ground-Water Resources of Beaver County, Oklahoma: OK. Geol. Survey Bull. 97, 74p.

Marine, I.W., 1963, Correlation of Water-Level Fluctuations with Climatic Cycles in the Oklahoma Panhandle: U.S. Geol. Survey Water-Supply Paper 1669-K, 10p.

Merriam, D.F., and J.C. Frye, 1954, Additional Studies of the Cenozoic of Western Kansas: KS. Geol. Sur. Bull. 109, pt.4, pp.49-64.

Merriam, D.F., 1955, Notes on the Ogallala Formation of Western Kansas: KS. Geol. Society 18th Field Conf. Guidebook, pp.66-73.

Morton, R.B., 1973, Preliminary Investigations of the Hydrogeology of the Middle Permian to Tertiary Rocks of the Oklahoma Panhandle: U.S. Geol. Survey Misc. Invest. Map I-738, scale 1:250,000, 2 sheets.

Morton, R.B., 1980a, Digital-Model Projection of Saturated Thickness and Recoverable Water in the Ogallala Aquifer, Texas County, Oklahoma: U.S. Geol. Survey Open-File Rept. 79-565, 30p.

Morton, R.B., 1980b, Reconnaissance of the Water Resources of the Woodward Quadrangle, Northwestern Oklahoma: OK. Geol. Survey Hydrol. Atlas 8, scale 1:250,000, 4 sheets.

Morton, R.B., and R.L. Goemaat, 1973, Reconnaissance of the Water Resources of Beaver County, Oklahoma: U.S. Geol. Survey Hydrol. Invest. Atlas HA-450, scale 1:125,000, 3 sheets.

Myers, B.N., 1964, Artificial-Recharge Studies, in A Summary of the Occurrence and Development of Ground Water in the Southern High Plains of Texas: U.S. Geol. Survey Water-Supply Paper 1669-K, pp.56-83.

National Oceanic and Atmospheric Administration. Climatological Data: Oklahoma.

Oklahoma Water Resources Board. Reported Water Use, Years 1968, 1970, 1972, 1974, 1976, 1978, 1980.

Oklahoma Water Resources Board, 1973a, Appraisal of the Water and Related Land Resources of Oklahoma: Region XII, 91p.

Oklahoma Water Resources Board, 1973b, Appraisal of the Water and Related Land Resources of Oklahoma: Region XI, 99p.

Oklahoma Water Resources Board, 1980, Oklahoma Comprehensive Water Plan: OK. Water Resources Board Pub. 94, 248p.

Oklahoma Water Resources Board, 1983, State Level Research Results for the Six-State High Plains Ogallala Aquifer Area Study: OK. Water Resources Board Pub. 113, 33p.

Pettyjohn, W.A., and R.J. Henning, 1979, Preliminary Estimate of Ground-Water Recharge Rates, Related Streamflow and Water Quality in Ohio: Ohio State University Water Resources Center, Rept. 552, 323p.

Pettyjohn, W.A., 1981, Introduction to Artificial Ground Water Recharge: National Water Well Assoc, NWWA/EPA series, 44p.

Pettyjohn, W.A., and A. Miller, 1982, Preliminary Estimate of Effective Ground-Water Recharge Rates in Central Oklahoma: Water Research Inst., OK. State Univ., Stillwater, 32p.

Pettyjohn, W.A., H. White, and S. Dunn, 1983, Water Atlas of Oklahoma: Univ. Center Water Research, OK. State Univ., Stillwater, 71p.

Pool, J.R., 1977, Morphology and Recharge Potential of Certain Playa Lakes of the Edwards Plateau of Texas: Baylor Geol. Studies Bull. 32, 19p.

Prickett, T.A., and C.G. Lonnquist, 1971, Selected Digital Computer Techniques for Groundwater Resource Evaluation: Illinois State Water Survey Bull. 55, 62p.

Rothrock, E.P., 1925, Geology of Cimarron County Oklahoma: OK. Geol. Survey Bull. 34, 107p.

Sapik, D.B., and R.L. Goemaat, 1973, Reconnaissance of the Ground-Water Resources of Cimarron County, Oklahoma: U.S. Geol. Survey Hydrol. Invest. Atlas HA-373, scale 1:125,000, 3 sheets.

Schoff, S.L., 1939, Geology and Ground Water Resources of Texas County, Oklahoma: OK. Geol. Survey Bull. 59, 248p.

Schoff, S.L., 1943, Geology and Ground Water Resources of Cimarron County, Oklahoma: OK. Geol. Survey Bull. 64, pp.100-118,228-246.

Schoff, S.L., 1953, Ground-Water Pumpage and Water Levels in the Oklahoma Panhandle: OK. Geol. Survey, The Hopper, Vol.13, Nos.9-12, pp.51-57.

Schoff, S.L., 1955, Map Showing Ground-Water Reservoirs in Oklahoma: OK. Geol. Sur. Map 72-2.

Schneider, A.D., and O.R. Jones, (in press), Recharge of the Ogallala Aquifer with Excavated Basins: Proc. Ogallala Aquifer Symposium, Lubbock, TX., 1984.

Stoner, J.D., 1981, Water Type and Suitability of Oklahoma Surface Waters for Public Supply and Irrigation, Part 3: Canadian, North Canadian, and Deep Fork River Basins Through 1979: U.S. Geol. Survey Water-Resources Invest. 81-80, 210p.

Theis, C.V., 1937, Amount of Ground-Water Recharge in the Southern High Plains: Am. Geophys. Union Trans. Vol.18, pp.564-568.

Thompson, D.G., 1921, Ground Water for Irrigation near Gage, Ellis County, Oklahoma: U.S. Geol. Survey Water-Supply Paper 500-B, pp.33-53.

Trescott, P.C., G.F. Pinder, and S.P. Larson, 1976, Finite-Difference Model for Aquifer Simulation in Two Dimensions with Results of Numerical Experiments: U.S. Geol. Survey Techniques Water-Resources Invest., book 7, chap. C1, 116p.

U.S. Geological Survey. Water Resources Data for Oklahoma, Years 1966-1981.

Wang, H.F., and M.P. Anderson, 1982, Introduction to Ground-Water Modeling: W.H. Freeman and Co., 237p.

Weeks, J.B., 1978, Plan of Study for the High Plains Regional Aquifer-System Analysis in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geol. Survey Water-Ressources Invest. 78-70, 28p.

Weeks, J.B., and E.D. Gutentag, 1981, Bedrock Geology, Altitude of Base, and 1980 Saturated Thickness of the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geol. Survey Hydrol. Invest. Atlas HA-648, scale 1:2,500,000, 2 sheets.

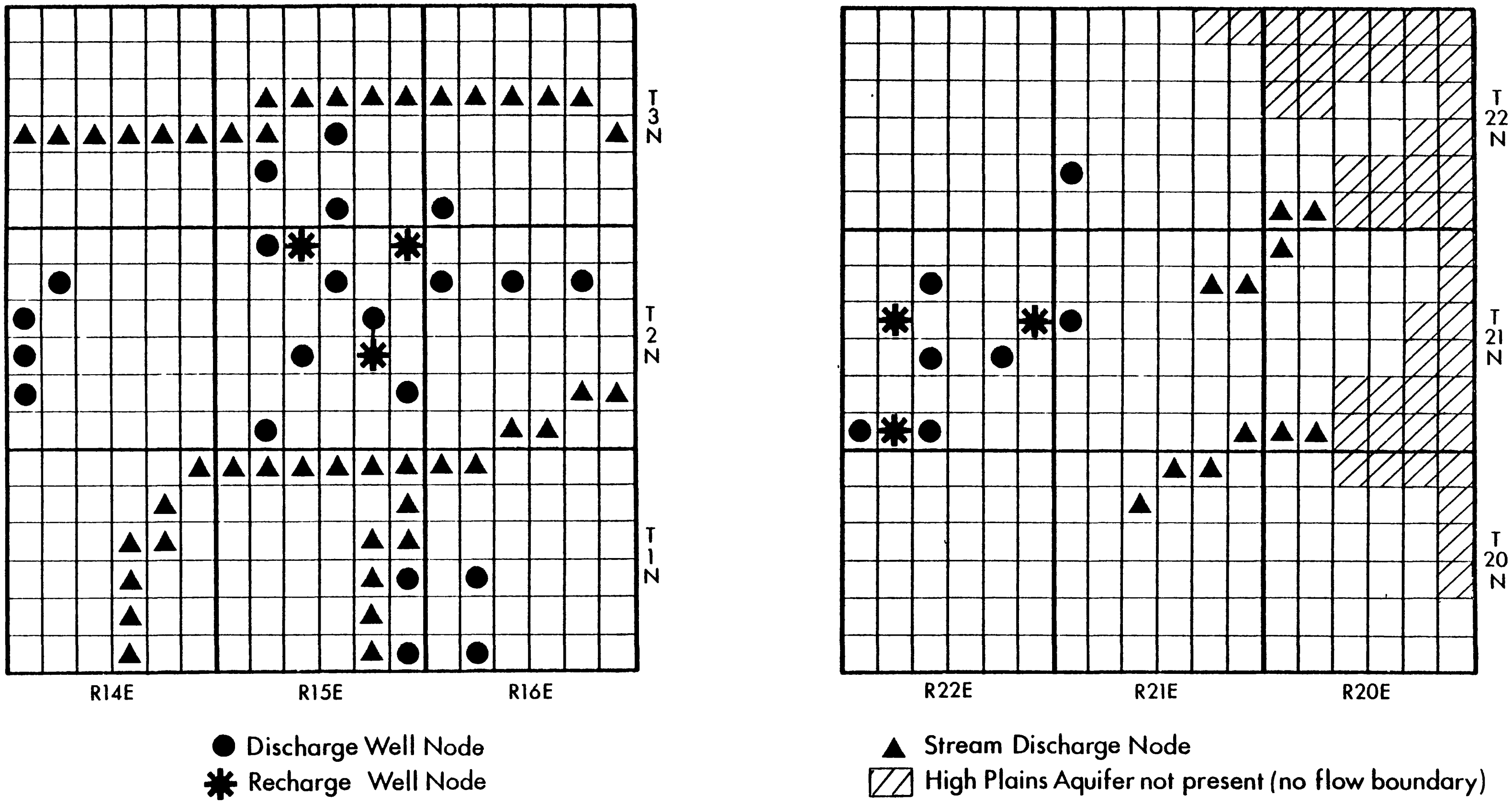
Wood, P.R., and B.L. Stacy, 1965, Geology and Ground-Water Resources of Woodward County, Oklahoma: OK. Water Resources Board Bull. 21, 114p.

Wood, P.R., and D.L. Hart, Jr., 1967, Availability of Ground Water in Texas County, Oklahoma: U.S. Geol. Survey Hydrol. Invest. Atlas HA-250, scale 1:125,000, 3 sheets.

Wood, W.W., and W.R. Osterkamp, (in press), Recharge to the Ogallala Aquifer from Playa Lake Basins on the Llano Estacado (An outrageous proposal?). Proc., 2nd Ogallala Symposium, Lubbock, TX, June 4-7, 1984.

APPENDIX A

INPUT DATA



(A) Guymon Site

(B) Woodward Site

FINITE-DIFFERENCE GRIDS

GUYMON SITE

Recharge .000342 gpd/sq.ft

	# of nodes	Discharge Rate
Discharge	44	1800000 gpd

Projected Pumping Schedule (GPD)

		1980-85	1985-90	1990-95	1995-2000
TIME (DAYS) =		1825	3650	5475	7300
	(X,Y)				
1	2,10	4000000	4000000	4000000	4000000
2	2,12	4500000	4500000	4500000	4500000
3	2,11	4500000	4500000	4500000	4500000
4	3,9	2500000	2500000	2500000	2500000
5	9,6	2400000	2400000	2400000	2400000
6	10,11	7710000	7710000	7710000	7710000
7	11,9	6670000	6670000	6670000	0
8	14,9	7600000	7600000	7600000	7600000
9	13,17	2750000	2750000	2750000	2750000
10	15,17	3050000	3050000	3050000	3050000
11	15,19	3850000	3850000	3850000	3850000
12	13,19	3850000	3850000	3850000	3850000
13	11,5	3800000	3800000	3850000	3850000
14	9,13	3450000	3450000	3450000	3450000
15	14,7	3600000	3600000	3600000	3600000
16	9,8	3400000	3400000	3400000	3400000
17	13,12	2900000	2900000	2900000	2900000
18	11,7	2650000	2650000	2650000	2650000
19	18,9	3100000	3100000	3100000	3100000
20	16,9	3900000	3900000	3900000	3900000
21	12,10	3830000	3830000	3830000	3830000

Artificial Recharge 1980-2000

(X,Y)	Recharge Rate (GPD)
10,8	646,000
12,11	646,000
13,8	646,000

GUYMON SITE

Calibration Pumping Schedule (GPD)

		1940-45	45-50	50-55	55-60	60-65	65-70	70-75	75-80
TIME (DAYS)=		1825	3650	5475	7300	9125	10950	12775	14600
	(X,Y)								
1	2,10	240000	380000	500000	640000	975500	2700000	3150000	4000000
2	2,12	280000	420000	550000	690000	1250000	3400000	3750000	4500000
3	2,11	280000	420000	550000	690000	1250000	3400000	3750000	4500000
4	3,9	160000	240000	3200E5	400000	550000	1700000	2000000	2500000
5	9,6	150000	230000	3100E5	390000	540000	1600000	1900000	2400000
6	10,11	770000	1220000	1310000	1870000	2760000	5840000	6640000	7710000
7	11,9	510000	612000	1150000	1490000	2040000	4190000	5740000	6670000
8	14,9	691000	908000	1220000	1640000	2480000	5710000	6500000	7600000
9	13,17	150000	240000	360000	490000	830000	1850000	2250000	2750000
10	15,17	180000	300000	400000	510000	870000	2050000	2350000	3050000
11	15,19	270000	400000	490000	600000	1100000	2550000	3100000	3850000
12	13,19	270000	400000	490000	600000	1100000	2550000	3100000	3850000
13	11,5	250000	370000	480000	570000	950000	2900000	3150000	3800000
14	9,13	230000	350000	460000	550000	920000	2500000	2900000	3450000
15	14,7	220000	350000	460000	550000	930000	2700000	2950000	3600000
16	9,8	200000	330000	440000	530000	910000	2500000	2750000	3400000
17	13,12	150000	260000	345000	395000	700000	1800000	2050000	2900000
18	11,7	130000	220000	320000	420000	710000	1750000	2055000	2650000
19	18,9	180000	270000	375000	465000	795000	2000000	2300000	3100000
20	16,9	230000	370000	490000	580000	930000	2750000	3000000	3900000
21	12,10	275000	347500	515000	598000	935000	2950000	3220000	3830000

WOODWARD SITE

Recharge .000769 gpd/sq.ft

	# of nodes	Discharge Rate
Discharge	11	424000 gpd

Calibration Pumping Schedule (GPD)

		1940-60	1960-80
	TIME (DAYS) =	7300	14600
	(X,Y)		
1	2,13	0	300,000
2	4,9	0	130,000
3	4,11	0	150,000
4	4,13	0	100,000
5	6,11	0	125,000
6	8,6	0	75,000
7	8,10	0	70,000

Projected Pumping Schedule (GPD)

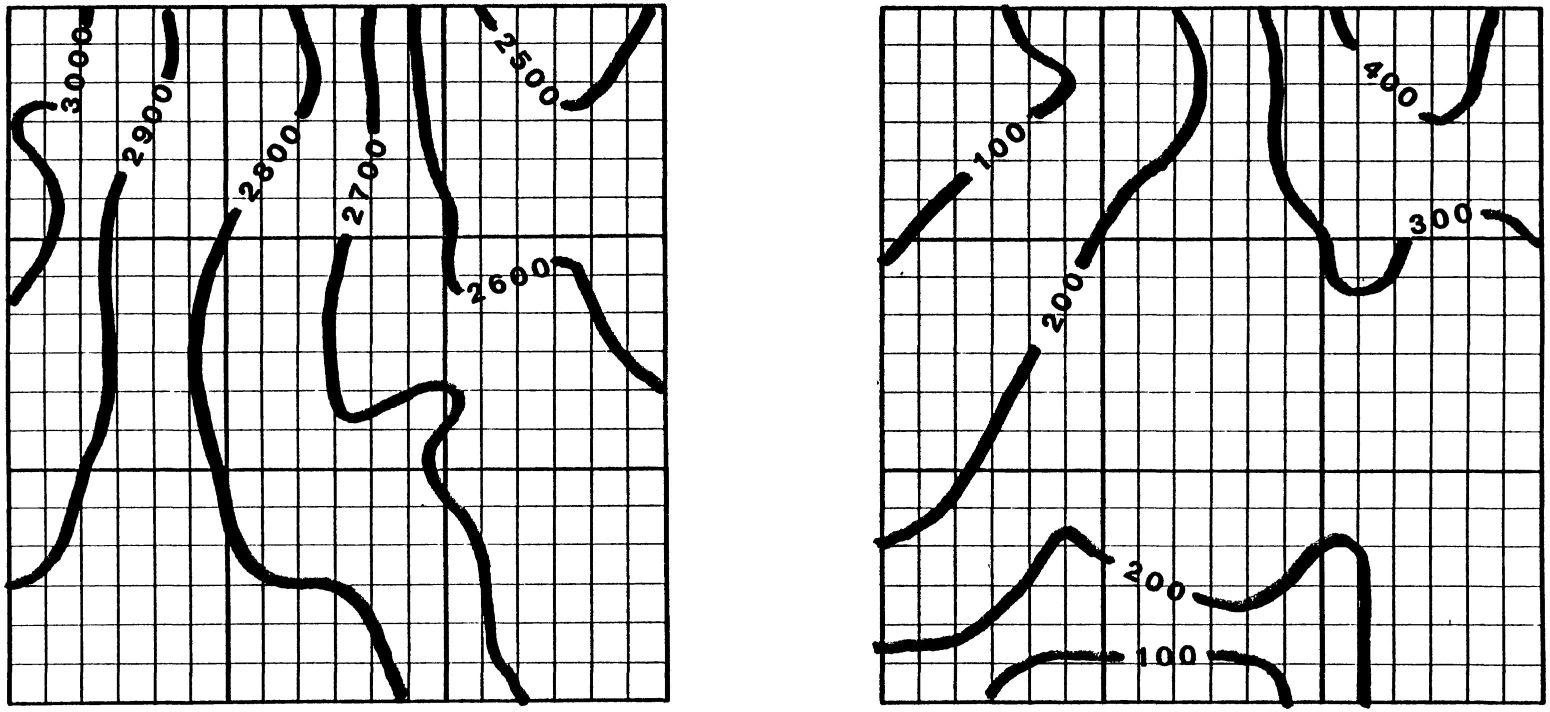
		1940-60	1960-80	1980-2000
	TIME (DAYS) =	7300	14600	21900
	(X,Y)			
1	2,13	0	300,000	300,000
2	4,9	0	130,000	130,000
3	4,11	0	150,000	150,000
4	4,13	0	100,000	100,000
5	6,11	0	125,000	125,000
6	8,6	0	75,000	75,000
7	8,10	0	70,000	70,000

Artificial Recharge 1980-2000

(X,Y)	Recharge Rate (GPD)
10,8	646,000
12,11	646,000
13,8	646,000

APPENDIX B

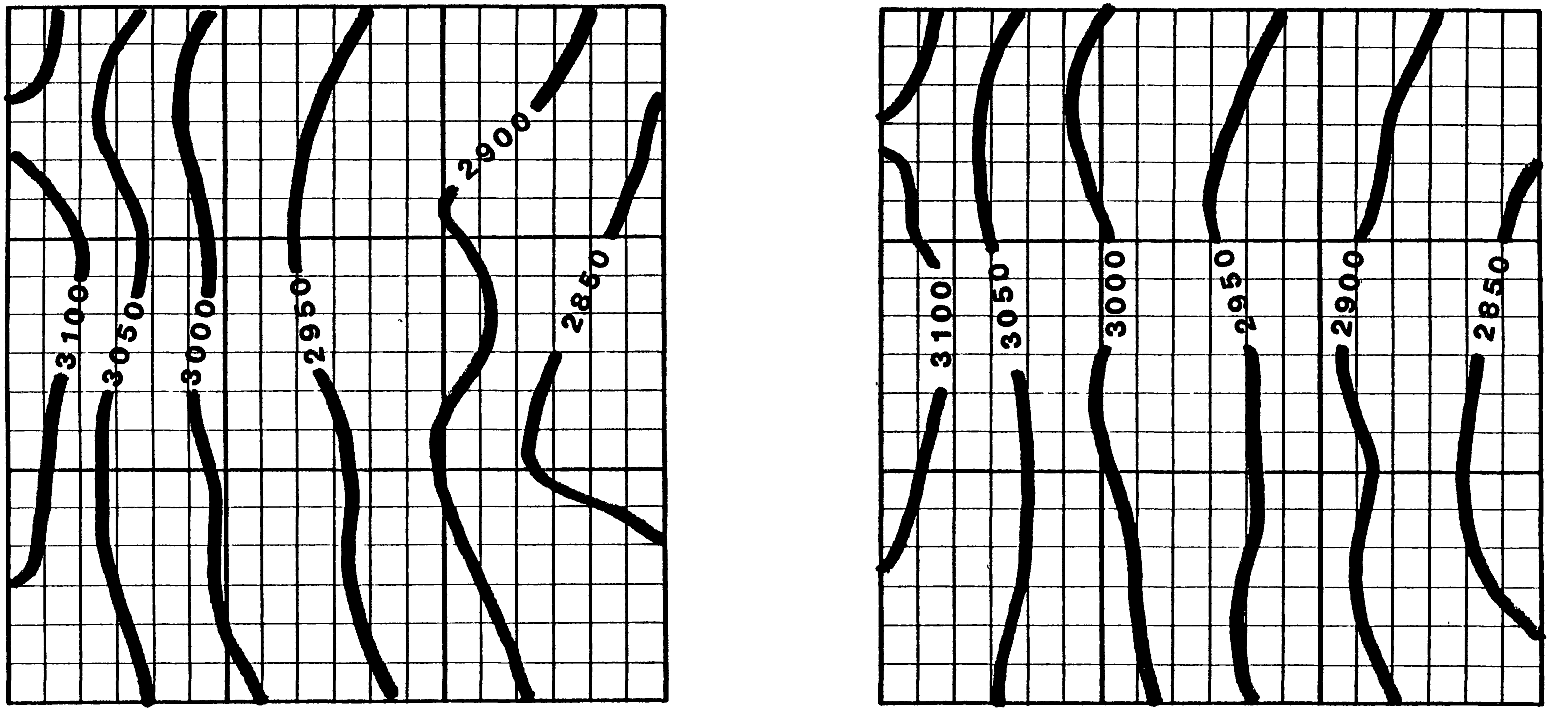
CALIBRATION MATRICES



(A) Elevation of the Base of the High-Plains Aquifer

(B) 1940 Saturated Thickness of the High-Plains Aquifer

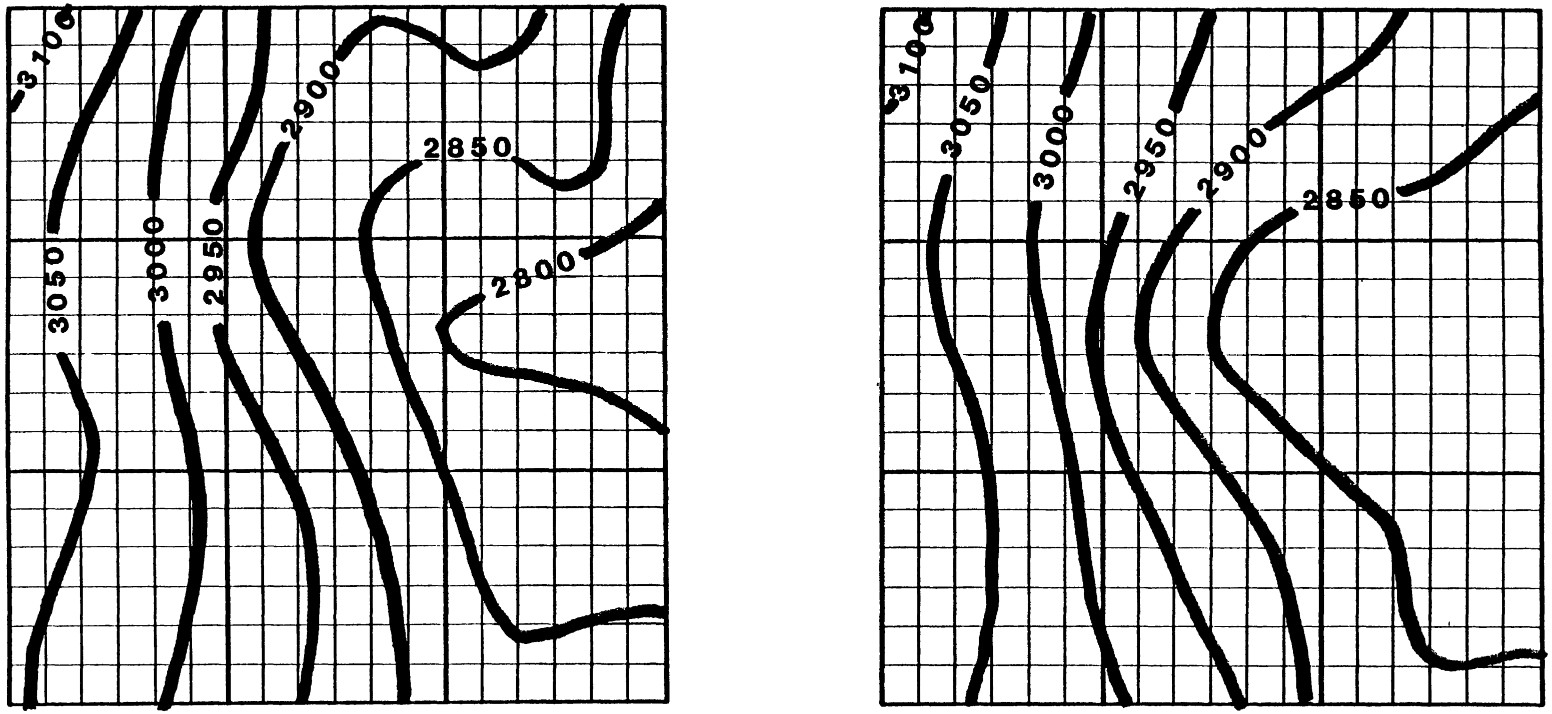
GUYMON SITE



(A) Observed 1940 Water-Table Elevations

(B) Simulated 1940 Water-Table Elevations

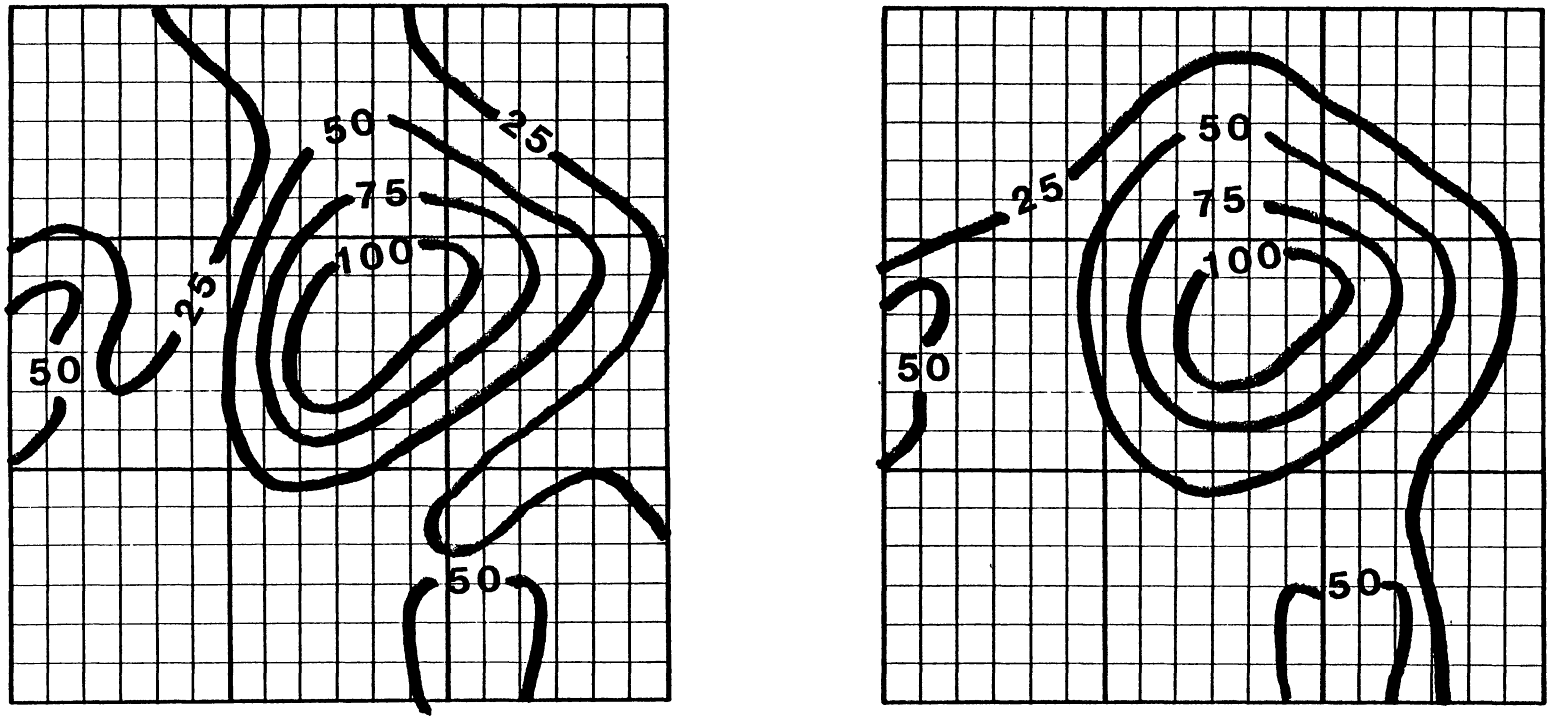
GUYMON SITE



(A) Observed 1980 Water-Table Elevations

(B) Simulated 1980 Water-Table Elevations

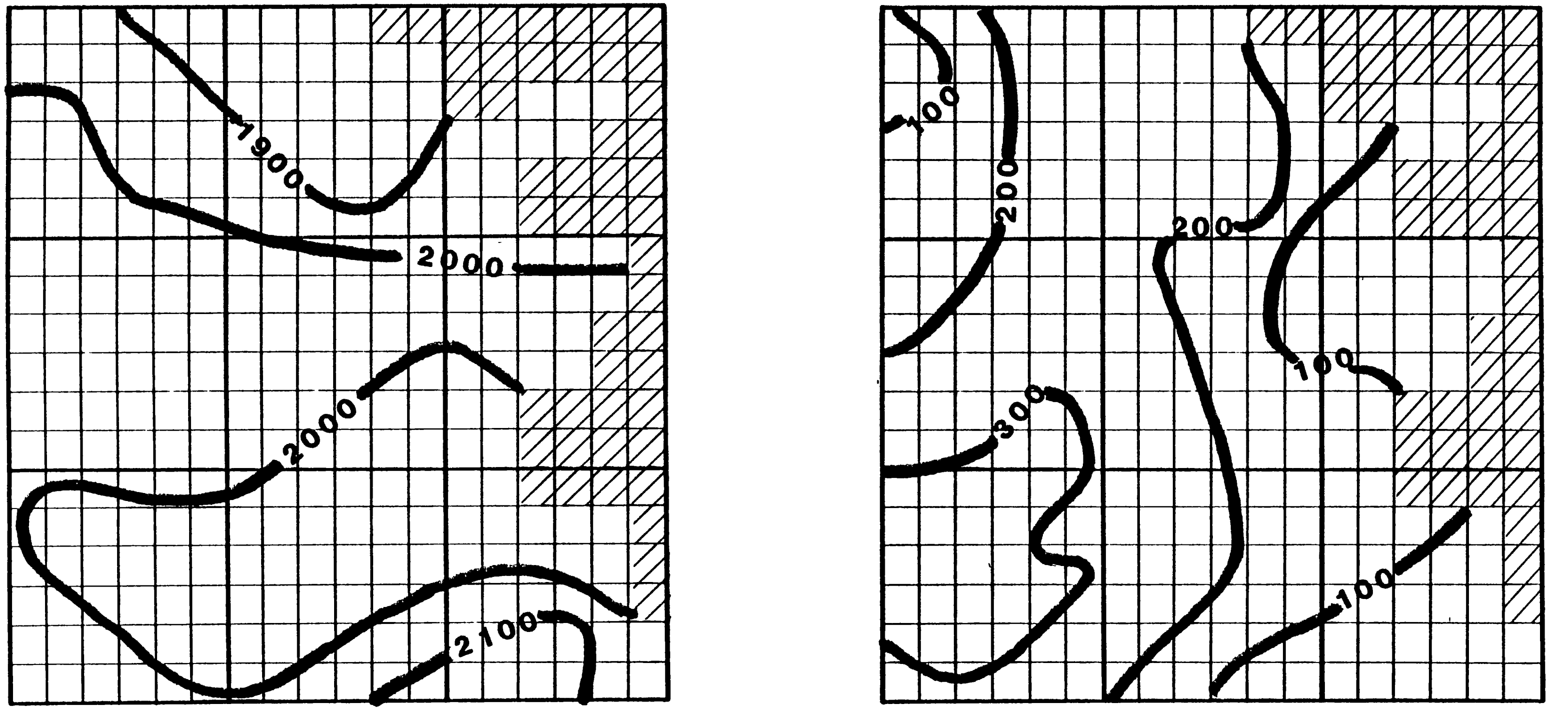
GUYMON SITE



(A) Observed Water-Level Declines
1940-1980

(B) Simulated Water-Level Declines
1940-1980

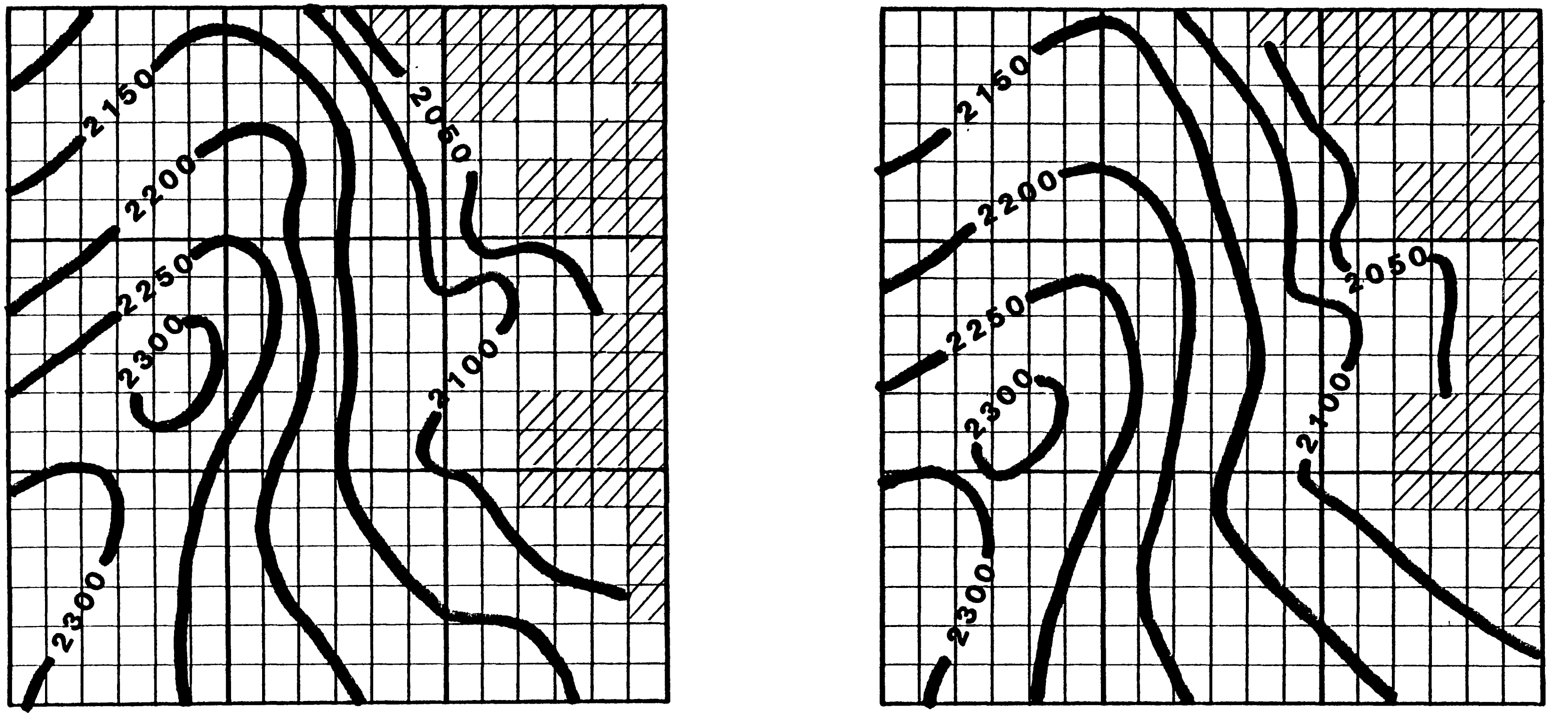
GUYMON SITE



(A) Elevation of the Base of the High-Plains Aquifer

(B) 1940 Saturated Thickness of the High-Plains Aquifer

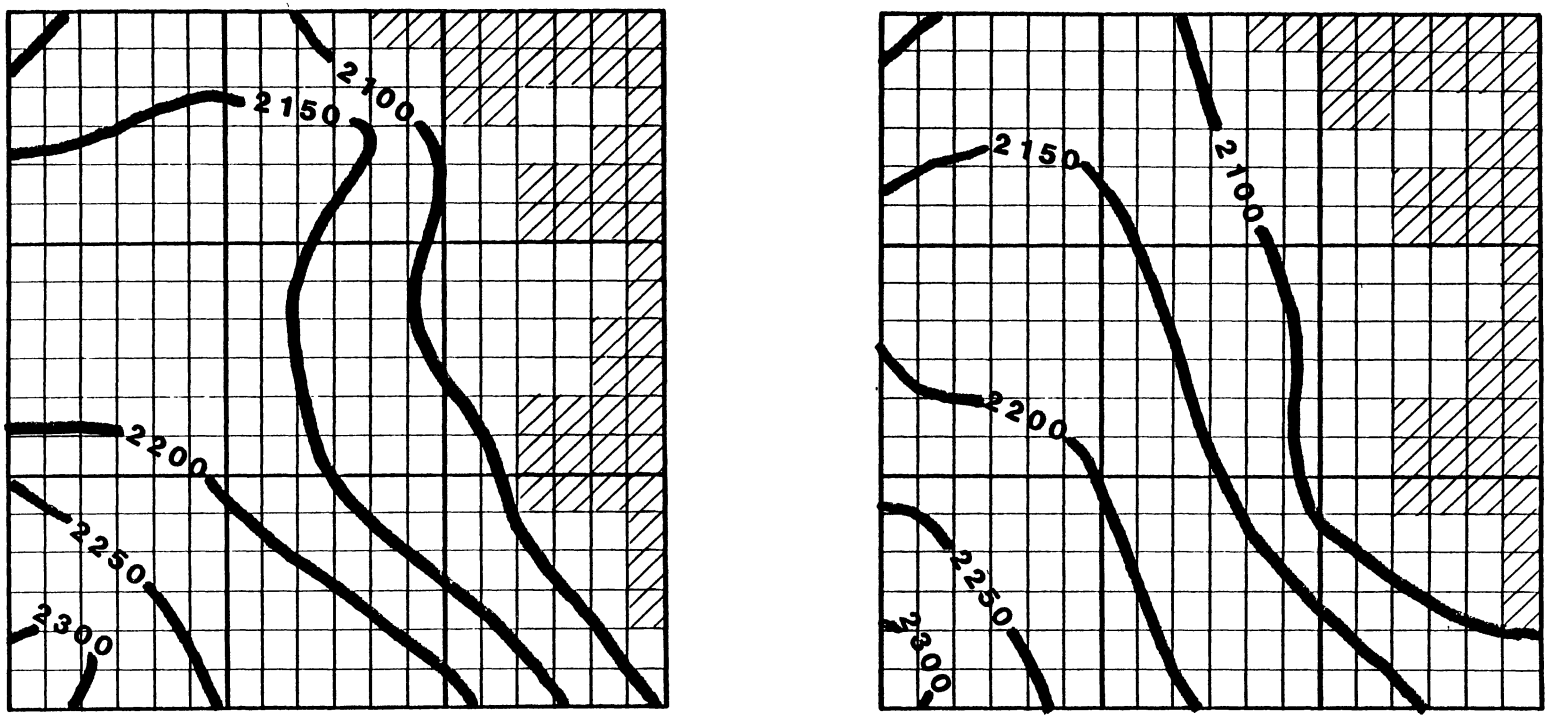
WOODWARD SITE



(A) Observed 1940 Water-Table Elevations

(B) Simulated 1940 Water-Table Elevations

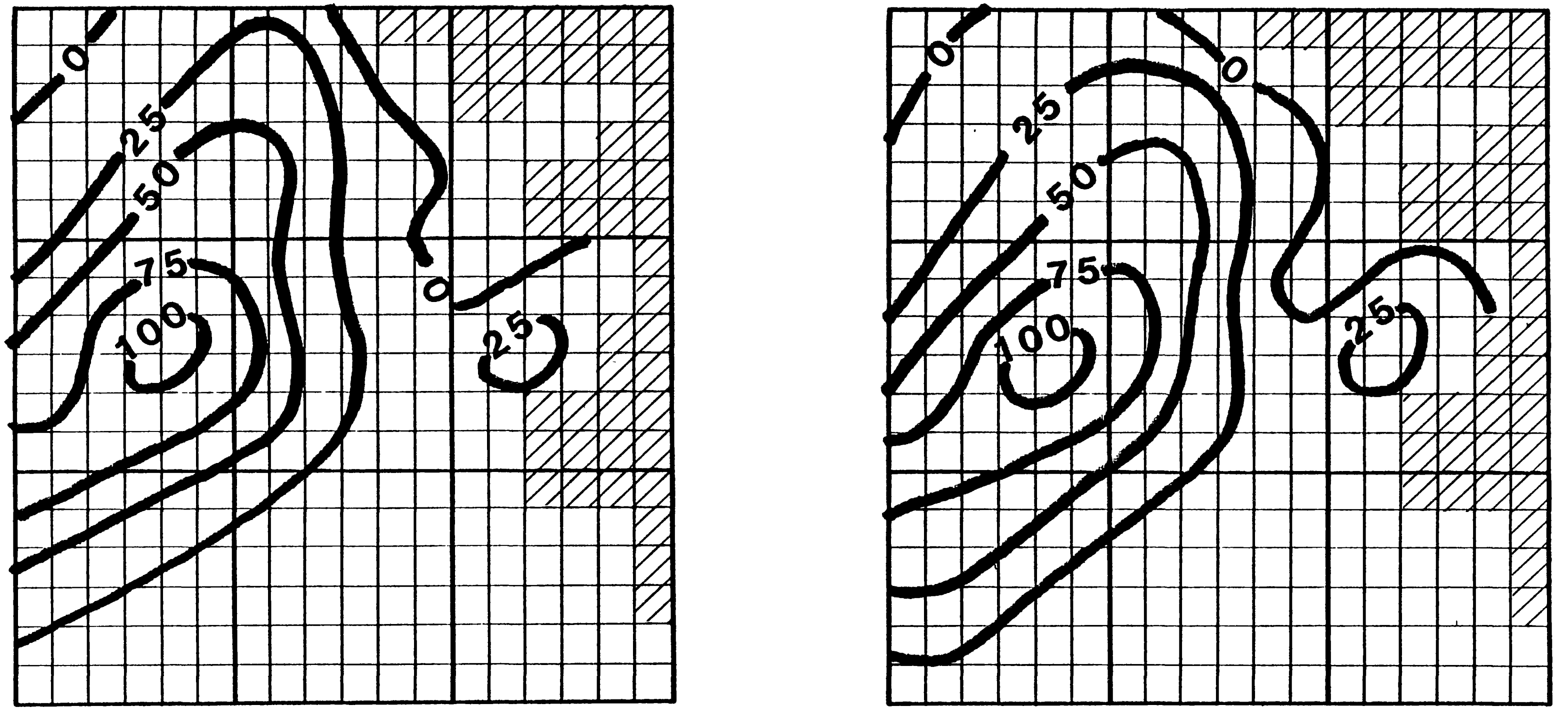
WOODWARD SITE



(A) Observed 1980 Water-Table Elevations

(B) Simulated 1980 Water-Table Elevations

WOODWARD SITE



(A) Observed Water-Level Declines 1940-1980

(B) Simulated Water-Level Declines 1940-1980

WOODWARD SITE

VITA

Harold O. White, Jr.

Candidate for the Degree of

Master of Science

Thesis: FEASIBILITY OF ARTIFICIAL RECHARGE TO THE HIGH PLAINS AQUIFER, NORTHWESTERN OKLAHOMA

Major Field: Geology

Biographical:

Personal Data: Born in Moscow, Idaho, January 17, 1958, the son of Harold O. and Dorothy K. White.

Education: Graduated from Washington-Lee High School, Arlington, Virginia, in June, 1976; received Bachelor of Science Degree in Geology from the College of William and Mary in Virginia, Williamsburg, Virginia in December, 1980; completed the requirements for the Master of Science Degree at Oklahoma State University in December, 1984.

Professional Experience: Research Assistant, Department of Geology, Oklahoma State University, June 1982, to December, 1984; Teaching Assistant, Department of Geology, Oklahoma State University, January 1983, to May, 1983.