THESIS

DISTRIBUTION OF GROUNDWATER RECHARGE

Submitted by

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In partial fulfillment of the requirements
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ABSTRACT

DISTRIBUTION OF GROUNDWATER RECHARGE

The primary objective of this study was to determine the average annual net rate and areal variation of natural recharge to the Ogallala Formation in the Northern High Plains of Colorado. This unconfined aquifer underlies approximately 9300 square miles in northeastern Colorado and is capable of yielding large amounts of water to wells.

Natural recharge to the Ogallala Formation is derived from precipitation falling within the basin. However, none of the previous investigations has attempted to describe the areal variation of groundwater recharge. Assuming that the Ogallala Formation was in a state of dynamic equilibrium prior to large scale development, the steady state form of the Boussinesq equation was written in finite difference form and a solution for the net recharge rate was obtained on the CDC 6600 digital computer.

To obtain the areal variation in net natural recharge, the Northern High Plains was subdivided into six square-mile grids, and a net recharge rate obtained for each grid. A wide variation in net recharge was obtained. In general, net recharge rates in excess of two inches per year are confined to the sandhill portion of the study area. Most of the area with surface exposures of Peorian Loess and

Ogallala Formation have net recharge rates of one inch per year or less.

The total volume of net recharge to the Ogallala Formation was computed to be 405,000 acre-feet per year or an average of about 0.82 inch per year. The subsurface underflow across the state line into Kansas and Nebraska was 175,000 acre-feet per year and the net groundwater runoff into the North and South Forks of the Republican River and Arikaree River was calculated to be 75,000 acre-feet per year. Another 50,000 acre-feet per year of groundwater is consumed by evapotranspiration.

An area of substantial discharge was disclosed along the subsurface outcrop of the White River Group and it is hypothesized that groundwater is being discharged from the Ogallala Formation into the White River Group. Another area of unexplained natural discharge is along the Smoky Hill River near Cheyenne Wells. This may also be the result of subsurface discharge, and a thorough investigation of the subsurface geology in the area is needed.

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Chapter I

INTRODUCTION

Natural groundwater reservoirs formed by rock formations generally have enormous storage capacities. In general the large volume of water stored underground is the result of receiving small amounts of recharge over long periods of time. If the withdrawal of ground water by wells should exceed recharge, eventual depletion of the groundwater reservoir may occur. Thus, recharge rates for aquifers need to be determined before groundwater resources can be evaluated and the consequences of development forecast.

Description of Problem

The Northern High Plains of Colorado is underlain by the Ogallala Formation. This unconfined aquifer underlies approximately 9300 square miles and is capable of yielding large amounts of water to wells. The number of large capacity wells increased from approximately 400 in 1960 (24) to 1350 in July 1966 (27). Irrigation wells comprise the largest percentage of these wells. With the increased demand for high capacity irrigation wells, a question naturally arises concerning the effects of large scale development on the aquifer. Before aquifer management practices are recommended, the amount of natural recharge to the Ogallala Formation should be evaluated.

Recharge involves the vertical movement of water from the land surface to the aquifer under the influence of vertical head differentials. Thus, recharge is defined as the net quantity of vertical leakage reaching the water table per unit of time. The most commonly used units for recharge are acre-feet per year, inches per year, or gallons per day per square mile.

Since the Ogallala Formation is an unconfined aquifer, the major sources of recharge are: (1) deep percolation of precipitation on the land surface and (2) infiltration of surface water from streams or lakes. The portion of the precipitation which penetrates to the water table is the residual item after all other demands on rainfall, such as runoff and evapotranspiration, have been met. The greatest percentage of annual precipitation occurs during the spring and summer months when evapotranspiration is highest. Therefore, it would appear that most recharge in the Northern High Plains area occurs during periods of excessive or prolonged rainfall.

Recharge to the Ogallala Formation is a variable in both time and space and depends upon several factors. Among these are the type and thickness of the soils and other deposits overlying the aquifer; the vertical hydraulic conductivity; the topography; the various methods of land use; the type and amount of vegetation; the soil moisture content; and the intensity, duration, and seasonal distribution of rainfall.

Purposes and Objectives

Preliminary investigations indicate that the rate of recharge to the Ogallala Formation is small and any development of groundwater, even to a small extent, could lead to a mining situation. Present estimates of recharge are reported as average values for the entire basin (3, 24). However, since groundwater demand and use are not uniform over the entire basin, an average figure for recharge is inadequate and a need exists for evaluating the areal distribution of recharge.

The primary objective of this study is to determine the average annual rate and areal variation of natural recharge to the Ogallala Formation in the Northern High Plains of Colorado. This information is vital for the sound management of the aquifer as a natural resource. The results will also be beneficial in implementing the Colorado Ground Water Law.

Method of Calculating Recharge

Before development, the groundwater in the Ogallala Formation is assumed to have been in a state of dynamic equilibrium. This means that the average recharge was balanced by an equal amount of natural discharge, and these in turn determined the rate of groundwater flow. Hence, by determining the rate of groundwater flow, the rate of recharge can be estimated. This would appear to be the most logical approach since the slow movement of groundwater tends to average out the effects of unequal recharge rates of short duration at different times.

Assuming dynamic equilibrium, a finite difference approach was used to evaluate the natural recharge rates necessary to maintain the groundwater gradient in a steady state prior to development. The steady state form of the Boussinesq equation was written in finite difference form and a solution for the recharge rate obtained on the digital computer.

Chapter II

DESCRIPTION OF STUDY AREA

Location of Area

The study area, located in northeastern Colorado, is shown in Figure 1. The area is a part of the High Plains Section of the Great Plains Physiographic Province (16) and underlies all or parts of the following counties: Sedgwick, Phillips, Logan, Yuma, Washington, Kit Carson, Lincoln, Kiowa and Cheyenne. The boundaries of the study area are the eastern boundary of the State of Colorado and that portion of the Ogallala Formation south of the South Platte River and east of Big Sandy Creek. The area contains approximately 9300 square miles.

Topography

The topography of the area is characterized by an eastward sloping, gently rolling plain. Large portions of the area have low undulating sand dunes which contrast with the relatively flat surrounding area. Also, throughout much of the area, numerous shallow depressions in the land surface are present. After heavy rains, these depressions retain runoff water to form temporary ponds. The elevation of the land surface ranges from about 6000 feet at Cedar Point north of Limon to about 3400 feet at the confluence of the Arikaree River and the North Fork of the Republican River.

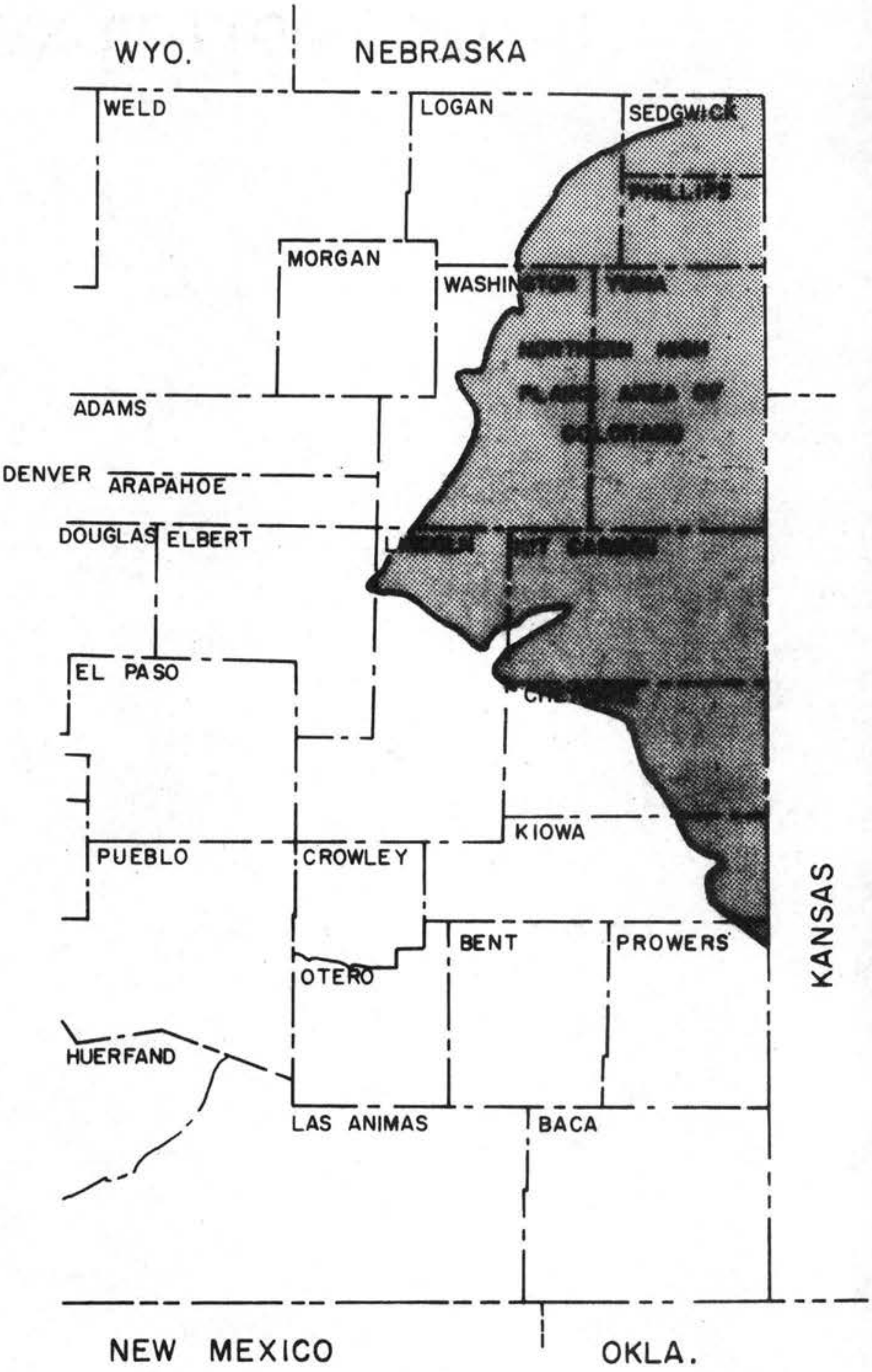

Figure 1. Boundaries of the Northern High Plains of Colorado used in this study.

A large portion of the study area is covered by loose silty and sandy soils. However, there are several areas with tight clay soils. Much of the soils of Kit Carson County are in this classification. The southeastern part of Phillips County, the northern half of Yuma County, the eastern half of Washington County and the northern part of Kit Carson County are covered with sand hills.

The boundary of the study area corresponds very closely to the easternmost surface water divides of the South Platte River and Arkansas River within Colorado. As a consequence, all streams of the area have their headwaters within the study area. The three major streams are the North and South Forks of the Republican River and the Arikaree River. All three discharge into Kansas and Nebraska. These streams are ephemeral and influent except for the lower reaches, which are effluent near the state line. Numerous small intermittent streams in the western portion of the study area discharge into the sand hills where they disappear.

Climate

The climate of the study area is semi-arid and is characterized by hot summers and cold winters. The temperature ranges from an average of about 33°F in the winter to 66°F in the summer. The average growing season is about 155 days.

Precipitation in the study area averages about 16-18 inches per year. Most of the precipitation occurs during the spring and summer months generally in the form of scattered thundershowers. Moderate to strong winds are common throughout the year. These winds cause blizzards in the winter and remove much of the soil moisture during the summer.

General Geology

The rocks that crop out in the Northern High Plains are sedimentary in origin, range in age from Mesozoic to Cenozoic, and include rocks belonging to the Cretaceous, Tertiary and Quaternary systems. Rocks ranging in age from Precambrian to Mesozoic are present in the subsurface. However, the geologic history pertinent to this study begins with the Cretaceous and a discussion of the older subsurface rocks is omitted. The following discussion has drawn heavily on the previous work of Cardwell and Jenkins (10), Weist (34), McGovern (23) and Boettcher (5).

Geologic History--At the beginning of Cretaceous time, the present area of the Northern High Plains (see Figure 2) was being subjected to erosion. In late Early Cretaceous time the sea advancing from the southeast was joined by the southward advancing waters of the Arctic Ocean. The broad structural trough formed by this sea encroachment is called the Rocky Mountain geosyncline. Deposits in these seas were removed by erosion during the subsequent emergence.

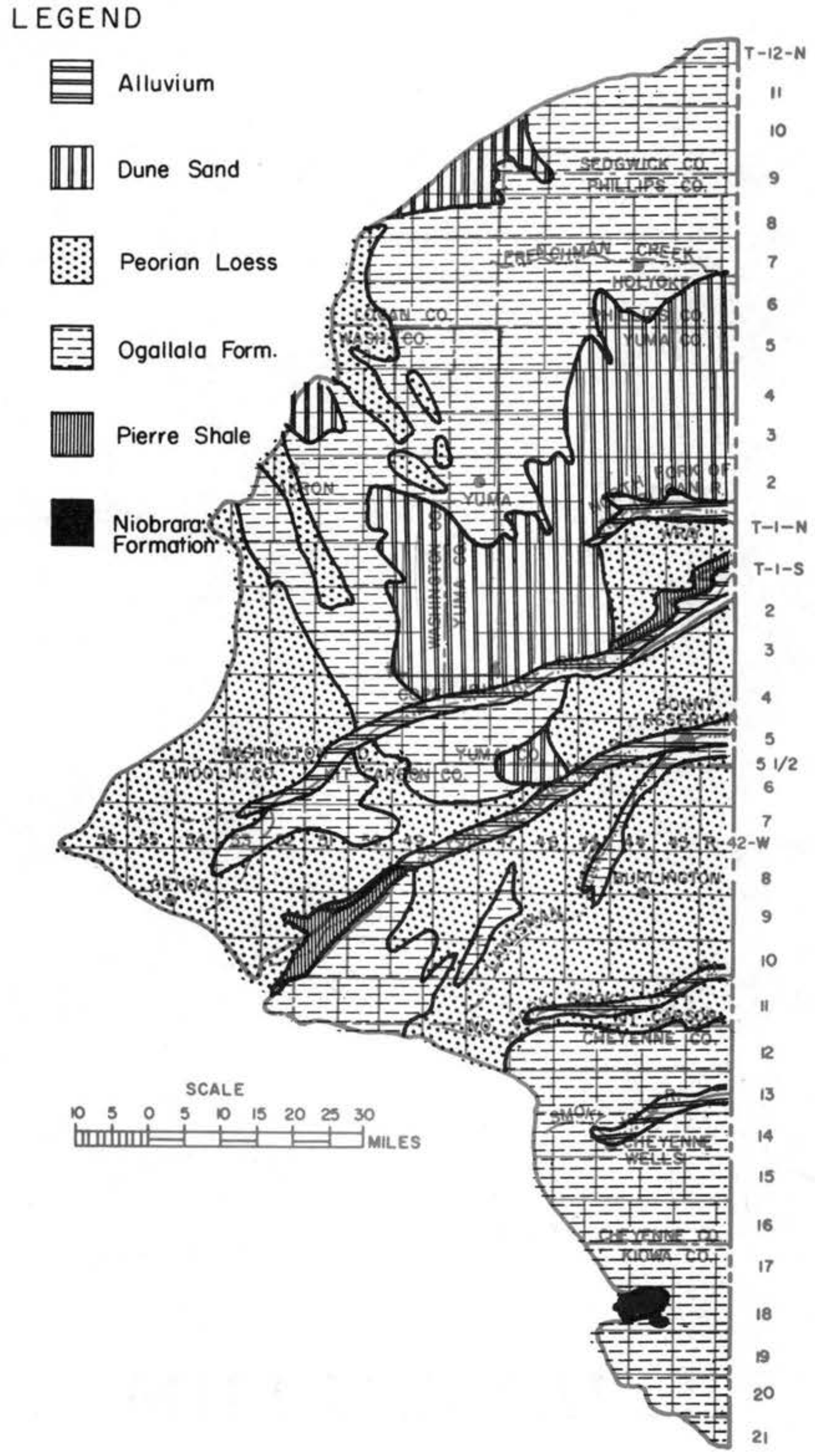

Figure 2. Generalized geologic map of the Northern High Plains of Colorado. (Modified from geologic map by Woodward, Clyde, Sherard and Associates (38)).

During Late Cretaceous time, the seas again invaded the area resulting in the deposition of several thousand feet of sandstone, limestone and shale. The Northern High Plains formations included in this marine deposition are the Dakota, Graneros, Greenhorn, Carlile, Niobrara and Pierre Formations. Near the close of the Cretaceous period orogenic movement along the Rocky Mountain geosyncline began and the sea receded. This was the last marine invasion of the North American interior.

The orogenic movement, uplift and volcanic activity along the Rocky Mountain geosyncline continued throughout Late Cretaceous time and at intervals during much of Cenozoic time. These widespread and repeated orogenics resulted in the development of the Rocky Mountains. Also, there was extensive erosion during this time period which removed some of the rocks of Cretaceous age.

The Cenozoic era was marked in the Northern High Plains by erosion and by the deposition of continental sediments derived largely from the rising Rocky Mountains. The building of the Northern High Plains by stream deposition was climaxed during the Cenozoic era.

The rise of the Rocky Mountains increased the gradients and debris-carrying power of the streams. The resulting sediments were deposited along areas bordering the east side of the mountains. Most rocks of Early Cenozoic age are absent in the Northern High Plains due to:

(1) the sediments were never deposited in the area and (2) the sediments were deposited but removed by subsequent erosion. For instance, the Castle Rock conglomerate of Oligocene age is composed of coarse detrital material and probably was not deposited as far east of the mountains as the High Plains. However, the White River Group of Oligocene age is present at various depths in the northern part of the High Plains area and it is probable that it once extended farther south but was removed by subsequent erosion during Miocene and early Pliocene time.

During Pliocene time the Rocky Mountains were uplifted again, increasing the gradients of the streams flowing eastward from the mountains. As the streams moved east with their sediment load, the gradients became smaller and the sediment began to be deposited. Erosion and sedimentation continued until the stream valleys were filled. Then the streams began to meander, and covered the eroded surfaces of the older rocks with enormous quantities of sediment.

This clastic sediment constitutes the Ogallala Formation which underlies the entire Northern High Plains. Toward the middle of Pliocene time the aggradation process came to an end and an era of erosion began which extends to the present time. This erosion removed the Ogallala Formation from areas adjacent to the mountains. Evidence of this erosion is given by the bold escarpment on the western side of the Northern High Plains which exposes the older rocks underlying the Ogallala. This erosion has resulted in the isolation of the Ogallala Formation from the Rocky Mountains and surrounding geologic formations.

The early part of the Quaternary period consisted largely of erosion. Although no glaciers extended into the Northern High Plains, their presence elsewhere affected the deposition in the area. The melting of continental glaciers formed streams which laid down the Grand Island Formation. The Sappa Formation and the Peorian Loess were deposited by winds blowing during the dry interglacial stages.

Dune sand of Pleistocene and Recent age covers approximately one-fifth of the Northern High Plains surface. Also, during these periods, the present drainage pattern was developing and the alluvium was being deposited along the stream channels.

Niobrara Formation--The Niobrara Formation of Cretaceous age is the oldest rock to crop out in the Northern High Plains. It is exposed in that part of the study area south of the Cheyenne-Kiowa County line, (Figure 2). The Niobrara Formation underlies the entire Northern High Plains and is the bedrock on which the Ogallala Formation rests in the southern part of the Northern High Plains. This formation ranges up to 700 feet thick in some areas and consists of a gray to blue-gray shaly marl. Weathered exposures may be yellow to light orange. The upper part of the formation contains numerous thin beds of bentonite and of gypsum crystals. Because of its character, the Niobrara Formation has an extremely low permeability and is not known to yield appreciable quantities of water to wells.

Pierre Shale--The Pierre Shale of Cretaceous age is distributed widely throughout the Great Plains Province. It underlies a large area of eastern Colorado, northwestern Kansas, Nebraska, South Dakota, North Dakota and parts of New Mexico, Wyoming, Montana and Minnesota. The formation underlies all of the study area north of the Cheyenne-Kiowa County line and is the bedrock underlying the Ogallala Formation in a large part of the area.

The Pierre Shale is primarily a fissile shale, but contains some siltstone with calcareous concretions. It ranges in color from dark gray to black with the upper few feet usually weathered to a yellowish-brown clay. The Pierre Shale may be as much as 4500 feet thick and outcrops at several places along the stream valleys.

The Pierre Shale is of little importance as an aquifer in the Northern High Plains. The small pore size and compactness of material inhibit the flow of water. However, fractured or sandy zones may yield small quantities of poor quality water. The shale serves as a nearly impervious boundary underneath much of the area and generally prevents the downward movement of water.

White River Group--Rocks of Oligocene age are represented in the Northern High Plains by the White River Group. This group consists of two formations, the Chadron Formation at the base and the Brule Formation at the top. The White River Group is limited to the northern portion of the study area in Logan, Phillips and Washington Counties. It lies unconformably over the Pierre Shale and immediately beneath the Ogallala Formation.

The Chadron Formation consists mainly of olive-green to brick-red silty to sandy clay and claystone which becomes siltier and lighter in color as it grades into the overlying Brule Formation. Channel deposits of sand and gravel are found in the Chadron Formation. These deposits are generally tightly cemented with siliceous cement. Because of its low permeability, the Chadron Formation is not considered a major source of ground water.

The Brule Formation was probably deposited by streams whose sediment load was mainly silt and clay. This formation generally consists of a buff to olive-green clayey silt and siltstone which grades into the upper Chadron Formation and the contact is therefore indistinct. The Brule Formation is hydrologically similar to the Chadron Formation and therefore is not a major source of water.

Although the formations of the White River Group are generally low in permeability, locally there may be channel-like deposits of sand which will serve as a water supply. Also, the formations may have fractured zones which would yield water to a well. In such cases the White River Group and the overlying Ogallala Formation are hydraulically connnected and the water in the White River Group is probably received by leakage from the overlying Ogallala Formation.

Ogallala Formation--The Pliocene Ogallala Formation underlies all of the Northern High Plains except for a few small areas along streams where it has been eroded away. It ranges in thickness from a few feet to about 460 feet and lies at the surface in a large part of the area. The Ogallala Formation consists of red and yellow clay; silt; fine to coarse, gray and buff-colored sand; gravel and caliche. On close examination, the formation seems to lens and interfinger in short vertical and horizontal distances indicating a highly heterogeneous nature. However, a study of well logs and several geologic sections of the Ogallala Formation along the North Fork of the Republican River indicate the beds actually are more continuous and better sorted than they at first appear. An apt description of the Ogallala Formation may well be that it is homogeneous in its heterogenity.

The Ogallala Formation is the most important source of ground water in the Northern High Plains and is the object of this study. Nearly all irrigation, stock, domestic and public-supply wells tap this formation. Well yields range from a few gallons per minute for small domestic and stock wells to as much as 2500 gallons per minute for some of the larger irrigation wells.

Grand Island Formation--The Grand Island Formation is a minor stratigraphic unit in the Northern High Plains. It consists of irregular lenticular deposits of reddish-brown fine to coarse sand and fine to medium gravel. This formation may be as thick as 50 feet in some areas and lies disconformably on the Ogallala Formation. It was laid down near the end of the Kansan stage of glaciation by streams flowing from the mountains and tablelands. The Grand Island Formation is not considered an aquifer since it lies above the water table. However, it is a moderately permeable surface deposit, and this permits natural recharge to the underlying Ogallala Formation.

Sappa Formation--In many places in the Northern High Plains, the Sappa Formation overlies the Grand Island Formation. It consists of calcareous sand and clayey, silty marl ranging in color from light gray to olive gray. The Sappa Formation is thin and discontinuous being less than 10 feet thick. Because of this it is not differentiated from overlying dune sand and loess on Figure 2. No known water supply has been developed in the Sappa Formation.

Peorian Loess--The Peorian Loess overlies the Ogallala Formation in a substantial area of the Northern High Plains. The thickness of this wind-deposited yellowish-gray calcareous silt ranges from a feather edge to 125 feet thick. The Peorian Loess is relatively impermeable and yields little or no water to wells. This low permeability also retards recharge to the underlying Ogallala Formation.

Dune Sand--Figure 2 shows a substantial portion of the Northern High Plains covered with sand dunes. The dunes are formed by loose well-sorted fine to coarse grains of quartz and feldspar. Deposits may be as much as 170 feet thick in some areas. The sand dunes lie mostly above the water table and are not a source of ground water. However, they do have a high permeability and a poor surface drainage system which makes them an important area for natural recharge to the Ogallala Formation.

Alluvium--Alluvium derived locally from the Ogallala Formation and Pleistocene deposits lies along the major stream valleys and some of the smaller creeks. The Alluvium is an unconsolidated sand and gravel with some silt and clay and ranges up to 100 feet in thickness. This aquifer is limited in areal extent, but where it is present, yields of up to 1500 gallons per minute have been obtained from wells. McGovern (23) indicates that the contact between the Alluvium and the Ogallala Formation cannot be differentiated in areas of Washington County. The Alluvium and Ogallala Formation are hydraulically connected and are considered as one aquifer in this study. Table 1 shows a generalized geologic section of the Northern High Plains of Colorado.

Table 1. Generalized Geologic Section of the Northern High Plains of Colorado.

System	Series	Stratigraphic Unit	Thickness (feet)	Physical Character	Water Supply
Quaternary	Recent and Pleistocene	Dune Sand	0 to 100±	Reddish-orange sand; primarily quartz and feldspar;wind deposited.	Yields little or no water to wells. Serves as an area of recharge.
		Alluvium	0 to 100±	Pink,brown and gray unconsolidated sand, gravel, clay, and silt; stream deposited.	Yields small to large quantities of water to wells.
	Pleistocene	Peorian Loess	0 to 120±	Yellowish-gray to gray silt and clay with some sand and calcareous concretions;wind deposited.	Yields little or no water to wells.
		Sappa Formation	0 to 10±	Light to medium gray sand and clayey, silty marl;wind deposited.	Not known to yield water to wells in the area.
		Grand Island Formation	0 to 50±	Reddish-brown to light gray sand and gravel;loosely consolidated; stream deposited.	Yields little or no water to wells.
Tertiary	Pliocene	Ogallala Formation	0 to 450±	Buff, gray to red, sand,gravel, silt and clay;contains abundant caliche;has caprock of algal limestone; stream deposited.	Yields small to large quantities of water to wells.Principle aquifer in the Northern High Plains.
	Oligocene	White River Group	0 to 600±	Massive,olive to tan siltstone containing lenses and channels of sandstone;stream deposited.	Yields small to moderate quantities of water from channel deposits and fractures;considered bedrock in northern part of the Northern High Plains.
Cretaceous	Upper Cretaceous	Pierre Shale	0 to 4500±	Thin bedded,gray to dark-gray shale and sandy shale;contains bentonitic clay and calcareous concretions;occasionly upper 4-8 feet are a yellow weathered zone.	Yields very small quantities of water to wells from upper weathered zones;considered bedrock over a large portion of the Northern High Plains.
		Smoky Hill Marl Member of the Niobrara Formation	700±	Gray, shaly marl; usually weathers to orange; contains thin bentonitic streaks; marine deposited.	Not known to yield water to wells.

Chapter III

GENERAL HYDROLOGY

The hydrological properties of major importance in studying a groundwater aquifer are: (1) the configuration of the bedrock surface, (2) the configuration of the water table, (3) the thickness of the saturated material, (4) the hydraulic conductivity of the aquifer and (5) the quantity of recharge and discharge. Other items of interest include depth of the water table below land surface, water table fluctuations, specific yield of the aquifer, and variation of precipitation over the area.

Configuration of the Bedrock Surface

As was pointed out in the preceding chapter the Ogallala Formation overlies an erosional bedrock surface cut in the Niobrara Formation, Pierre Shale and White River Group. Figure 3 shows the portion of the study area underlain by each of the three types of bedrock material. The configuration of the bedrock surface is shown by means of contours in Figure 4. A knowledge of the bedrock surface is important in determining the thickness of the overlying Ogallala Formation and in studying the ancestral drainage pattern.

Delineation of the bedrock surface is based on driller's logs of wells and shot holes in the study area. More than 2000 logs were examined and approximately 1600 of

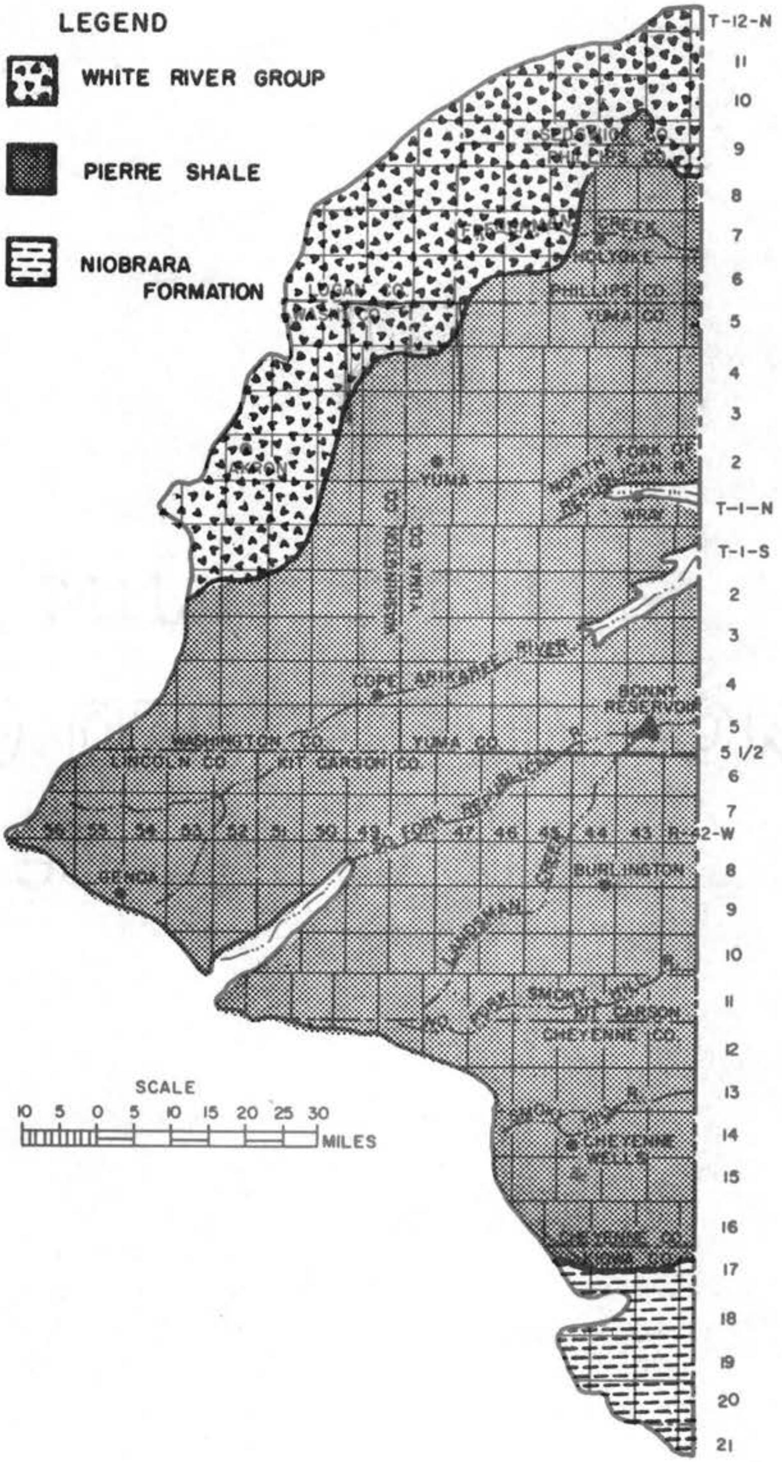

Figure 3. Map of the Northern High Plains of Colorado showing the approximate subsurface extent of the three different bedrock materials beneath the Ogallala Formation.

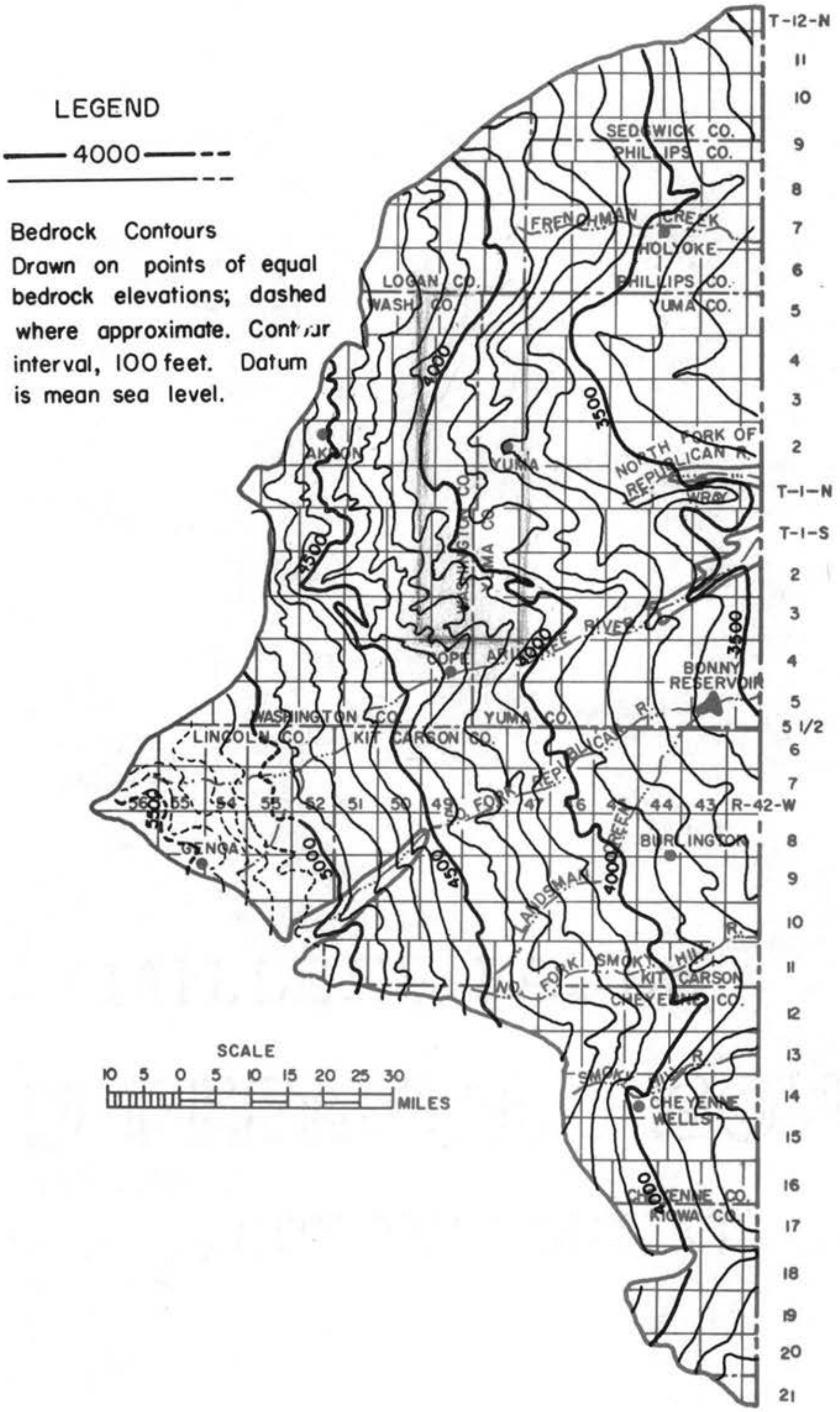

Figure 4. Bedrock map of the Northern High Plains of Colorado showing the approximate elevation of the base of the Ogallala Formation.

of these were selected as control points for preparing the bedrock contour map. The 400 deleted logs were for partially penetrating wells which did not give any information about the bedrock surface. In general, the quantity and quality of the available logs were adequate for preparing the bedrock map except in some areas of Sedgwick, Yuma, Washington, and Lincoln Counties. In these areas, previously published maps (10, 23, 34, 38) were used to supplement the available data.

The bedrock elevation map shown in Figure 4 has a contour interval of 100 feet. This map was used for publication purposes only. A bedrock map with contours every 50 feet and a scale of approximately five miles per inch was used in making the analysis for this study.

Cross sections showing the thickness of the geologic formations and the relations of some of the prominent features of the bedrock floor are shown in Figures 5 and 6. Several bedrock highs and buried valleys are depicted along this line. The greatest thickness of the Ogallala Formation (about 460 feet) along the line of the cross section is in the low point of the buried valley immediately south of the Phillips-Yuma County line.

Figure 6 shows numerous irregularities in the bedrock floor along the east-west section. The most conspicuous characteristic of this section is the presence of several small buried channels eroded in the bedrock surface. The

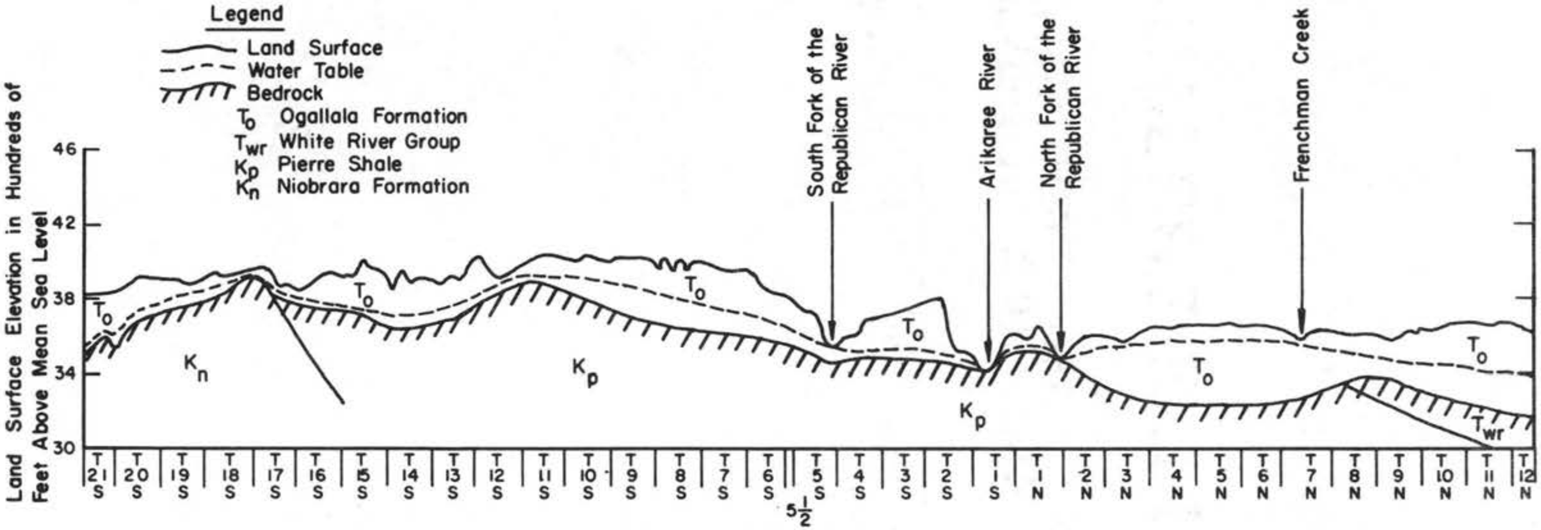

Figure 5. Geologic cross section of the Ogallala Formation looking west along the Colorado-Kansas-Nebraska state line from T-21-S to T-12-N.

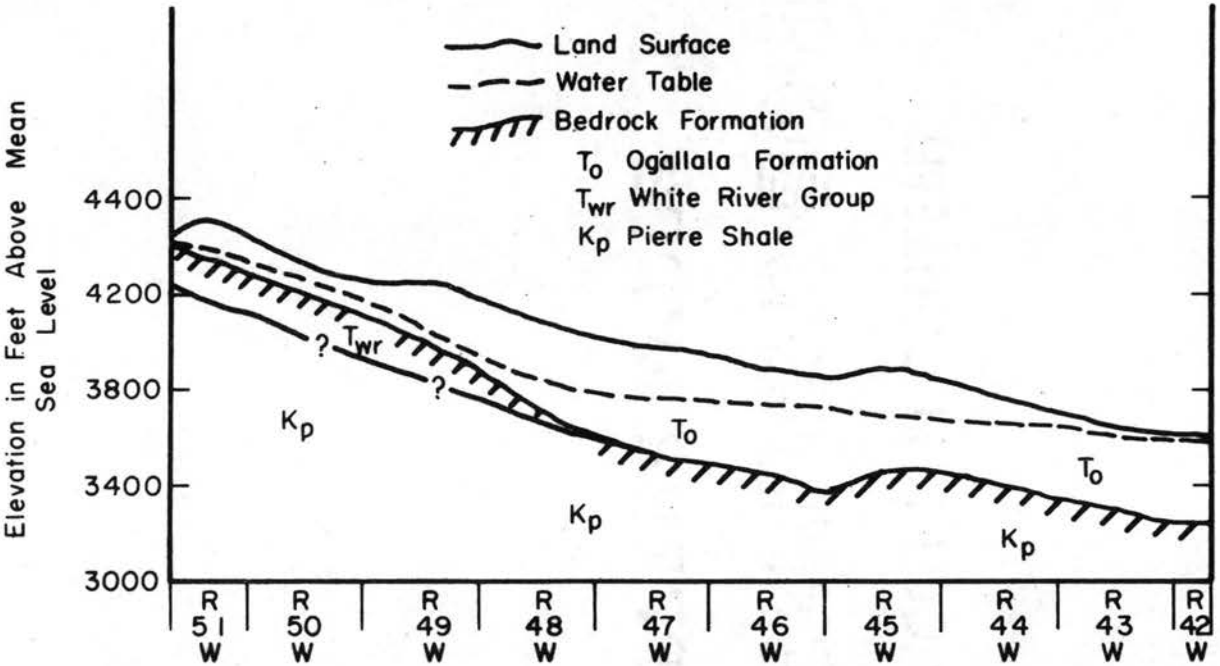

Figure 6. Geologic cross section of the Ogallala Formation looking north along T-4-N from R-51-W to R-42-W.

lateral extent of these features is shown on the bedrock contour map of Figure 4. In general, the bedrock slopes in an east-northeast direction at about 22 feet per mile.

Configuration of the Water Table

Preparation of the water table map shown in Figure 7 is based on previously published measurements of water levels (5, 9, 10, 11, 22, 33). Over 3000 water level measurements were studied and approximately 1800 were selected as control points for preparing the water table map. Those that were deleted consisted of duplications of the same record. These duplications resulted from measuring the same well several times over a period of years or from the measurement of several wells within 300 to 400 yards of each other. The quantity, quality and distribution of water level measurements were considered good for preparing the water table map in all of the study area except Lincoln County. A previously published map (38) was used to prepare the water table contours in Lincoln County.

Because of the dynamic equilibrium assumption used in this study, water levels from the earliest possible dates were used in preparing the water table map. In general, the water levels were selected from the 1951-1957 period prior to any large scale well development. Localized areas had experienced some intensive development, but these were very small in areal extent.

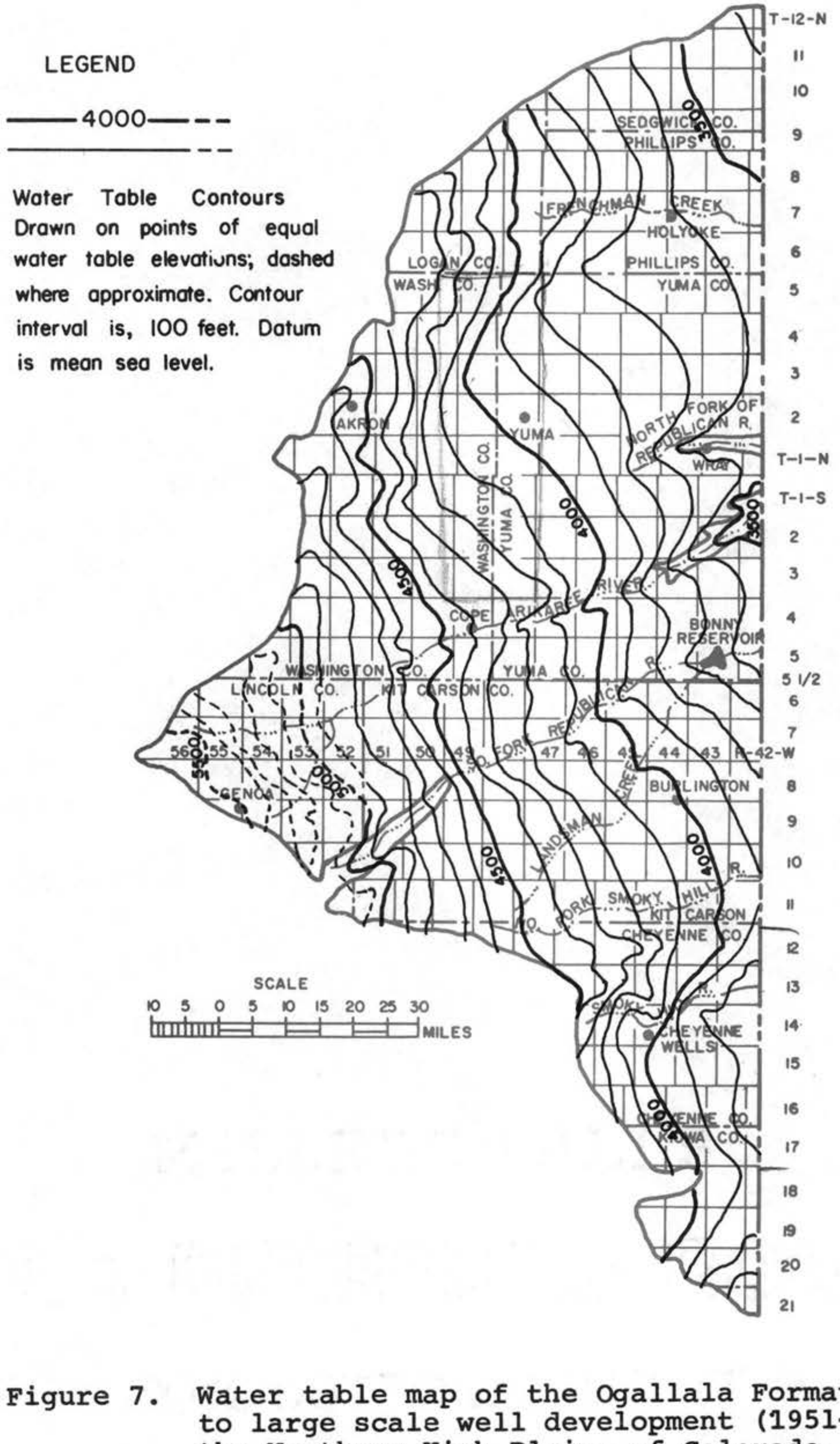

Figure 7. Water table map of the Ogallala Formation prior to large scale well development (1951-1957) in the Northern High Plains of Colorado.

The water level measurements for Sedgwick, Logan and Phillips Counties were made during the years of 1951 and 1952 in connection with an investigation of the Frenchman Creek area of Colorado and Nebraska (10). At the end of 1952, Sedgwick County had three large capacity wells. Logan County had one large capacity well and Phillips County had 14 large capacity wells. Numerous wells were measured in Washington County in 1952; however, the largest number was measured in 1957 when there were 79 large capacity wells. Water level measurements for 1952, 1956 and 1957 were used in Yuma County where 128 large capacity wells were being used at the end of 1957. The measurements for Kit Carson County were taken over an eight year period, 1950-1957, with about 160 large capacity wells in operation at the end of 1957. Cheyenne County had 16 wells and Kiowa County had five wells at the end of 1960 when most of the water level measurements were made in those counties. No date was attached to the previously published map (38) used for preparing the water table map of Lincoln County; however, there were only 14 large capacity wells in Lincoln County at the end of 1965.

From the above information, it is readily recognizable that only two counties, Kit Carson and Yuma, present a serious problem in assuming that Figure 7 depicts the water table prior to large scale development. However, Kit Carson County had only 48 wells and Yuma County had only 49 wells at the end of 1953. It is believed that during the four year period 1954-1957, little change in the water table in these two counties would be noticed because of the slowness of an aquifer in reacting to any new flow conditions. Therefore, the assumption that Figure 7 depicts the water table prior to large scale development of the aquifer can be made without appreciable error in the final results.

Groundwater moves in a direction at right angles to a given water table contour line. The steepness of the slope of the water table is indicated by the spacing of the contour lines; the slope being relatively gentle if the lines are far apart, and relatively steep if they are closely spaced. The map of Figure 7 shows that the water table generally slopes east-northeast towards the state line indicating that groundwater flows from Colorado into Nebraska and Kansas. The slope of the water table averages about 18 feet per mile and roughly parallels the slope of the bedrock surface and the land surface.

For this study, a water table map with a contour interval of 25 feet and a scale of approximately five miles per inch was prepared. However, for purposes of publication, Figure 7 with a 100 foot contour interval was substituted for the original work map.

Saturated Thickness

Figure 8 shows the approximate thickness of the saturated zone of the Ogallala Formation in the Northern High Plains of Colorado prior to large scale development of ground water. The map shows the saturated thickness as of about 1951-1957. The map was prepared by superimposing the water table map on the bedrock map and graphically subtracting the bedrock elevations from the water table elevations. Lines were then drawn through points of equal saturated thickness.

Coefficient of Storage and Specific Yield

The volume of water an aquifer releases from or takes into storage per unit of surface area of the aquifer per unit change in the component of head normal to that surface is called the coefficient of storage. The specific yield of a porous media is the ratio of the volume of water that the media will yield by gravity, after being saturated, to its bulk volume.

The coefficient of storage is calculated from pumping test data while specific yield is normally obtained from laboratory tests. If the aquifer is unconfined (such as the Ogallala Formation), Boulton (8) has shown that the computed coefficient of storage increases with the time of the pumping test and approaches the specific yield in value. Therefore, if a pumping test in a water table aquifer is run sufficiently long enough (several weeks

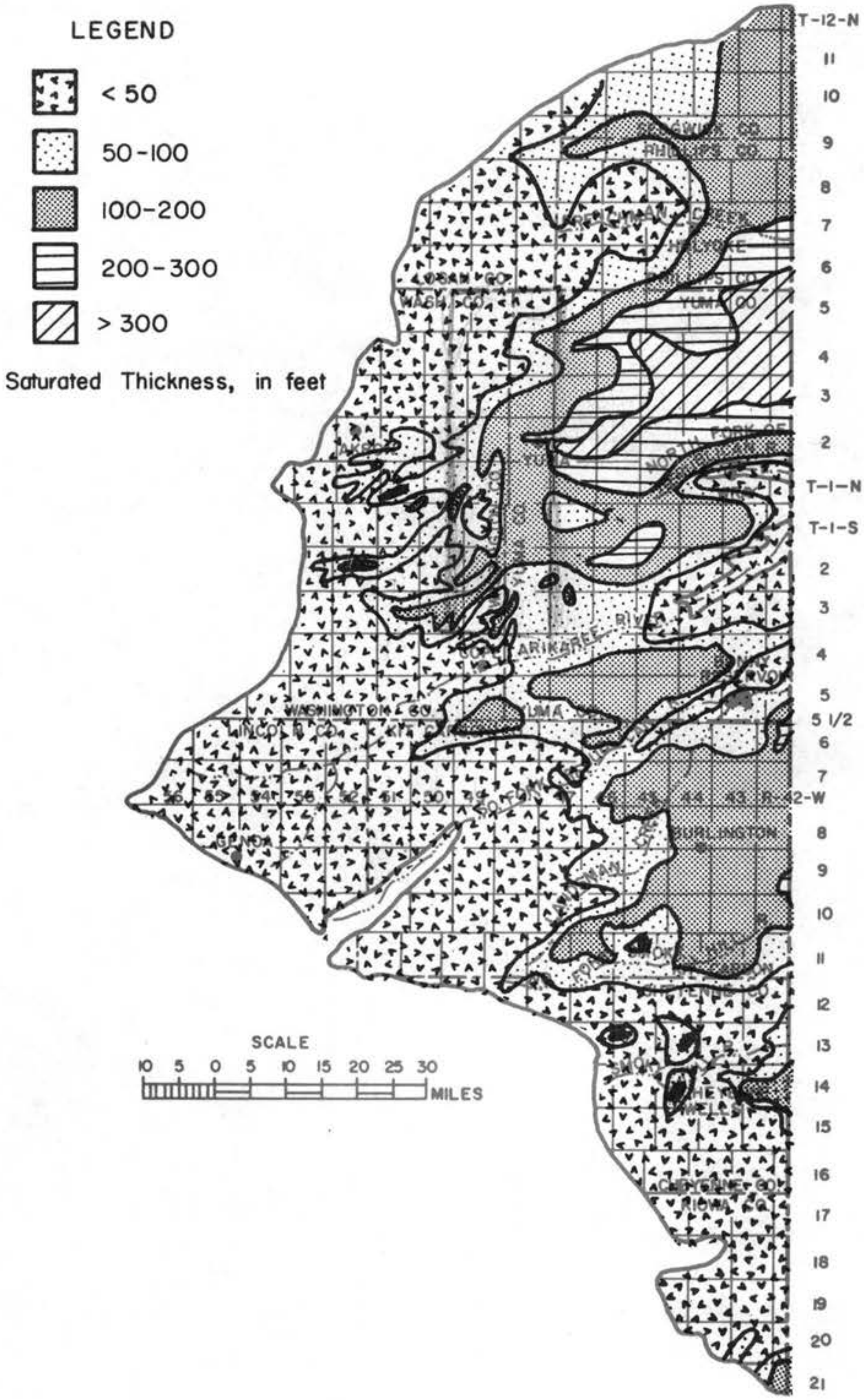

Figure 8. Saturated thickness map of the Ogallala Formation prior to large scale well development (1951-1957) in the Northern High Plains of Colorado.

duration), the coefficient of storage and specific yield are approximately equal.

All of the pumping test data collected in the Northern High Plains, except one, were for periods of a few hours to a few days. These tests will not give an accurate picture of the specific yield because of their limited duration. One test conducted on well number C8-46-9bcc in Kit Carson County was run for 17 days. (The well numbering system used in this report is described in Appendix A). The coefficient of storage calculated from an observation well 100 feet away from the pumping well was 0.29, while that in a well 502 feet distance was 0.13 (37).

Cardwell and Jenkins (10) report that laboratory tests for the specific yield of aquifer material in the Frenchman Creek area ranged from 25.5 to 30.4 percent. Chase (11) gives values of the specific yield for Kit Carson County which range from 23.9 to 35.2 percent. In view of these analyses, it is estimated conservatively that the average specific yield throughout the Northern High Plains is not less than 20 percent.

Hydraulic Conductivity

The transmissibility of an aquifer is given by the relationship:

$$T = KD \qquad (3\text{-}1)$$

where T is transmissibility, K is hydraulic conductivity and D is the saturated thickness of the aquifer. The transmissibility of an aquifer is usually determined from long-term pumping tests on wells, and the hydraulic conductivity can be calculated by dividing the transmissibility by the saturated thickness.

A search for all available pumping tests made in the Ogallala Formation of the Northern High Plains produced only 52 tests for which a value of the transmissibility had been calculated (37). These data are shown in Table B-1 of Appendix B. This was entirely inadequate for the type of aquifer analysis used in this study.

To supplement the available transmissibility data, it was decided to estimate values of transmissibility using specific capacities of wells. Previous work by Theis (29) and Hurr (18) have outlined methods of estimating transmissibility from specific capacity data. However, both of these methods involve rather cumbersome graphical techniques and a certain amount of error is introduced when values of specific yield are assumed for the aquifer. Since an error is introduced in the deterministic methods of Theis and Hurr by assuming certain values for specific yield, it was felt that a multiple linear regression analysis might provide an adequate equation for predicting transmissibility. An equation of the form:

$$X_1 = B_1 + B_2X_2 + B_3X_3 + B_4X_4 \qquad (3\text{-}2)$$

was assumed where X_1 is the transmissibility in 1000 gallons per day per foot; B_1, B_2, B_3, and B_4 are regression coefficients; X_2 is the specific capacity in gallons per minute per foot of drawdown, X_3 is the duration of the pumping test in hours and X_4 is the diameter of the well casing in inches.

The method of least squares was used to estimate the regression coefficients. Tests of various hypotheses revealed that B_1, B_3 and B_4 were not significantly different from zero at the 95 percent level. The estimate of B_2 was 2.45 and it was significantly different from zero at the 95 percent level. Therefore, equation 3-2 reduced to:

$$X_1 = 2.45 X_2 \qquad (3-3)$$

Equation 3-3 is an adequate estimator of transmissibility; accounting for 95 percent of the total variance of the model. The correlation coefficient was 0.97 and the standard error of estimate was 18,310 gpd/ft or about 17.0 percent of the observed values. The 95 percent confidence limit for B_2 is:

$$2.35 < B_2 < 2.55 \qquad (3-4)$$

The complete procedure for estimating the regression coefficients and testing the various hypotheses is given in Appendix B.

Using published records of the U.S.G.S. (10), the Colorado Water Conservation Board (6, 11, 22, 33) and unpublished data at Colorado State University (21), 320 values of specific capacity were obtained. With the use of equation 3-3, values of transmissibility were estimated from the specific capacity data. The calculated values of transmissibility were then divided by the saturated thickness to obtain values of hydraulic conductivity. The results of this analysis are shown in Tables B-2 and B-3 of Appendix B. Figure 9 shows isolines of equal hydraulic conductivity on a 250 gpd/ft^2 interval.

Fluctuations of the Water Table

The water table is not a stationary surface, but fluctuates with time under the influence of several phenomena. Boettcher (6) has noted the relative efficiency with which well number C12-48-10abd, located in the Ogallala Formation of Cheyenne County, measures changes in barometric pressure. Barometric pressure accounts for as much as 1.8 feet of total fluctuation in this well as seen in Figure 10.

Recharge and discharge may cause changes in ground water storage, thus creating a fluctuating water table. If recharge exceeds discharge then the water level must rise, and if discharge exceeds recharge the water level must decline. Under the case of dynamic equilibrium, which is being assumed for this study, the amount of fluctuation over a period of time should remain practically constant because recharge and discharge are assumed equal.

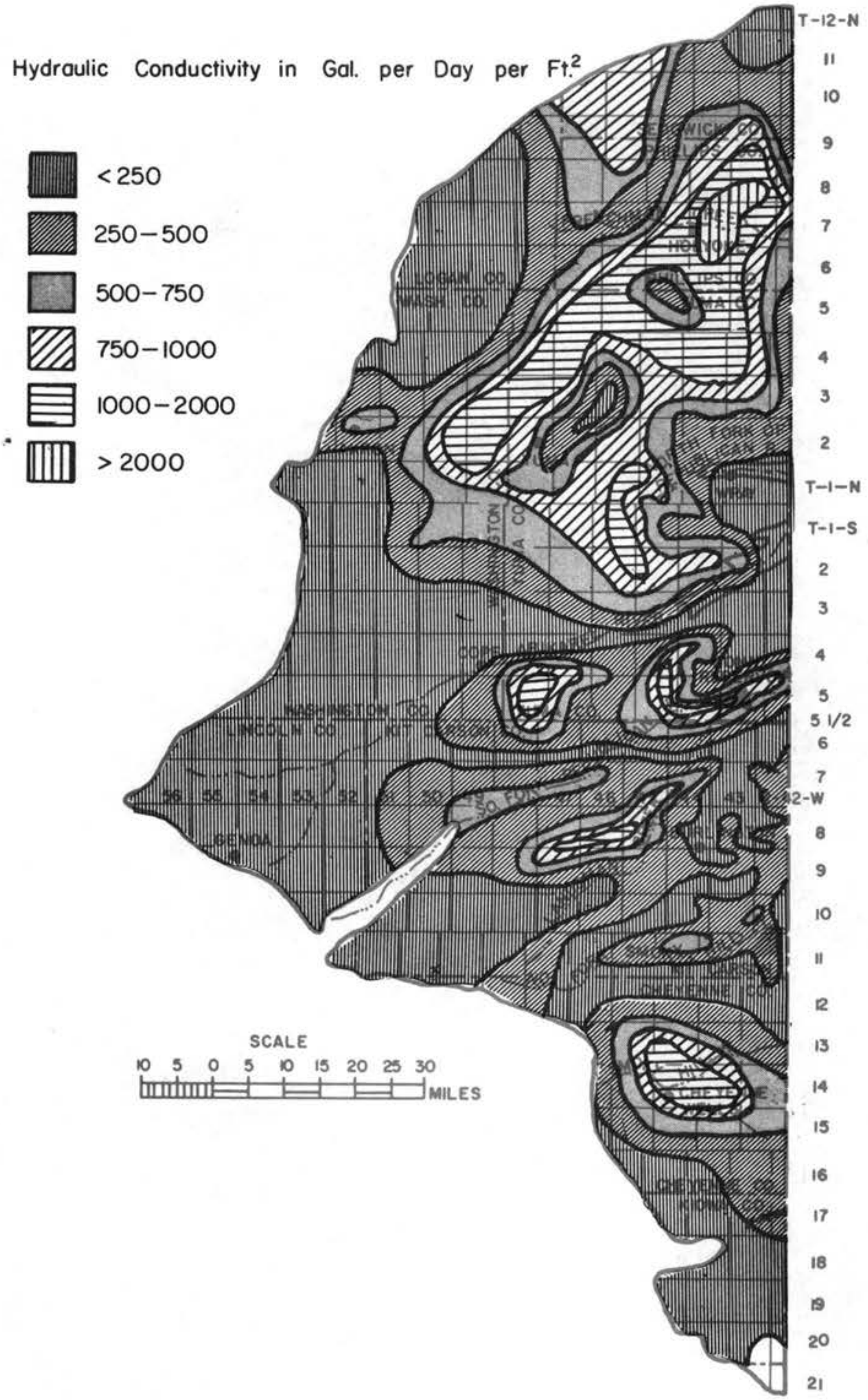

Figure 9. Hydraulic conductivity map for the Ogallala Formation in the Northern High Plains of Colorado.

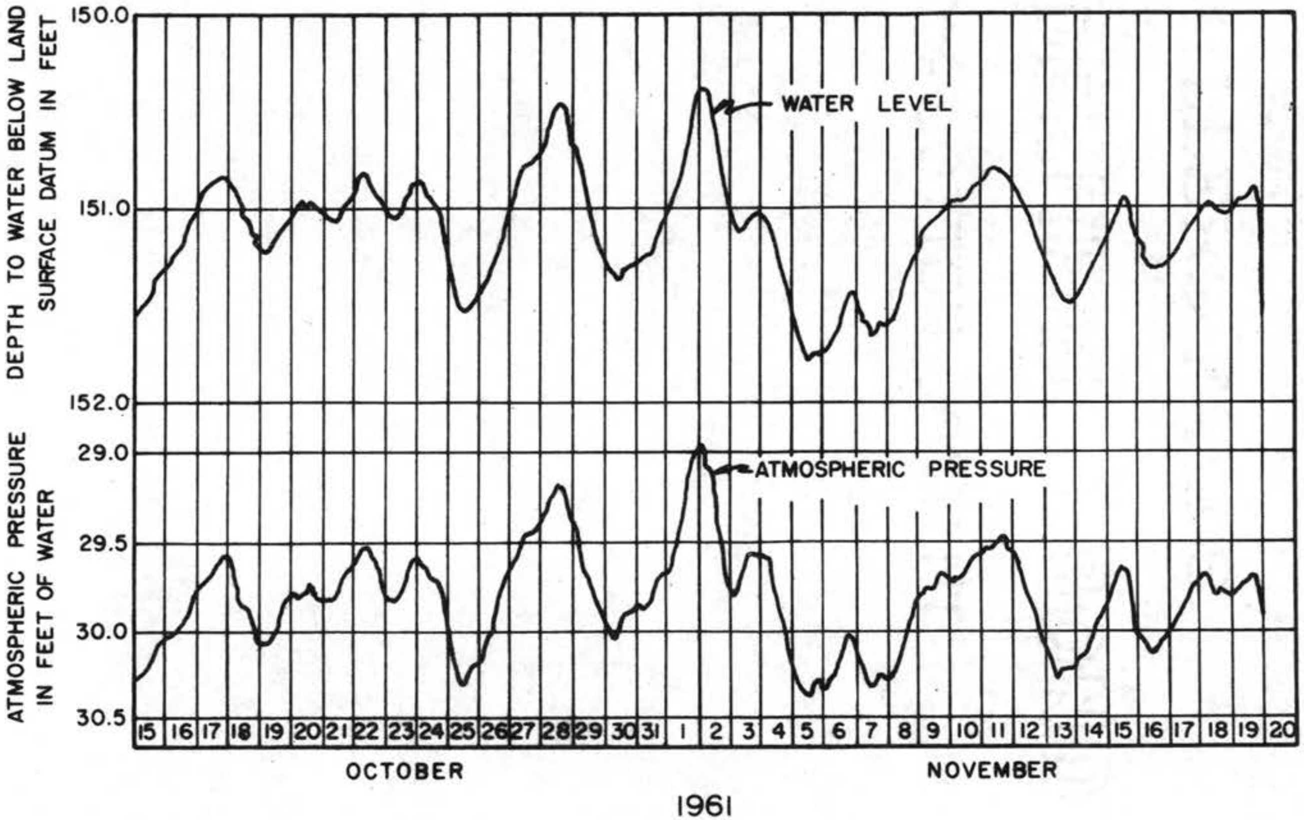

Figure 10. Relationship between barometric pressure and the water level in a well (after Boettcher (6)).

Hydrographs of water levels in representative wells drilled in the Ogallala Formation are shown in Figure 11. These hydrographs show only minor fluctuations in the water table thru 1957, and very few of the wells reflect any type of major disturbances thru 1965. With this information, the assumption of dynamic equilibrium for the Ogallala Formation prior to 1957 is apparently valid.

Depth to the Water Table

The depth to water in the Ogallala Formation of the Northern High Plains ranges from less than 50 feet to more than 300 feet below land surface as shown by Figure 12. The depth to water is affected by the topography of the land surface, the proximity to areas of recharge and discharge and by the configuration of the bedrock surface.

The shallow depth to water (less than 50 feet) in the sandhills area of Northeastern Yuma County is undoubtedly due to the high rates of recharge in the sandhills. Groundwater in the Northern High Plains moves generally in an east-northeast direction and bedrock highs may act as barriers causing the groundwater to accumulate on the west and southwest sides of these highs. Areas of shallow water along the Arikaree River, North and South Forks of the Republican River and around Flagler in west-central Kit Carson County are apparently areas of discharge because of the upstream flexure of the water table contours in these areas.

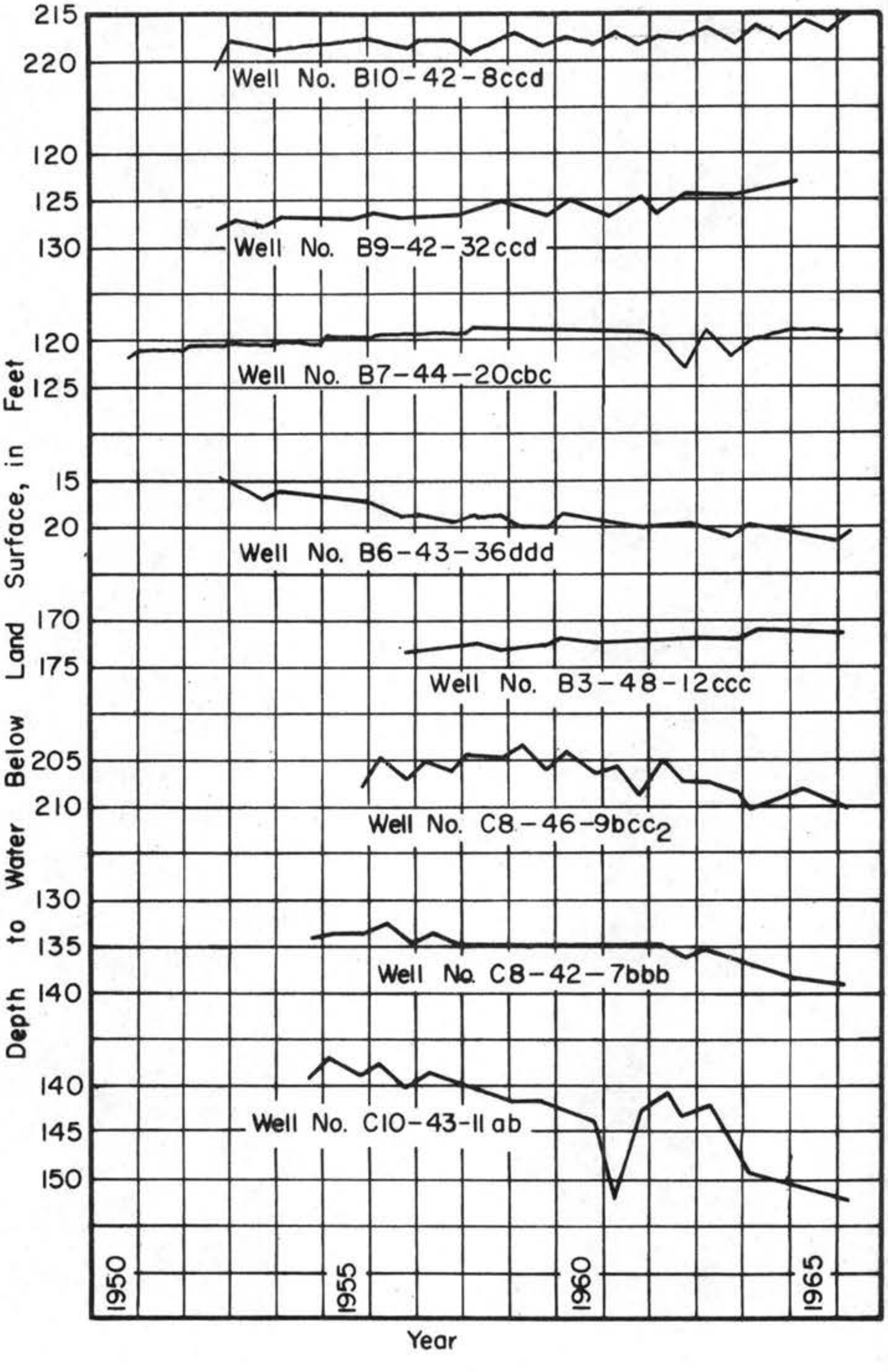

Figure 11. Hydrographs of selected wells in the Ogallala Formation of the Northern High Plains of Colorado (from water level records at Colorado State University (9)).

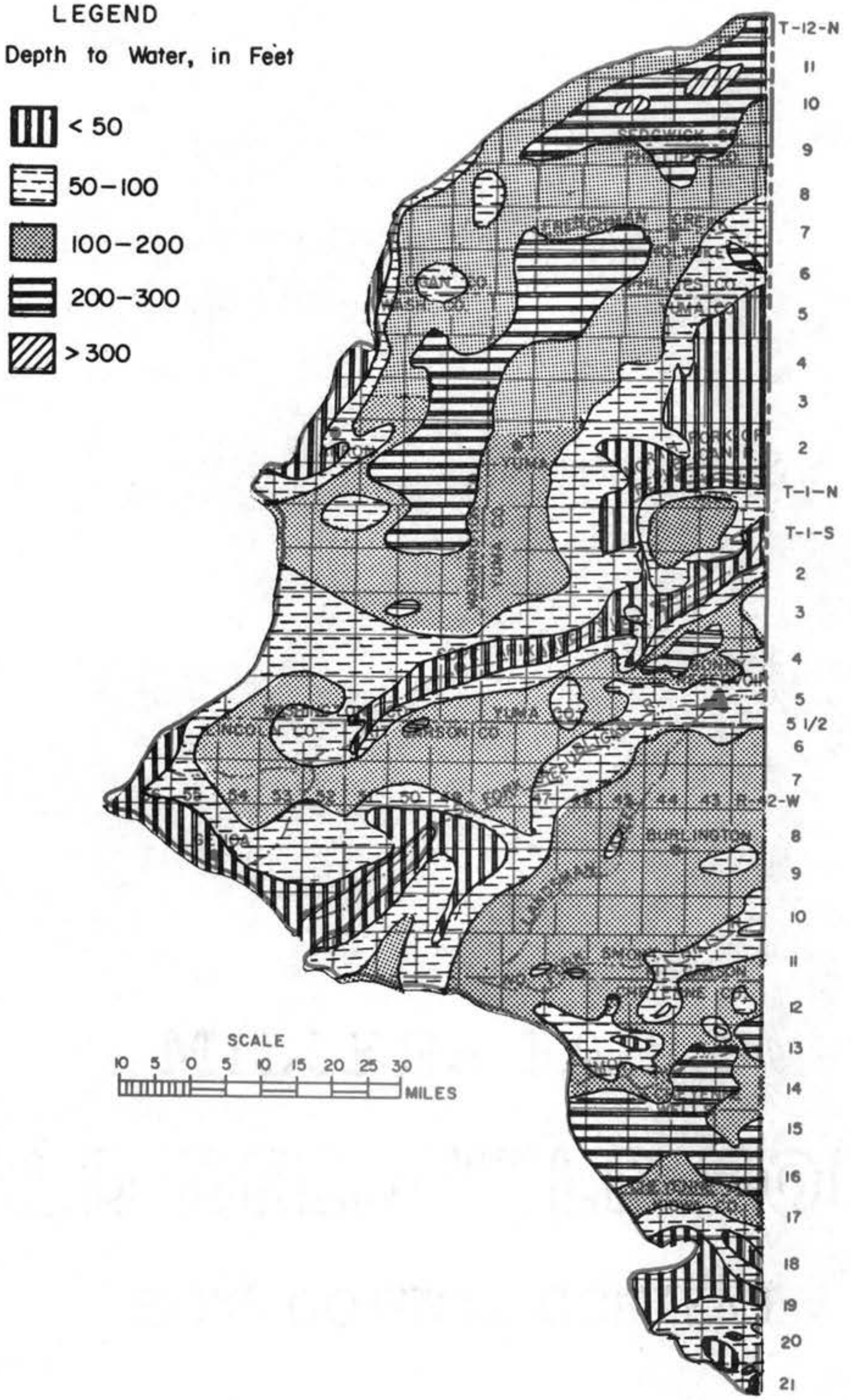

Figure 12. Depth to water in the Ogallala Formation prior to large scale well development in the Northern High Plains of Colorado.

Natural Recharge and Discharge

As was pointed out in the discussion on geologic history, the Ogallala Formation has been isolated by erosion from the surrounding geologic formations. Thus, the only underground connection between the Ogallala Formation and other geologic formations is the underlying bedrock. Recharge from the bedrock material into the Ogallala Formation is highly unlikely. In fact, a more probable hypothesis would be that the groundwater in the Ogallala Formation exists at a higher piezometric head than that in the lower formations and thus the Ogallala Formation may be the source of recharge for some of the underlying formations.

Variation of Precipitation

The annual precipitation for the study area is generally between 16 and 18 inches. However, a wide fluctuation exists around this mean. For instance, annual amounts between 7.67 inches and 24.08 inches have been reported at Burlington, Colorado (20). The greatest percentage of the annual precipitation occurs during the spring and summer. Convective activity in the summer produces some thundershowers of high intensity.

Using the double-mass curve technique, Smith and Schulz (28) have developed maps showing isolines of equal monthly and annual precipitation for all of eastern Colorado. Figure 13 was adapted from these published

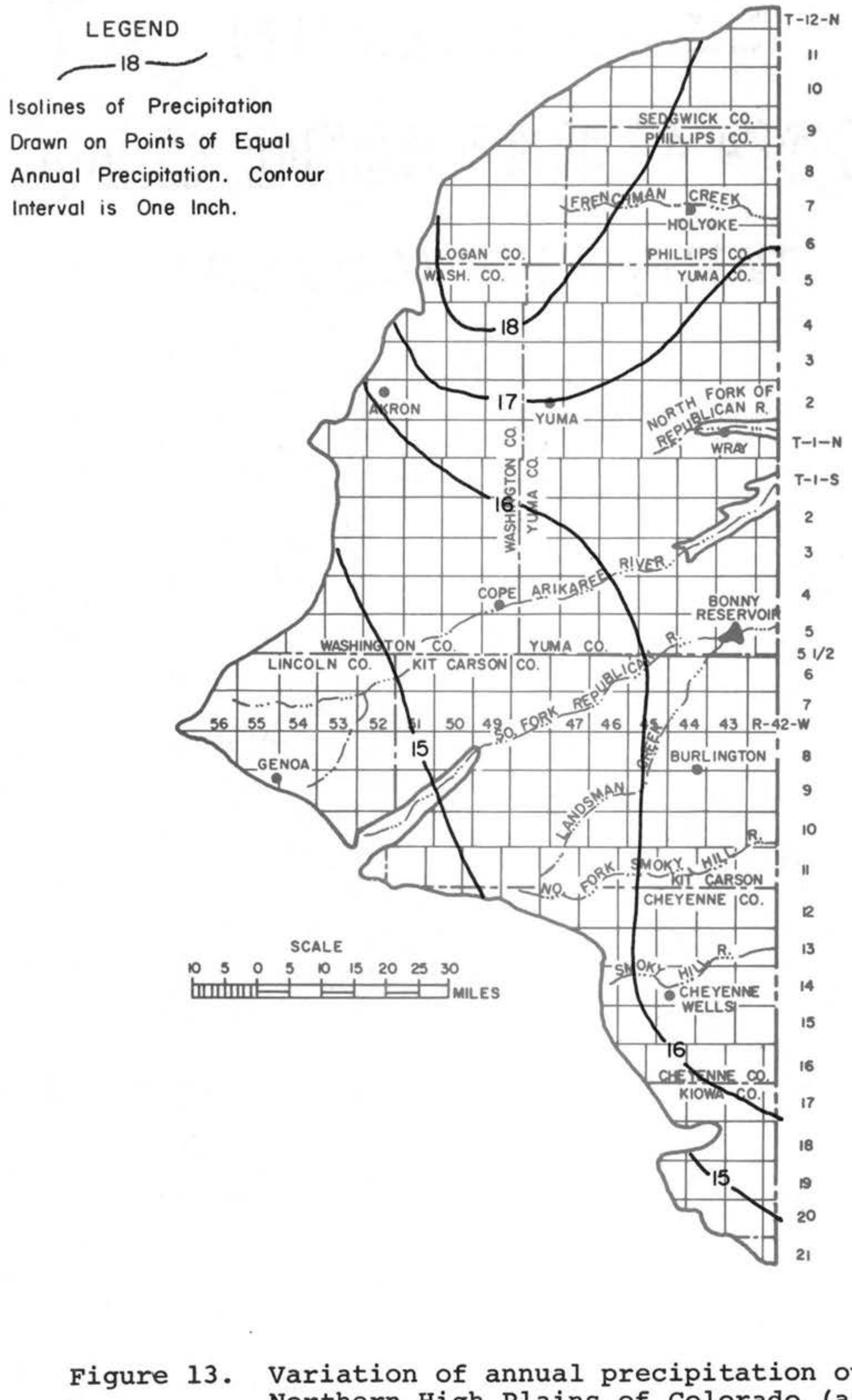

Figure 13. Variation of annual precipitation over the Northern High Plains of Colorado (after Smith (28)).

maps to show the variation in annual precipitation over the Northern High Plains of Colorado. As can be seen, the precipitation is higher in the northern part of the study area than in the southern part.

Chapter IV

GROUNDWATER RECHARGE INVESTIGATIONS

Historical Concepts of Groundwater Recharge

Prior to the latter part of the seventeenth century it was generally assumed that the water discharged by springs could not be derived from precipitation. This was the result of a general belief that rainfall was inadequate in quantity and that the earth was too impermeable to permit infiltration.

Meinzer (26) gives an excellent historical development of hydrology in which the early influence of philosophers such as Homer (1000 B.C.), Thales (650 B.C.), Plato (427-347 B.C.) and Aristotle (384-322 B.C.) are quite evident. Two main recharge theories were developed by these early philosophers. One theory dealt with how sea water meandered thru underground channels, was freed from its salt and elevated to the altitude of springs. The other theory dealt with underground condensation similar to atmospheric condensation.

The infiltration theory, which present day hydrologists accept, was first introduced by Marcus Vitruvius (26) at about the time of Christ. This theory involves the infiltration of a small amount of precipitation into the soil and its slow percolation to points of discharge such as springs or seeps. For centuries the infiltration theory was advocated by only a few people, notably by Leonardo da Vinci (1452-1519) and Bernard Palissy (1509-1589).

Possibly the earliest attempt to quantitatively determine the rate of groundwater recharge was made by Perrault (1608-80) and Mariotte (1620-84). Perrault made crude measurements of rainfall and estimated the area of the drainage basin of the Seine River and of the runoff from this basin (26). Mariotte essentially verified Perrault's results (25). The work of Perrault and Mariotte, although crude, demonstrated the fallacy of the ancient assumption that rainfall is inadequate for supplying the groundwater discharged by springs.

Methods of Estimating Groundwater Recharge

In the years that have elapsed since the work of Perrault and Mariotte, several methods for estimating recharge have evolved. Of these, the following nine methods are considered worthy of discussion: (1) Lysimeters, (2) Percentage of Precipitation, (3) Aquifer Overflow, (4) Water Level Fluctuations, (5) Aquifer Strip Analysis, (6) Aquifer Underflow, (7) Consumptive Use and Runoff, (8) Tracers and (9) Finite Difference Methods.

Lysimeters--One of the oldest and most popular methods for estimating recharge from the time of Mariotte to the early twentieth century was by lysimeters. This method involves the insertion of a pan or other vessel into the soil below the root zone for the purpose of catching the downward percolating waters. Meinzer (25) points out that many of the early lysimeter tests ran for long periods of time. The longest one was run for 49 years, from 1835 to 1884 by Dickinson and Evans in England.

The disturbing thing about the lysimeter is that it does not always produce accurate results. According to Corey (12) the main reason is that in partially saturated soil the water is under a capillary pressure while the air above the lysimeter is usually at atmospheric pressure. Therefore, water will not flow into the lysimeter because the air above the lysimeter is at a higher pressure than the water. Instead the water will follow the surface of the soil grains and move around any vessel placed underground to catch it. It is conceivable that some type of specially constructed lysimeter might work. However, the apparatus would have to be constructed with full knowledge of the laws of two-phase flow in porous media.

Percentage of Precipitation--In the past one of the most common methods of estimating recharge has been to determine the quantity of precipitation falling annually over an area and then assume that a percentage of the precipitation reaches the water table as recharge. This method is of little value, unless there is a reliable basis for the percentage assumed.

Woodward, Clyde, Sherard and Associates (38) used this method in estimating the recharge to the Northern High Plains of Colorado. They assumed that five percent of the precipitation became recharge, or 423,500 acre-feet per year eventually reached the zone of saturation.

Aquifer Overflow Method--The overflow of an aquifer exists when the aquifer is filled to capacity and ground water is discharged by means of springs, seeps or evapotranspiration. If the aquifer is assumed to be in dynamic equilibrium, the measurement of the volume of discharge will give a value for the recharge. This method was employed by White, Broadhurst and Lang (35) in an area of the Southern High Plains of Texas comprising about 9000 square miles.

The White study involved the location, mapping, and measurement of discharge for all known springs and seeps. The lands covered by different kinds of grasses and subirrigated alfalfa that used groundwater were mapped, and estimates were made of the volume of water used by the plants. From these measurements, the total natural discharge was estimated to be 25,000 to 30,000 acre-feet per year representing about 0.05 inch per year of recharge over the 9000 square mile area.

Water Level Fluctuations--Another method for estimating recharge is by studying the fluctuations of water levels in wells. This method may be used in areas where recharge is small and the water table is deep enough to prevent transpiration losses. Accurate records of water level measurements, preferably with automatic water-level recorders, are needed along with a reliable estimate of specific yield. Theis (30) used this method for estimating recharge in Lea County, New Mexico. The water level fluctuations should be analyzed closely to make sure that they are related to changes in recharge and not some other phenomenon such as barometric pressure as was shown in Figure 10.

Aquifer Strip Analysis--Theis (30) also used an aquifer strip analysis for estimating the recharge in the Southern High Plains of New Mexico and Texas. Using the equation for uni-directional groundwater flow over a uniformly sloping impermeable barrier, theoretical profiles for different rates of annual recharge were calculated and compared with the actual profile of the water table. He assumed an average slope of the bedrock of ten feet per mile, a uniform recharge rate, and a homogeneous and isotropic aquifer with a hydraulic conductivity of 1000 gpd/ft^2. From this analysis Theis concluded that the recharge rate for the Southern High Plains of New Mexico and Texas was between one-fourth and one-half inch per year.

Aquifer Underflow--At the present time, aquifer underflow is probably one of the most popular methods for estimating the recharge to a given area. This method involves the calculation of flow across a selected cross section of an aquifer, and the division of this quantity by the tributary area. The flow can be calculated using Darcy's law while the tributary area can be determined from geologic or water table maps. This method assumes steady state conditions and must be corrected for withdrawals above the selected cross section.

This method has been used extensively by Walton (32) in calculating recharge to aquifers in Illinois. Water table maps were prepared and two flow lines spaced several miles apart were drawn at right angles to water-table contours. Darcy's law was used to calculate the flow entering (Q_1) and leaving (Q_2) the flow channel. The quantity (Q_2-Q_1) divided by the area of the flow channel gives the recharge rate.

This method provides good estimates of natural recharge, limited only by the accuracy of the data used in making the calculation. It is usually used for fairly large tributary areas and thus does not provide sufficient detail on the areal distribution of groundwater recharge.

Consumptive Use and Runoff--Another method for calculating recharge is by determining the volume of consumptive use and runoff for an area and subtracting this value from the volume of precipitation. This method has not been popular in the past because of the errors involved in calculating both consumptive use and runoff. However, as techniques for estimating consumptive use and runoff become refined, this method may gain in popularity.

Blaney and Taylor (4) used this method in a three year study (1927-1929) on unirrigated native vegetation areas of the Santa Ana River Basin in Southern California. Willardson and others (36) have done some recent work on the separation of evapotranspiration and deep percolation which could prove useful in determining recharge rates for various areas and soils. The problem with this method is that a number of characteristic curves for various crops would need to be developed and accurate records of the time, place and amounts of rainfall and irrigation would need to be kept for calculating the recharge to an entire aquifer.

Tracers--This method involves the use of any tracer element which will remain stable in a groundwater aquifer. The element may be radioactive or non-radioactive. Chemical elements such as carbonates, bicarbonates, chlorides, or sulphates may be used in connection with geochemical techniques for determining sources and quantities of recharge.

Bergstrom and Aten (2) located areas of recharge for an aquifer in Kuwait using as criteria the appearance of the piezometric surface and water quality data. The important item in their investigation was the use of tritium (H_3) and radio carbon (C_{14}) for dating the groundwater and thus confirm their theoretical delineation of recharge areas. Water from the recharge areas was from one to eight years old and that from a well three miles downdip was 30 to 500 years old in terms of time since the water entered the ground. With further research and development of techniques, this could be one of the better methods for recharge studies.

Finite Difference Method--This method was developed for use in this study. It involves the use of a mathematical model in finite difference form for groundwater flow. A solution for the rate of recharge is then obtained on the digital computer. This method is fully developed in the following chapters and used in calculating the areal distribution and rates of recharge in the Northern High Plains of Colorado.

Previous Estimates of Recharge in the Northern High Plains OF Colorado

The most detailed investigation of recharge for an area of the Northern High Plains was probably made by Cardwell and Jenkins (10). This study was in connection with a groundwater investigation of the Frenchman Creek basin. The area studied includes the part of the Frenchman Creek basin that lies in Colorado; and the part of the basin in Nebraska upstream from Palisade, Nebraska. This investigation includes that portion of the present study area north of T-11-N.

Using a combination of the consumptive use method and underflow method, the amount of recharge for the Colorado portion of the Frenchman Creek basin was determined. Underflow along the Colorado-Nebraska state line was calculated by dividing the cross section into nine sections. Climatological data was used to calculate the amount of evapotranspiration. These calculations yielded 90,000 acre-feet of underflow, 15,000 acre-feet of evapotranspiration losses and 6,000 acre-feet of pumpage for a total of 111,000 acre-feet of recharge. Dividing by the tributary area, the recharge rate was determined to be 0.80 inch per year for the portion of the Frenchman Creek basin in Colorado.

A groundwater investigation of Yuma County by Weist (33) yielded little additional information. He believed that it was not practical to estimate the amount of recharge in Yuma County and concluded that Yuma County probably receives an amount similar to the Frenchman Creek basin. (Weist used a figure of 0.90 inch per year for the Frenchman Creek recharge. It should be noted that this is the value Cardwell and Jenkins calculated for the entire Frenchman Creek area, both in Colorado and Nebraska.)

McGovern (23) used the underflow method for calculating the recharge rate in Washington County. He assumed that the rate of recharge to the Ogallala Formation is approximately equal to the rate of underflow from the county. Choosing the Yuma-Washington County line as his cross section, the amount of underflow was calculated to be 83,000 acre-feet per year representing a recharge rate of about 0.95 inch per year.

Boettcher (5) also used the underflow method for calculating recharge to the Ogallala Formation in Cheyenne and Kiowa Counties. Using the Colorado-Kansas state line as his cross section, the annual groundwater discharge from the Ogallala Formation is approximately 52,000 acre-feet. The natural recharge for the 1300 square-mile tributary area was 0.75 inch per year.

A value of 0.85 inch per year for the rate of recharge to the Ogallala Formation in the Northern High Plains of Colorado was calculated by McGovern and Coffin (24). The amount of underflow across the state line was determined to be 390,000 acre-feet per year and groundwater runoff into streams was reported as 40,000 acre-feet per year giving a total recharge rate of 430,000 acre-feet per year. This is the figure which has been widely accepted and used when discussing recharge to the Ogallala Formation of the Northern High Plains.

In an investigation for the Colorado Water Conservation Board, Woodward, Clyde, Sherard and Associates (38) used the percentage of precipitation method to calculate recharge. They calculated the volume of precipitation on the Northern High Plains as 8,470,000 acre-feet annually. Without giving any apparent reasons, five percent of the rainfall was assumed to be recharge. This gives a value of 423,500 acre-feet per year for the recharge to the Ogallala Formation. Assuming an average figure of 1000 gallons per day per square foot for the hydraulic conductivity along the state line, a value of 298,500 acre-feet per year was calculated for the underflow across the state line. Based on a tributary area of 9300 square miles, the 423,500 acre-feet of recharge gives a rate of recharge of about 0.85 inch per year.

Table 2 is a summary of the recharge investigations in the Northern High Plains of Colorado. These investigations appear to converge on an average rate of recharge to the Ogallala Formation of about 0.85 inch per year. It should be noted that these investigations cover large areas. Most of them cover areas in excess of 1,000,000 acres. None of the studies has attempted to give any information on the areal distribution of groundwater recharge. The determination of recharge over such large areas may tend to obscure localized recharge patterns of major importance. A description of these localized patterns is a necessity before adequate groundwater management programs can be implemented.

Table 2. Summary of Recharge Investigations for the Ogallala Formation in the Northern High Plains of Colorado.

Investigator	Area of Investigation	Tributary area (acres)	Volume of Recharge (acre-feet per year)	Volume of Evapotranspiration (acre-feet per year)	Volume of Groundwater Runoff (acre-feet per year)	Volume of Underflow across state line (acre-feet per year)	Rate of Recharge (inches per year)
Cardwell and Jenkins (10)	Frenchman Creek basin	1,648,000	111,000 (a)	15,000	0	90,000	0.80
Weist (33)	Yuma County	1,526,000	-	-	-	-	0.90
McGovern (23)	Washington County	1,046,000	83,000	0	0	0	0.95
Boettcher (6)	Cheyenne and Kiowa Counties	831,000	52,000 (b)	0	0	47,000	0.75
McGovern and Coffin (24)	Entire Northern High Plains	6,080,000	430,000	0	40,000	390,000	0.85
Woodward, Clyde, Sherard and Associates (38)	Entire Northern High Plains	5,950,000	423,500 (c)	?	?	298,500	0.85

(a) Includes an estimated 6000 acre-feet of discharge by wells.
(b) Includes 5000 acre-feet of underflow into Kit Carson County and Prowers County.
(c) Woodward, Clyde, Sherard and Associates estimate 76,980 acre-feet per year of surface water discharge from the study area by principle streams into Nebraska and Kansas. It is not clear as to what portion of this amount is groundwater runoff. They estimate another 50,000 acre-feet per year of groundwater discharge to streams from springs and evapotranspiration from seepage areas.

Chapter V

TECHNIQUE OF INVESTIGATION

Mathematical Model

A model of a groundwater flow system may be a scaled physical simulator such as the Hele-Shaw model or it may be a mathematical model suitable for digital or analog computers. The selected model must adequately portray the physical characteristics of a groundwater aquifer. The model may be based upon known physical laws, or it may incorporate certain empirical relationships verified by experiments.

A mathematical model is an equation, or set of equations, that best satisfies the criteria of the model design. The mathematical model developed for analyzing recharge to the Ogallala Formation incorporates a set of equations which describes fluid flow through porous media. This set of equations includes Darcy's law, the continuity equation and the Dupuit assumptions.

Darcy's Law--The flow of viscous liquids through a saturated porous media is given by the relationship:

$$Q = -KA \frac{\Delta H}{L} \qquad (5\text{-}1)$$

where Q is the volume discharge rate, K is the hydraulic conductivity, A is the cross-sectional area of the porous media perpendicular to the direction of flow, and ΔH is the piezometric head loss in the distance L. Equation 5-1 was determined experimentally in 1856 by Henri Darcy (13), a French hydraulic engineer, and is known as Darcy's Law.

It should be noted that the piezometric head H is the sum of the elevation head Z and the pressure head $P/\rho g$. The velocity head is not included in Darcy's law. For most groundwater conditions, the velocity of flow is small and Darcy's law is a valid physical concept.

If the flow field is assumed to be irrotational on a macroscopic basis, then the flow system can be replaced by a mathematical continuum (14) and equation 5-1 may be written as:

$$q_x = - K_x \frac{\partial H}{\partial X} \qquad (5\text{-}2)$$

where q_x is the volume flux Q/A in the x-direction at a point in the porous media and K_x is the hydraulic conductivity in the x-direction. The volume flux q and piezometric head H are regarded as continuous functions of x, the direction of flow.

Although Darcy's law was first discovered by experiment, the equation can be derived from the general Navier-Stokes equations for viscous flow (17). Such a derivation is achieved from statistical considerations and simplifications of the complicated micropore structure. Thus, Darcy's law is an empirical equivalent of the Navier-Stokes equations.

Dupuit Assumptions--In an unconfined aquifer the upper flow boundary is indeterminate. It is usually assumed to be at the water table, but a better approximation would be at a height above the water table equal to the thickness of the capillary fringe. The importance of the capillary fringe depends on its magnitude relative to the saturated thickness of the aquifer.

The boundary conditions imposed by a water table present a formidable mathematical problem. Therefore, certain assumptions will be made that lead to a simplification of the problem. These assumptions are attributed to the work of Dupuit and have been widely used in solving problems of flow in groundwater hydraulics (18). The assumptions made by Dupuit are: (1) the velocity of flow at the water table is proportional to the slope of the water table, (2) in any vertical section the flow is horizontal at the water table and everywhere below it and (3) the velocity is uniform throughout the depth of flow.

Clearly, these assumptions are not rigorously valid. However, when the slope of the water table is small, use of these assumptions leads to reasonable results. The Dupuit assumptions make it possible to simplify the mathematics of groundwater flow in unconfined aquifers.

Continuity Equation--An important relationship in flow phenomena of any kind is obtained from the principle of conservation of mass. In the case of fluid flow, the principle is a statement of material balance with respect to a volume element fixed in space. For the case where no source or sink exists within the volume element, the continuity principle is given by:

(Mass of Fluid entering element) -
(Mass of Fluid leaving element) =
(Net change of Mass of Fluid in element) (5-3)

<u>Boussinesq Equation</u>--The mathematical model is developed for a small prism of the aquifer by considering the aquifer to be a network of interconnected prisms. The development is based on a mass balance. The selected prism of saturated aquifer is bounded by two pairs of infinitely close vertical planes parallel to the XH and YH coordinate planes (Figure 14). The prism is bounded above by the water table and below by an impermeable bed. Each prism is connected on four sides with other prisms of the aquifer; thus, making the model two-dimensional.

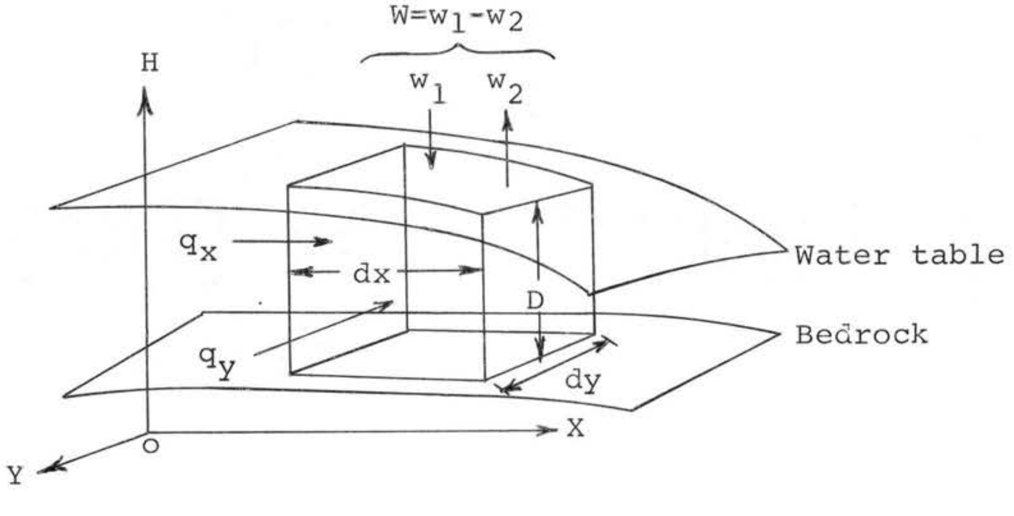

Figure 14. Element of aquifer used for developing the mathematical model.

Using Darcy's law and the Dupuit assumptions, the mass of a fluid with density ρ flowing through the left-hand face of the selected prism during the time dt is:

$$M_x = -\rho K_x D \frac{\partial H}{\partial X} dy\ dt . \qquad (5\text{-}4)$$

The mass flowing through the right-hand face during the same time period is:

$$M_{x+dx} = -\rho K_x D \frac{\partial H}{\partial X} dy\ dt - \rho \frac{\partial}{\partial X} (K_x D \frac{\partial H}{\partial X})\ dx\ dy\ dt. \qquad (5\text{-}5)$$

where D represents the depth of flow. The mass accumulating in the prism during the time dt is the difference in the two masses, i.e.,

$$\Delta M_x = \rho \frac{\partial}{\partial X} (K_x D \frac{\partial H}{\partial X})\ dx\ dy\ dt . \qquad (5\text{-}6)$$

Similarly, by considering the mass flow in the y-direction, an expression for the mass accumulation during the time dt is:

$$\Delta M_y = \rho \frac{\partial}{\partial y} (K_y D \frac{\partial H}{\partial y})\ dx\ dy\ dt. \qquad (5\text{-}7)$$

In addition, an assumed constant recharge rate w_1 reaches the aquifer and an assumed constant discharge rate w_2 is withdrawn from the aquifer. The net rate of recharge or discharge is thus given by $W = w_1 - w_2$; net recharge being positive and net discharge being negative. In cases where the depth to water below land surface is large, w_2 will be very small and the net recharge W approaches the gross recharge w_1. In cases where the water table is shallow such as along effluent streams, w_1 will be small compared to w_2 and the net discharge $-W$ will approach the gross discharge w_2 in value. The net mass of fluid entering the prism due to recharge or discharge is given by:

$$\Delta M_R = \rho W \, dx \, dy \, dt. \tag{5-8}$$

By summing equations 5-6, 5-7, and 5-8, the total mass accumulated in the prism during the time dt is:

$$\Sigma \Delta M = \rho \left[\frac{\partial}{\partial X} (K_x D \frac{\partial H}{\partial X}) + \frac{\partial}{\partial y} (K_y D \frac{\partial H}{\partial y}) + W \right] dx \, dy \, dt \tag{5-9}$$

The mass of fluid filling the prism is $\rho SD \, dx \, dy$, where S is the effective porosity or drainable voids ratio. After time dt, the mass in the prism is changed due to either a rise or decline in the water table. This change is equal to:

$$\Sigma \Delta M = \rho S \frac{\partial D}{\partial t} dx \, dy \, dt \tag{5-10}$$

To satisfy the continuity condition, equations 5-9 and 5-10 are equated and then divided by $\rho dx \, dy \, dt$ to obtain:

$$\frac{\partial}{\partial X} (K_x D \frac{\partial H}{\partial X}) + \frac{\partial}{\partial y} (K_y D \frac{\partial H}{\partial y}) + W = S \frac{\partial D}{\partial t} . \tag{5-11}$$

Equation 5-11 is a form of the Boussinesq equation (1) in two dimensions and represents a mathematical model for flow in an unconfined aquifer under non-steady conditions.

Groundwater movement is steady or time independent when its flow characteristics are not changed with time. In the most strict sense of the definition, there are no steady groundwater aquifers. However, in some problems it suffices to obtain average values of the time dependent variables such as head or saturated thickness. The boundary condition is averaged over a given time interval and a steady state solution obtained.

By assuming a steady state condition, derivatives with respect to time can be eliminated and equation 5-11 may be written as:

$$\frac{\partial}{\partial X} (K_x D \frac{\partial H}{\partial X}) + \frac{\partial}{\partial y} (K_y D \frac{\partial H}{\partial y}) = - W \qquad (5\text{-}12)$$

Equation 5-12 is used as the mathematical model for analyzing net recharge rates in this study.

<u>Digital Computer Solution of Mathematical Model</u>

To gain the greatest amount of information possible, it is desired to make use of equation 5-12 without altering its form. This equation is a nonlinear, second-order partial differential equation, for which no general solution has been obtained. In this investigation we are interested in calculating the areal distribution of net recharge W. To do this we will use a finite difference form of equation 5-12 and calculate the net recharge rate directly.

Eshett and Longenbaugh (15) have presented a finite difference method for an equation very similar to equation

5-12. The following development has drawn heavily on their discussion. Five grids are arranged as in Figure 15 where i and j are block numbers in the coordinate system (x,y), m is the number of grids in the y-direction and n is the number of grids in the x-direction.

Employing a central finite-difference scheme, equation 5-12 may be written with respect to grid (i,j) in the following form:

$$\frac{(KD)_{i,j+1} + (KD)_{i,j}}{2} \; \frac{H_{i,j} - H_{i,j+1}}{\frac{\Delta X_{i,j+1}}{2} + \frac{\Delta X_{i,j}}{2}} \; \Delta y_{i,j}$$

$$- \frac{(KD)_{i,j-1} + (KD)_{i,j}}{2} \; \frac{H_{i,j-1} - H_{i,j}}{\frac{\Delta X_{i,j-1}}{2} + \frac{\Delta X_{i,j}}{2}} \; \Delta y_{i,j}$$

$$+ \frac{(KD)_{i-1,j} + (KD)_{i,j}}{2} \; \frac{H_{i,j} - H_{i-1,j}}{\frac{\Delta y_{i-1,j}}{2} + \frac{\Delta y_{i,j}}{2}} \; \Delta X_{i,j}$$

$$- \frac{(KD)_{i+1,j} + (KD)_{i,j}}{2} \; \frac{H_{i+1,j} - H_{i,j}}{\frac{\Delta y_{i+1,j}}{2} + \frac{\Delta y_{i,j}}{2}} \; \Delta X_{i,j}$$

$$= W \;\; \Delta X_{i,j} \; \Delta y_{i,j} \qquad (5\text{-}13)$$

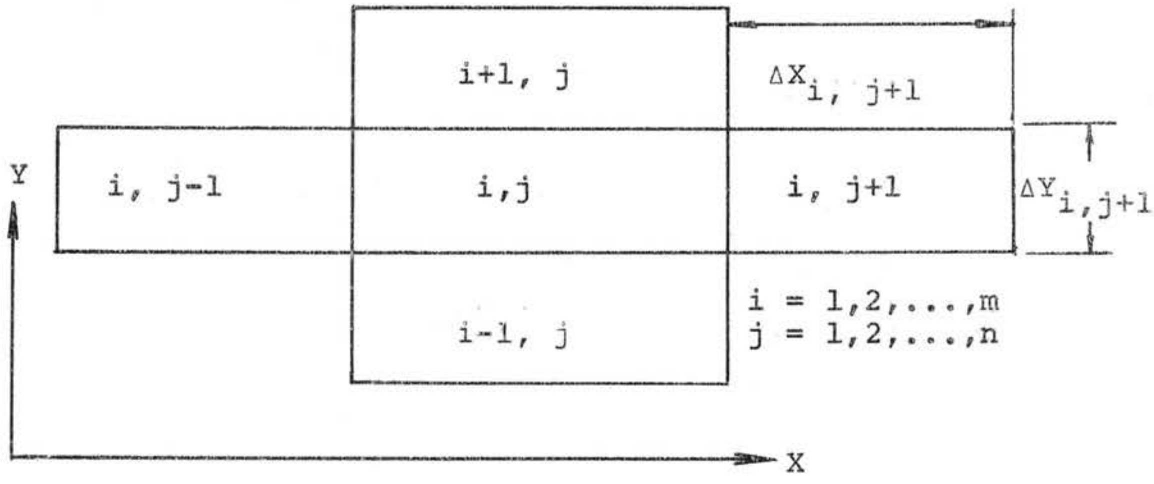

Figure 15. Typical grid system used in developing finite difference equation.

Rearrangement of equation 5-13 yields:

$$\left[\frac{(KD)_{i,j+1} + (KD)_{i,j}}{\Delta X_{i,j}(\Delta X_{i,j+1} + \Delta X_{i,j})}\right]\left[H_{i,j} - H_{i,j+1}\right]$$

$$-\left[\frac{(KD)_{i,j-1} + (KD)_{i,j}}{\Delta X_{i,j}(\Delta X_{i,j-1} + \Delta X_{i,j})}\right]\left[H_{i,j-1} - H_{i,j}\right]$$

$$+\left[\frac{(KD)_{i-1,j} + (KD)_{i,j}}{\Delta y_{i,j}(\Delta y_{i-1,j} + \Delta y_{i,j})}\right]\left[H_{i,j} - H_{i-1,j}\right]$$

$$-\left[\frac{(KD)_{i+1,j} + (KD)_{i,j}}{\Delta y_{i,j}(\Delta y_{i+1,j} + \Delta y_{i,j})}\right]\left[H_{i+1,j} - H_{i,j}\right] = W \qquad (5\text{-}14)$$

To determine the areal distribution of recharge, the Northern High Plains was divided into a square grid network with Δx and Δy equal to six miles (see Figure 16). Equation 5-14 was then written for each grid and a value for the net recharge rate W calculated. The following assumptions were made: (1) Darcy's law is valid, (2) the Dupuit assumptions are met, (3) the aquifer is under steady state conditions, (4) net recharge is distributed uniformly in both time and space over each grid, (5) the aquifer is homogeneous and isotropic within each grid and (6) the lower boundary is impermeable.

Figure 17 gives an illustration of what the calculated net recharge rate W might represent. In the largest percentage of the Northern High Plains area, the depth to the water table will be large (see Figure 12) and w_2 will be very small. Thus, the net recharge W closely represents the gross recharge w_1. If the grid size were made smaller the net recharge W would more closely approximate the gross recharge w_1. However, the basic data for this study is not of sufficient accuracy to justify the use of a smaller sized grid.

To solve equation 5-14, values for K, D, H, Δx and Δy are needed for each of the grids. Values of hydraulic conductivity K were determined for each grid by superimposing the grid network of Figure 16 onto the hydraulic conductivity map of Figure 9. An average value of K for each grid was then determined by visual inspection.

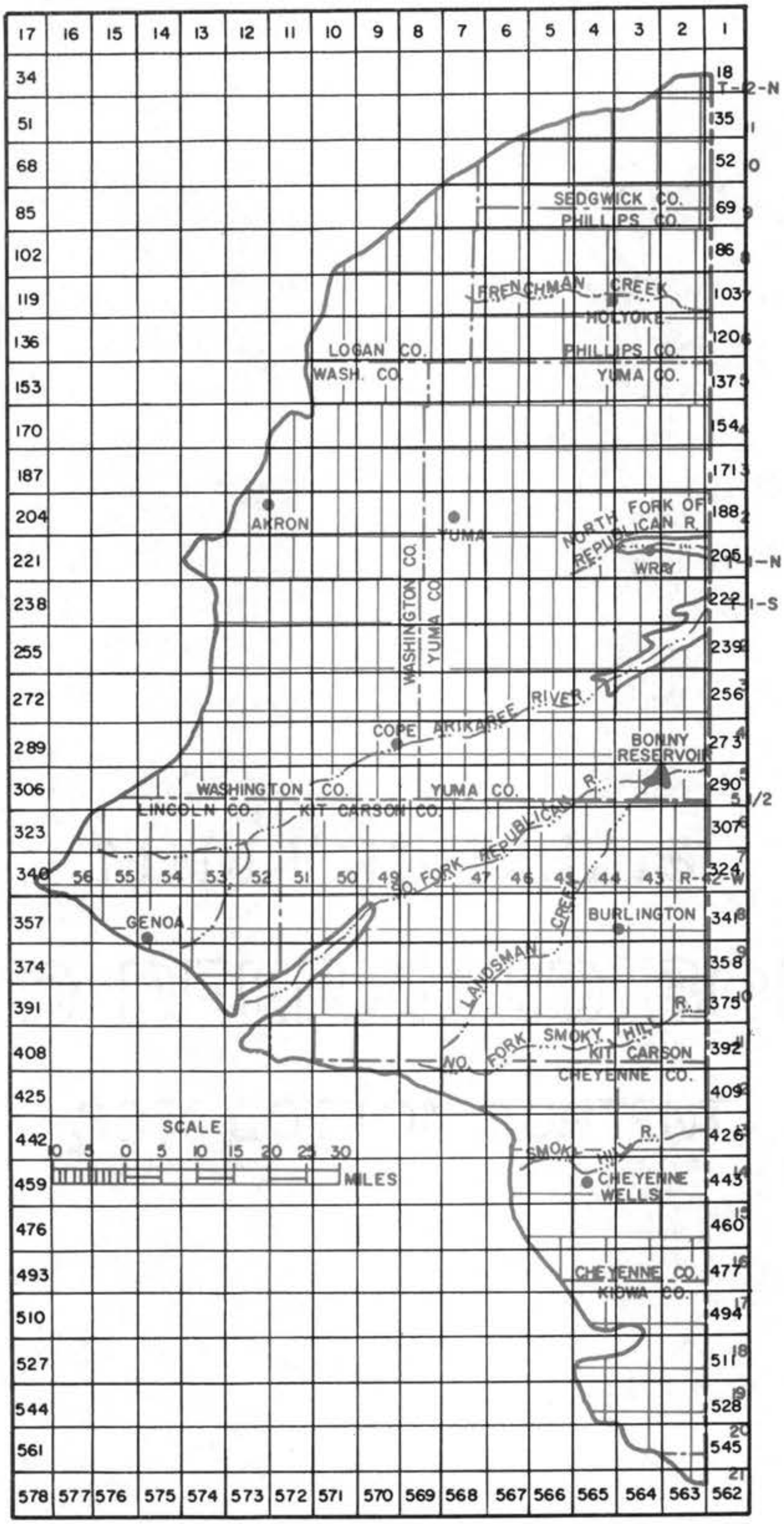

Figure 16. Six square mile grid system used in the finite difference method of calculating net recharge to the Ogallala Formation of the Northern High Plains of Colorado.

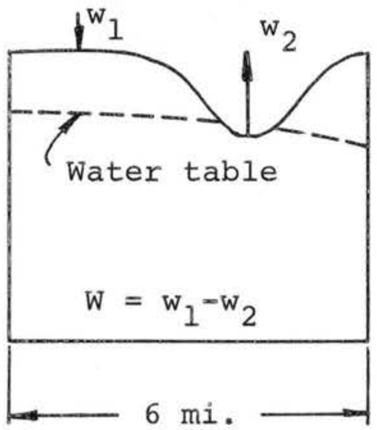

Figure 17. Grid cross section showing the concept of net recharge and gross recharge.

The grid network was also superimposed onto the water table map, Figure 7, and the bedrock map, Figure 4. The area within each contour of each grid was planimetered and an average water table elevation H and bedrock elevation Z determined for each grid. The average saturated thickness D was calculated by subtracting the average bedrock elevation from the average water table elevation ($D = H-Z$).

A Fortran IV program for the CDC 6600 digital computer was written and values of net recharge W were calculated using equation 5-14. A positive value for net recharge represents water being added to the aquifer from the surface. A negative value of net recharge indicates that the aquifer is discharging water. The Fortran IV program is given in Appendix C and the input data for K, D, H, Z, Δx and Δy are given in Appendix D.

This model represents a detailed simulation of the area, limited only by the adequacy of the data used in the calculations. The method is closely related to the underflow method except that the size of the area is greatly reduced, thus giving more areal detail.

Chapter VI

RESULTS AND DISCUSSION

Distribution of Natural Recharge in the Northern High Plains of Colorado

Figure 18 presents the results of this study in the form of isolines of equal rates of net recharge. The results in the form of a computer print out sheet are also given in Appendix E. A wide variation in net recharge is shown; varying from negative quantities (indicating areas of natural discharge) to as much as six inches of net recharge per year in the sandhills north of Wray. In general, net recharge rates in excess of two inches per year are confined to the sandhill portion of the study area. Most of the area with surface exposures of Peorian Loess and Ogallala Formation have net recharge rates of one inch per year or less.

By using the finite difference method, the total volume of net recharge to the Ogallala Formation was computed to be 405,000 acre-feet per year or an average of about 0.82 inch per year over the entire study area. It should be pointed out that the net recharge rate of 405,000 acre-feet per year is something less than the gross recharge rate (see Figure 17). However, because of the great depth to the water table over a large portion of the Northern High Plains, the 405,000 acre-feet per year is believed to closely approximate the gross recharge rate.

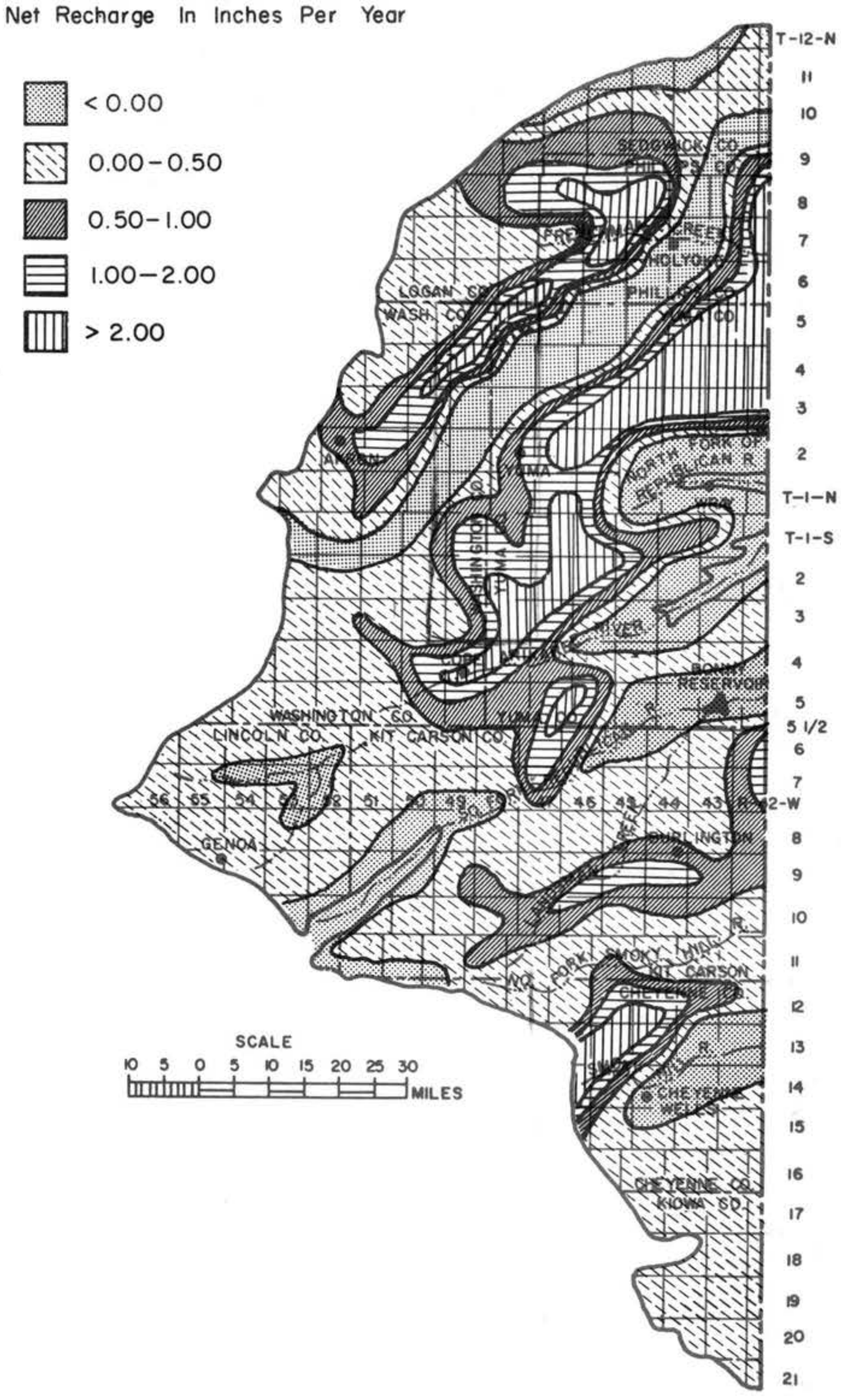

Figure 18. Distribution of groundwater recharge for the Ogallala Formation in the Northern High Plains of Colorado.

The total volume of net recharge to the Ogallala Formation is distributed unevenly over the study area. An indication of this variation can be obtained by inspection of the average net recharge rates for the various counties as shown in Table 3. Yuma County (covered mostly by the sandhill area) has the highest average net recharge rate of 1.45 inches per year while Kiowa County at the southern tip of the study area has the lowest average net recharge rate of 0.15 inch per year.

Table 3. Average Net Recharge Rates for the Counties of the Northern High Plains of Colorado.

County	Average Annual Net Recharge (inches per year)
Sedgwick	0.90
Phillips	0.95
Logan	0.55
Washington	0.80
Yuma	1.45
Kit Carson	0.40
Lincoln	0.20
Cheyenne	0.65
Kiowa	0.15
Entire Northern High Plains	0.82

Distribution of Net Natural Discharge in the Northern High Plains of Colorado

Referring to Figure 17, a value for the net natural discharge $-W$ will be obtained if the gross natural discharge w_2 is larger than the gross recharge w_1. The actual computed values of net discharge will be less than the gross natural discharge. However, along the effluent portions of the North and South Forks of the Republican River and the Arikaree River, the recharge rate w_1 is probably small compared to the discharge rate w_2. Thus, the net natural discharge $-W$ is probably a good estimate of the gross discharge w_2.

Areal distribution of net natural discharge in the Northern High Plains produced some highly unexpected results. All of the suspected areas of discharge along the North and South Forks of the Republican River and the Arikaree River were clearly defined by the finite difference method as shown in Figure 18. However, two areas of natural discharge are shown that were not expected. One of these areas is along the Smoky Hill River near Cheyenne Wells and the other extends diagonally in a long narrow band from southeastern Sedgwick County to 18 miles south of Akron in Washington County. Each of the discharge areas is discussed in detail later.

Underflow Across State Line--As was pointed out previously, the water table map of Figure 7 indicates that groundwater flows from Colorado into Kansas and Nebraska.

The mathematical model used for the calculation of recharge rates was also used to calculate the quantity of underflow out of Colorado. The state line was divided into 32 segments six miles in length. Values of K, ΔH, Z, and D were selected for each segment and using Darcy's law the groundwater underflow across the state line was calculated to be 175,000 acre-feet per year.

Net Natural Discharge Along the North Fork of the Republican River--The net recharge map of Figure 18 indicates a large discharge area along the North Fork of the Republican River near Wray. By the finite difference method, the net discharge was calculated to be 50,000 acre-feet per year. The author observed that this is an area of significant groundwater runoff during a field trip to the area in March, 1967. Numerous seeps, springs and bogs are prevalent in the area as shown by the photographs in Figure 19.

Surface water records published by the U.S. Geological Survey show that a stream gaging station was maintained on the North Fork of the Republican River 100 feet east of the Colorado-Nebraska state line for several years (31). The records from this station are noted as being good by the U.S. Geological Survey. To keep within the dynamic equilibrium assumption used in this study, the earlier streamflow records from 1940 to 1950 were reviewed at this station. The month of February was selected as a base for

(a)

(b)

Figure 19. (a) Groundwater standing in a stagnant pool at the headwaters of the North Fork of the Republican River. (b) A spring east of Wray which discharges into the North Fork of the Republican River.

groundwater runoff in the area because transpiration by plants would be small and evaporation would be at a minimum. Also, records during February do not seem to reflect icing effects as much as January. Runoff from precipitation is also very small during February.

The mean monthly flow for February at this station from 1940 to 1950 varied from 58.7 second-feet to 76.4 second-feet and averaged 70 second-feet or about 51,000 acre-feet per year. Within the limits of the accuracy of the station and the assumption that February is a good base for computing groundwater runoff, this 51,000 acre-feet per year should be very close to the gross natural discharge. Therefore, the 50,000 acre-feet per year of net natural discharge as computed by the finite difference method should be slightly less than the 51,000 acre-feet per year of gross natural discharge. Good agreement is obtained between the two results.

The base flow of the North Fork of the Republican River decreases to less than 20 second-feet during the summer months. This indicates that a large percentage of the groundwater discharge is lost to evapotranspiration during the summer. Assuming 50 second-feet lost to evapotranspiration for five months, it is estimated that approximately 15,000 acre-feet per year of groundwater is lost to evapotranspiration and 35,000 acre-feet per year is lost as groundwater runoff in this area.

Net Natural Discharge Along the South Fork of the Republican River--Results obtained from the finite difference method indicated 35,000 acre-feet per year of net groundwater discharge along the South Fork of the Republican River. The area is indicated around Bonny Reservoir on Figure 18. This was also confirmed as a groundwater discharge area by field inspection (see Figure 20).

A stream gaging station on the South Fork of the Republican River was established two miles downstream from the state line in 1947. However, Bonny Reservoir was constructed in 1950 and the stream flow records for the remaining years indicate that the stream flow was reduced from the virgin flow conditions.

The mean monthly flow for the month of February at this station from 1947 to 1950 varied from 58.4 to 76.5 second-feet and averaged 63.5 second-feet or 46,000 acre-feet per year of gross discharge. Remembering that this station is two miles below the state line and that net discharge is less than gross discharge, it is believed that good agreement exists between the 35,000 acre-feet calculated by the finite difference method and the actual gaged runoff.

The streamflow records for the South Fork of the Republican River also indicate that evapotranspiration during the summer months is rather high. These records indicate that approximately 10,000 acre-feet per year of groundwater are lost to evapotranspiration and 25,000 acre-feet per year are lost as groundwater runoff.

Discharge Along the Arikaree River--The Arikaree River upstream from the state line is also a discharge area as shown by Figure 18. The net groundwater discharge in this area was calculated to be 20,000 acre-feet per year. A photograph showing the groundwater runoff in March 1967 is shown in Figure 21.

No stream gaging station close to the state line has been established on the Arikaree River. The nearest is located approximately six or seven miles downstream near Haigler, Nebraska. Records for this station, which are considered poor by the U. S. Geological Survey, indicate a mean monthly runoff from 1940 to 1950 for February of 26.1 second-feet or about 19,000 acre-feet annually. Since the gaging station is six or seven miles downstream from the state line, the gross groundwater runoff at the state line would have to be less than the 19,000 acre-feet per year at the gaging station. Therefore, since net discharge is supposed to be less than gross discharge, poor agreement exists between the 20,000 acre-feet calculated by the finite difference method and the actual gaged runoff. However, since the records at this station are considered poor by the U.S. Geological Survey, a closer agreement may exist than that shown. An estimated 5,000 acre-feet per year of

Figure 20. Groundwater runoff into Landsman Creek which discharges into the South Fork of the Republican River.

Figure 21. Groundwater runoff in the Arikaree River approximately 15 miles upstream from the state line.

groundwater is lost to evapotranspiration along the Arikaree River with the remaining 15,000 acre-feet per year being lost to groundwater runoff.

Net Natural Discharge Around Cheyenne Wells--Results from the finite difference method revealed 30,000 acre-feet per year of net groundwater discharge in the Cheyenne Wells area (see Figure 18). This was not expected because no known surface water flow due to groundwater exists along the Smoky Hill River in Colorado. However, the water table map (Figure 7) shows a fairly sharp upstream flexure of the water table contours indicating a possible discharge area. Figure 12 indicates that the depth to water in this area is 100 feet or greater, fairly well excluding surface discharge of any kind. However, the density of the water level measurements in the area may not have been great enough to pick up areas of shallow water along the river.

One possible reason for this discharge area is that a large amount of withdrawals by pumping has occurred and our dynamic equilibrium assumption has broken down. However, Boettcher (6) indicates that the 14 irrigation wells in use in Cheyenne and Kiowa Counties during 1960 pumped only about 2000 acre-feet of water. If all of these wells were localized in the Cheyenne Wells area, it is highly unlikely that the withdrawal of 2000 acre-feet annually would cause such a sharp upstream flexure in the water table contours.

Another possibility is that the saturated thickness of the Ogallala may be greater than indicated. Boettcher (7) notes that clay beds in the Ogallala vary from dark green to dark brown and in places are as much as 20 feet thick. These beds are similar to the weathered beds of the Pierre Shale and Niobrara Formation in drilling characteristics and in color and texture. Therefore, many drillers may mistake clay beds in the Ogallala Formation for the Pierre Shale or Niobrara Formation and fail to penetrate the entire thickness of the Ogallala Formation.

The remaining possibility is that our assumption of an impermeable lower boundary has broken down. It should be noted that the subsurface geology is changing in this area and a few miles to the south the bedrock changes from Pierre Shale to Niobrara Formation. It is beyond the scope of this study to investigate the possibility of subsurface discharge into underlying formations. Much more detail on the subsurface geology of the Pierre Shale and Niobrara Formation in this area is needed.

<u>Net Natural Discharge Along a Line from Southeastern Sedgwick County to 18 Miles South of Akron</u>--This area of natural discharge was also completely unexpected. However, results from the finite difference method indicate that about 75,000 acre-feet of groundwater discharge per year occurs in this area. Field investigation revealed no surface discharge and pumping by wells in the area, especially prior

to large scale development, is not enough to account for such a large amount of discharge.

Upon studying Figures 3 and 18, it was found that this narrow discharge area compares closely with the approximate subsurface extent of the White River Group. Figure 22 was prepared to show this relationship. As was pointed out in the geological description of the area, the White River Group may contain small amounts of water in hydraulic connection with the Ogallala Formation. Several wells in the area have been noted to penetrate sand layers in the White River Group. If such a sand member could be stratigraphically located over the entire area, then it seems possible that water is moving from the Ogallala Formation laterally into the White River Group and down gradient in the White River Group to the South Platte River. The north-south geologic cross section of Figure 23 running northward from the discharge area to the South Platte River illustrates this hypothesis. Insufficient subsurface data are available to confirm this hypothesis at the present time. However, it is hoped that an extensive field investigation will be undertaken to study the possibility of subsurface discharge from the Ogallala Formation in this area. If this is a subsurface discharge area, it should be noted that the actual amount of subsurface discharge will be larger than the calculated 75,000 acre-feet per year. This is because of the breakdown in the assumption that the lower boundary is impermeable.

Do these agree with figs 3 or 18? Dusk

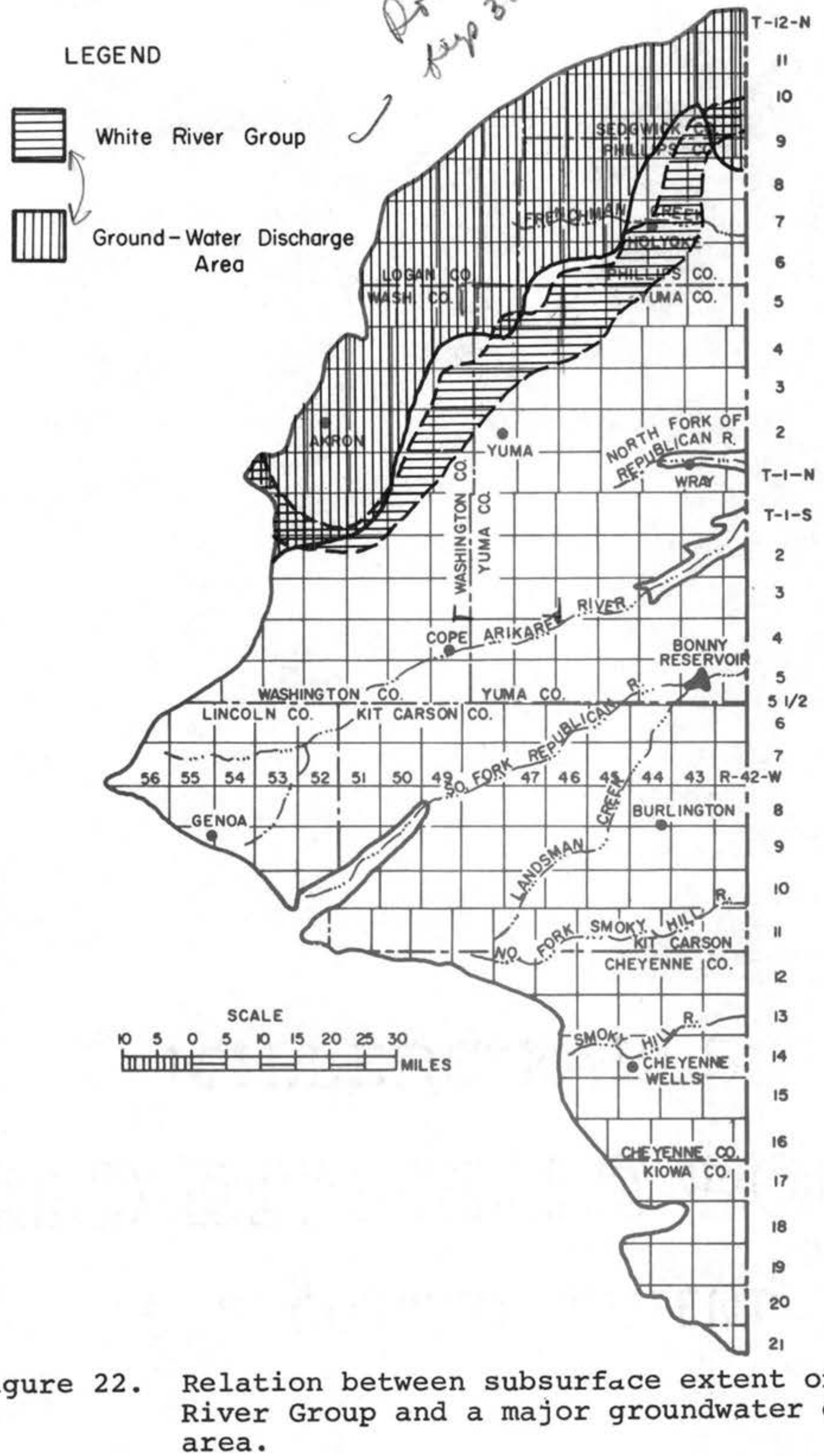

Figure 22. Relation between subsurface extent of the White River Group and a major groundwater discharge area.

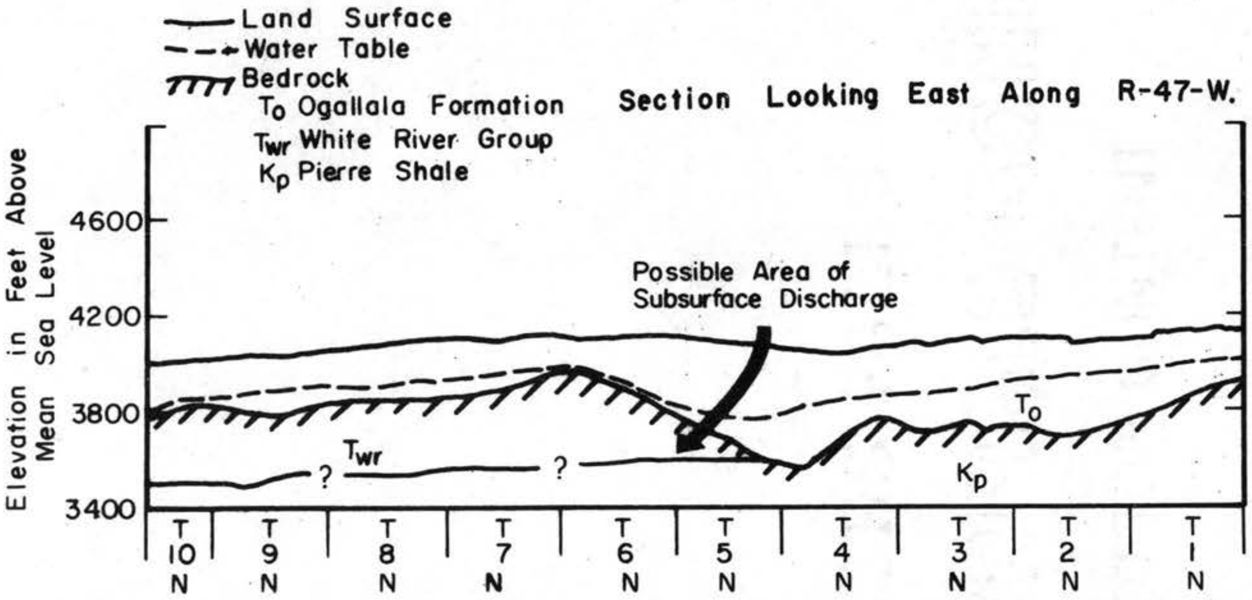

Figure 23. Geologic cross section of the northern part of the Northern High Plains indicating a hypothetical possibility for subsurface discharge from the Ogallala Formation into the White River Group.

Miscellaneous Discharge Areas--Several minor discharge areas are indicated on Figure 18. A value of about 3000 acre-feet of net discharge per year was obtained for a small area at the head waters of the Arikaree River in Lincoln County. This small amount of discharge probably does not reflect any streamflow, but is more likely to be entirely the result of evapotranspiration losses.

Another small discharge area is located along the head waters of the South Fork of the Republican River. A value of about 3000 acre-feet per year was calculated for this area. This quantity of net discharge is probably consumed by evapotranspiration.

An estimated 7000 acre-feet per year of net discharge is indicated along the northern edge of the High Plains in Sedgwick County and Logan County. This probably occurs as seeps or small springs along the escarpment. Another 7000 acre-feet of net discharge per year occurs at scattered and isolated points along the western edge of the study area, notably in Washington County and northwestern Cheyenne County. This volume of discharge is also probably due to seeps along the escarpment. Table 4 summarizes the groundwater discharge calculations.

Table 4. Summary of Net Natural Groundwater Discharge Calculations in the Northern High Plains of Colorado.

Area	Evapotrans-piration (ac-ft/yr)	Ground-water Runoff (ac-ft/yr)	Subsurface Discharge (ac-ft/yr)	Total for area (ac-ft/yr)
North Fork of the Republican River	15,000	35,000		50,000
South Fork of the Republican River	10,000	25,000		35,000
Arikaree River	5,000	15,000		20,000
Cheyenne Wells			30,000	30,000
Southern Sedgwick County to 18 miles South of Akron			75,000	75,000
Head of Arikaree River	3,000			3,000
Head of the South Fork of the Republican River	3,000			3,000
Northern Sedgwick	7,000			7,000
Miscellaneous	7,000			7,000
Totals for Northern High Plains	50,000	75,000	105,000	230,000
		Underflow across State Line		175,000
		Grand Total of net discharge		405,000

Finite Difference Method as a Qualitative Tool for Recharge Analysis

Besides being a powerful quantitative technique, the finite difference method appears to be a good qualitative tool for recharge analysis. For instance, a range of hydraulic conductivities were used in this study to determine their effect on the recharge and discharge areas. The variations of hydraulic conductivity changed the arithmetic values, but the essential patterns of the recharge and discharge areas remained intact. Changing the saturated thickness produced the same effect. The discharge areas seem to be an inherent feature of the hydraulic flow system and the finite difference method will outline such areas even though the available quantitative data are meager. Also, the areas of high and low recharge rates were clearly defined by almost any reasonable hydraulic conductivity and saturated thickness used. The results from all the runs made in this study showing this qualitative feature are shown in Appendix E. These results are given as the printout sheets from the computer. They are arranged exactly as the grids shown on Figure 16; each value in the printout being for a corresponding grid in Figure 16.

Chapter VII

CONCLUSIONS AND RECOMMENDATIONS

The finite difference method for analyzing the areal distribution of net natural recharge offers a powerful tool for aquifer analysis. The method is limited in its quantitative results by the quality of the input data used in the calculations. For instance, hydraulic conductivity data in some areas of the present study area will undoubtedly need revision as more and better data become available. The bedrock data will also need minor revisions as new information becomes available. However, the results presented are based on the best information available at this time and are believed to be of the right order of magnitude. The best check available of the accuracy of the method is given by the close correspondence between the net discharge calculations from the finite difference method and the gross discharge as estimated from streamflow measurements on the North and South Forks of the Republican River and the Arikaree River. The finite difference method also was shown to qualitatively portray the net recharge and net discharge patterns of the aquifer even though inferior data are available.

Several recommendations for future studies are indicated as a result of this study. Some involve more field studies and others involve theoretical studies to be done in the office. These recommendations are:

(1) An intensive undertaking by several agencies to obtain additional information on the hydraulic properties of the aquifer. Personnel from state, local and federal agencies should establish a central committee for the purpose of conducting pumping tests and analyzing the results.

(2) A thorough subsurface geological study of the White River Group to investigate the possibilities of subsurface discharge from the Ogallala Formation into the White River Group.

(3) A detailed field study of the area around Cheyenne Wells to determine the process by which natural discharge occurs in this area.

(4) A topographic mapping program needs to be initiated to provide high quality topographic maps of the Northern High Plains area.

(5) With the recharge and discharge information developed in this study, a theoretical analysis should be conducted to determine the effects of locating pumping centers in various areas. For instance, it might be advantageous to temporarily over-develop an area so that some of the present natural discharge could be diverted into the pumping area.

(6) The greatest recharge rates and the largest volumes of groundwater occur in the sandhill area. This land is not considered irrigable and will probably not be developed. However, this resource should not go undeveloped. Economic studies should be made toward the possibility of attracting industry to the area that could use the water.

In closing, it should be noted that the results presented in this study should be continuously updated as new information on the Ogallala Formation becomes available. This information should then be disseminated to the appropriate agencies involved with the management of the groundwater supply in the Northern High Plains of Colorado.

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APPENDIX A

Well Numbering System

WELL NUMBERING SYSTEM

The well numbering system used in this study is based on the U.S. Bureau of Land Management system of land subdivision. The number shows the location of the well or test hole by quadrant, township, range, section, and position within the section. A graphical illustration of this method of location is shown in Figure A-1. The capital letter at the beginning of the location number indicates the quadrant in which the well is located. Four quadrants are formed by the intersection of the base line and the principal meridian--A indicates the northeast quadrant, B the northwest quadrant, C the southwest quadrant, and D the southeast quadrant. The first numeral indicates the township, the second indicates the range, and the third indicates the section in which the well is located. Lowercase letters following the section number locate the well within the section. The first letter denotes the quarter section, the second letter denotes the quarter-quarter section, and the third letter denotes the quarter-quarter-quarter section. The letters are assigned within the section in a counterclockwise direction, beginning with (a) in the northeast quarter of the section. Letters are assigned within each quarter section and within each quarter-quarter section in the same manner. Where two or more locations are within the smallest subdivision, consecutive numbers

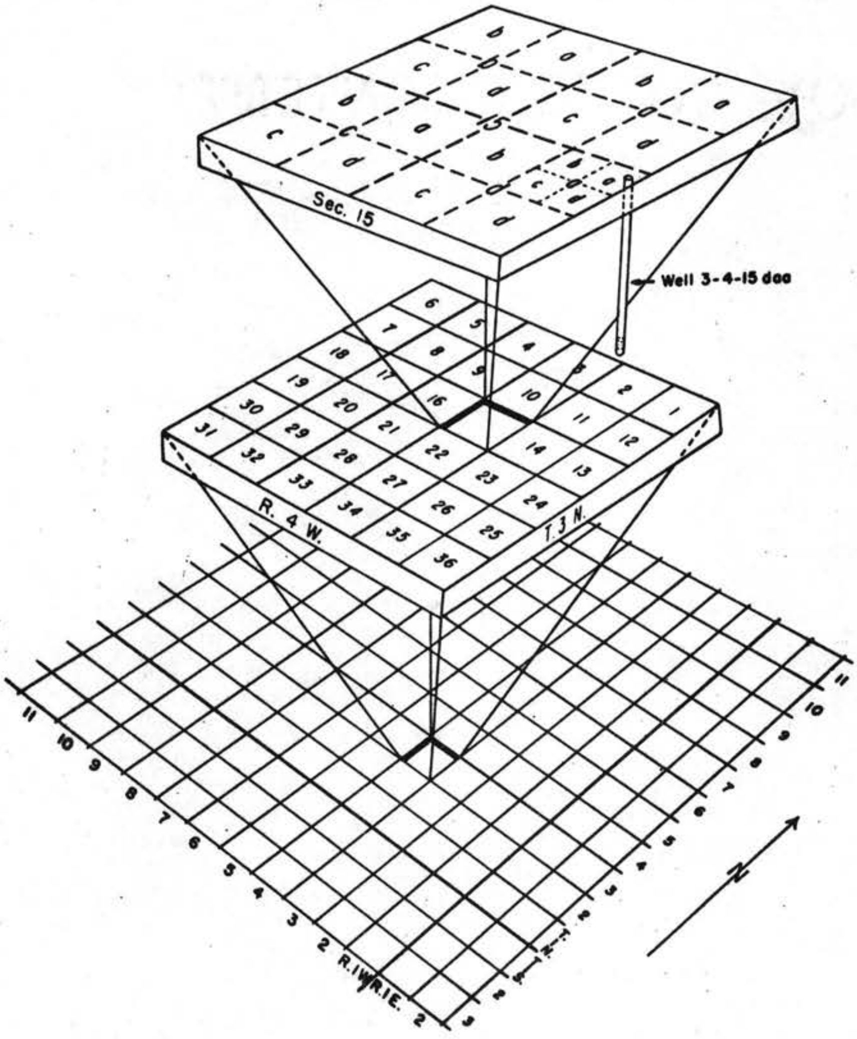

Figure A-1. System of numbering wells in this study.

beginning with 2 are added to the letters in the order in which the wells or test holes were inventoried. For example, C4-55-12abc2 indicates a well in the southwest quarter of the northwest quarter of the northeast quarter of sec. 12, T. 4S., R 55 W., and shows that this is the second well inventoried in the quarter-quarter-quarter section. The capital letter C indicates the township is south of the base line and that the range is west of the principal meridian.

APPENDIX B

Calculation of Transmissibility from Specific Capacity

Calculation of Transmissibility from Specific Capacity

Numerous data are available which might prove beneficial in estimating transmissibility. A statistical analysis of some of these data was made to determine a satisfactory regression model. A multiple linear regression technique of the form:

$$X_1 = B_1 + B_2 X_2 + B_3 X_3 + B_4 X_4 \qquad \text{(B-1)}$$

was assumed where X_1 is the transmissibility in 1000 gallons per day per foot; B_1, B_2, B_3. and B_4 are regression coefficients; X_2 is the specific capacity of a well in gallons per minute per foot of drawdown; X_3 is the duration of the pumping test in hours; and X_4 is the diameter of the well casing in inches.

The method of least squares was employed to calculate the regression coefficients in equation B-1. This method makes the $\Sigma(X_1 - \hat{X}_1)^2$ a minimum for the particular model assumed. When using the least squares technique, two basic assumptions are involved: (1) the independent variables are fixed and measured without error and (2) the deviations $(X_1 - \hat{X}_1)$ are normal, independent variables with constant mean and variance.

All available transmissibility data for the Ogallala Formation in the Northern High Plains of Colorado were collected. These data are shown in Table B-1. A program from the Colorado State University Computer Center for the

IBM 1620 digital computer was used to estimate the regression coefficients of equation B-1 from the data in Table B-1. The following regression equation was obtained:

$$X_1 = 26.85 + 2.48\ X_2 + 0.03\ X_3 - 1.77\ X_4 \qquad \text{(B-2)}$$

Equation B-1 accounts for 95 percent of the total sum of squares and has a multiple correlation coefficient of 0.97. The following analysis of variance shows that B_1, B_3, and B_4 are not significantly different from zero at the 95 percent level.

Source	Sum of Squares	Degrees of Freedom	Mean Square	Calculated "F" Value	Conclusion at 95% Significance Level
Total	898,584	52			
Mean	593,137	1			
H_o:B_1=0	373	1	373	1.097	Accept:B_1=0
H_o:B_2=0	268,002	1	268,002	788.241	Reject:B_2=0
H_o:B_3=0	249	1	249	0.732	Accept:B_3=0
H_o:B_4=0	429	1	429	1.261	Accept:B_4=0
Error	16,296	48	340		

From this analysis it would appear that we may assume B_1, B_3, and B_4 are zero and that equation B-1 reduces to:

$$X_1 = B_2X_2 \qquad \text{(B-3)}$$

To determine if equation B-3 is an adequate model, another regression analysis was run and the following regression equation obtained:

$$X_1 = 2.45\ X_2 \qquad \text{(B-4)}$$

Equation B-4 accounts for 95 percent of the total sum of squares and has a multiple correlation coefficient of 0.97. (These figures are the same to two significant figures as those for equation B-1). The following analysis of variance shows that equation B-4 is an adequate model at the 95 percent significance level.

Source	Sum of Squares	Degrees of Freedom	Mean Square	Calculated "F" Value	Conclusion at 95% Significance Level
Total	898,584	52			
Mean	593,137	1			
Equation B-2	882,287	4			
Equation B-4	881,620	1			
$H_o: B_1 = B_3 = B_4 = 0$	667	3	222	0.652	Accept: $B_1 = B_3 = B_4 = 0$ and eq. B-4 is adequate model.
Error	16,296	48	340		

The variance of B_2, as used in equation B-4, is 0.002 and the 95 percent confidence interval for B_2 is:

$$2.35 < B_2 < 2.55 \qquad \text{(B-5)}$$

Figure B-1 shows the relationship between the actual values of X_1 and the predicted values of X_1 from equation B-4. It should be noted that 72 percent of the points fall within one standard deviation and 96 percent are within two standard deviations. This indicates that the deviations $(X_1 - \hat{X}_1)$ are approximately normally distributed with constant mean and variance.

Using published records of the U.S. Geological Survey (10) and the Colorado Water Conservation Board (5, 11, 22, 23), values of transmissibility were estimated using equation B-4. These data are shown in Table B-2. Also, some specific capacity data were available from the files of Colorado State University (21). The estimated transmissibilities from these data are shown in Table B-3.

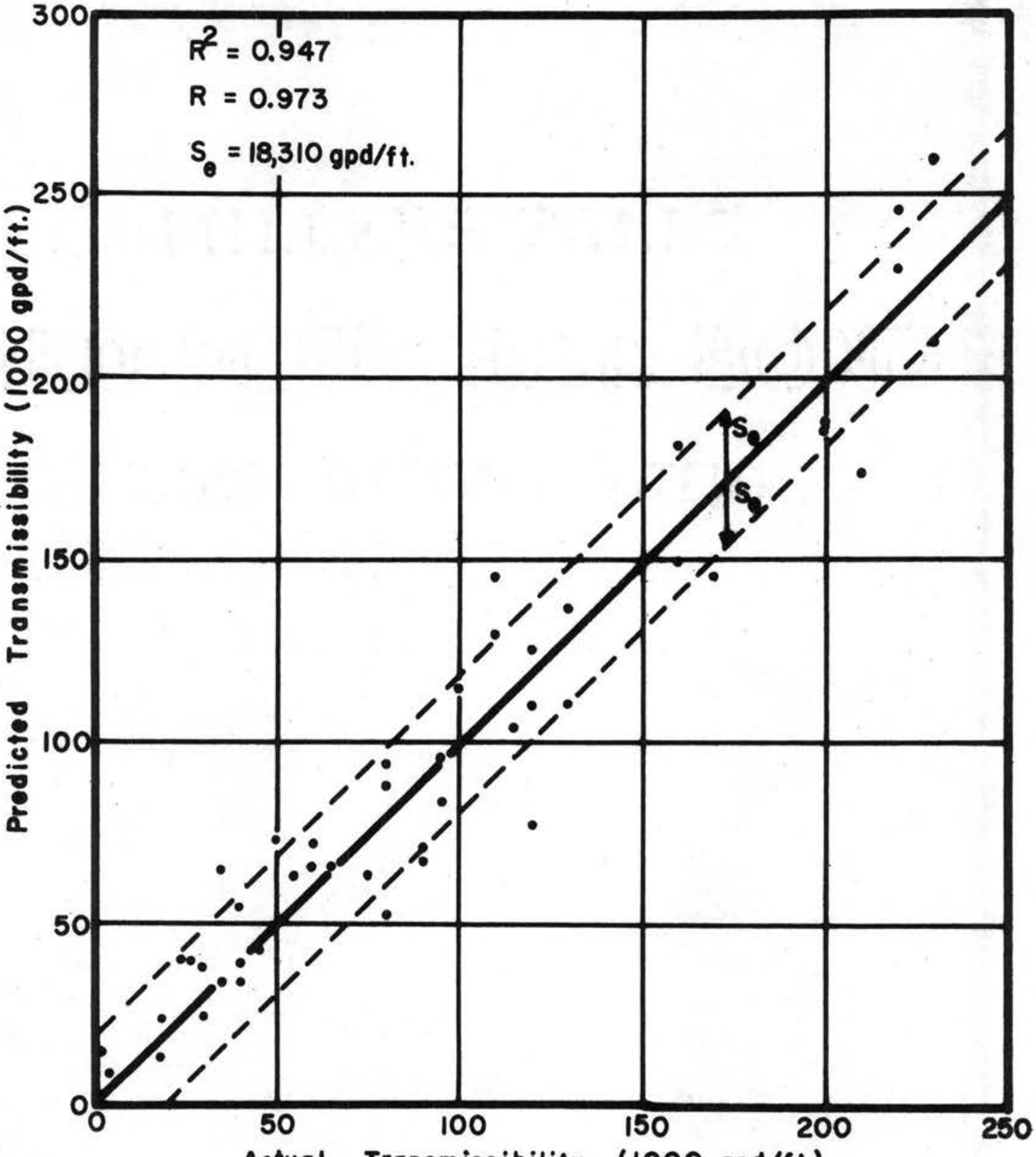

Figure B-1. Plot of actual values of transmissibility versus predicted values from equation B-4.

Table B-1. Pumping Test Data for the Ogallala Formation in the Northern High Plains of Colorado.[a]

Well Location Number	Specific Capacity (gpm/ft)	Duration of Test (hours)	Well Diameter (inches)	Transmissibility (1000 gpd/ft)	Saturated Thickness (feet)	Hydraulic Conductivity (gpd/ft^2)
			Cheyenne County			
C13-41-31baa	--	67	--	190	101	1900
			Kiowa County			
C17-43-17ccc	1	7	8	2	11	200
C20-41-30cdd	42	9	16	120	98	1200
			Kit Carson County			
C5½-44-31cbb	106	38	--	190	71	2600
C5½-44-36acd	27	12	18	75	91	820
C6-42-23-bdb	16	41	--	90	130	690
C8-42-32baa	10	16	16	19	126	150
C8-44-25ccd	14	6	16	35	166	210
C8-46-9bcc	29	667	16	90	58	1550
C10-42-30cba	37	34	18	80	128	620
C10-43-11bab2	19	16	18	45	177	250
C11-44-4add	27	10	16	65	113	580
			Phillips County			
B7-43-18abb	101	13	18	220	190	1200
B7-43-27bbb	62	117	18	160	237	680
B7-43-33acd	72	333	18	210	254	830
B7-43-35bcc	113	10	18	270	255	1100
			Sedgwick County			
B10-43-3dcb	24	6	18	20	152	130
			Yuma County			
B1-45-27bbb	93	10	16	220	172	1300
B1-47-4cad	85	3	16	230	209	1100
B2-42-27bbc	12	--	18	30	111	270
B2-48-34bca	53	4	16	110	239	460
B3-43-33cda	13	4	12	30	91	330
B3-46-5bca	51	24	16	120	181	660
B4-47-26abd	18	14	18	27	110	250
B4-47-32cbb	105	30	16	300	118	2600
B5-43-24abb	67	--	--	250	236	1000
C1-44-10acc	14	24	16	35	161	110
C1-44-27bbb	47	2	16	100	142	730
C1-45-35bad	38	24	16	80	143	560
C3-42-31ccc	7	24	18	18	63	290
C4-42-3bbb	4	24	16	4	64	60
C4-43-26cbb	16	10	16	40	82	490
C4-44-31cbd	39	24	16	95	111	850
C4-44-35bbb	14	24	16	40	99	400
C4-48-35dab	83	--	--	250	162	1600
C5-44-30bcb	36	--	--	100	60	1650
C5-47-14dcb	76	24	16	200	137	1400
C5-47-20bab	27	24	16	60	167	360
			Tests Located in Nearby Kansas			
C8-42-18cbc	31	24	18	50	183	270
C13-43-36baa	59	24	16	170	105	1600

Table B-1 Continued.

Well Location Number	Specific Capacity (gpm/ft)	Duration of Test (hours)	Well Diameter (inches)	Transmissibility (1000 gpd/ft)	Saturated Thickness (feet)	Hydraulic Conductivity (gpd/ft^2)
			Tests Located in Nearby Nebraska			
B5-34-28bca	27	60	16	90	70	1300
B5-39-35cba	77	1	18	200	270	740
B6-39-30bbc	45	10	16	130	270	480
B6-41-1bbb	26	11	16	55	54	1000
B7-38-5ada	33	10	18	120	137	880
B7-40-5bbb	60	78	18	110	169	650
B7-40-28bbb	52	436	18	130	264	490
B7-41-21abb	35	52	18	95	241	390
B8-40-26bcd	31	13	18	60	194	310
B8-41-34abc	46	16	18	120	163	740
B10-41-11dab2	23	11	18	80	119	670
B11-39-21bcd	28	10	18	35	200	180

[a]Compilation of records from U.S. Geological Survey (5, 8, 31, 34).

Table B-2. Transmissibility of the Ogallala Formation Calculated from Specific Capacity, Q/s, Using the Regression Equation $T = 2.45\ Q/s$.[a]

Well Location Number	Specific Capacity (gpm/ft)	Transmissibility (1000 gpd/ft)	Saturated Thickness (feet)	Hydraulic Conductivity (gpd/ft^2)
		Cheyenne County		
C14-41-30bbb	3.2	7	121	65
C14-42-9bdb	32.7	80	173	460
		Kiowa County		
C17-43-17ccc	1.3	3	15	210
C20-42-17acb	14.2	34	110	320
C20-42-36bcc	15.4	37	126	300
		Kit Carson County		
C5½-42-33adc	3.5	8	84	100
C5½-44-33ddb	15.1	37	58	640
C5½-44-36acd	29.5	72	92	790
C6-42-16dcb	11.3	27	119	230
C6-42-22abb	10.5	25	128	200
C6-42-23bbd	15.9	39	130	300
C6-42-27dba	8.6	21	133	160
C6-44-24acc	8.8	21	119	180
C6-44-25bcc	34.1	83	124	670
C6-44-35bca	40.7	99	121	820
C6-45-12cdc	29.0	71	106	670
C6-46-8dbc	11.8	28	97	300
C6-48-12bbd	122.0	299	55	5400
C6-50-3bcc	73.0	179	68	2600
C6-50-9abb	26.4	64	46	1410
C7-42-19cdd	13.3	32	145	220
C7-43-1dca	17.7	43	132	330
C7-43-14abc	8.9	21	144	150
C7-43-20bbb	7.1	17	119	150
C7-44-3abd	36.4	76	114	670
C7-44-23cbb	24.1	59	107	550
C7-45-22bcd	15.3	37	118	320
C7-45-23cbb	35.8	87	129	680
C7-45-29acb	45.6	111	127	880
C7-45-31ccb	29.1	71	121	590
C7-45-32dba	54.1	132	124	1070
C8-42-3cbc	28.6	70	161	440
C8-42-9bbb	21.2	52	183	280
C8-42-11ada	15.1	37	158	230
C8-42-15baa	18.3	44	167	270
C8-42-20cab	17.2	42	110	380
C8-42-32baa	10.2	24	126	200
C8-43-1acd	13.1	32	172	190
C8-43-9bcc	21.9	53	166	320
C8-43-23cbb	30.6	75	152	490
C8-43-24acd	18.5	45	182	250
C8-43-31bcb	11.2	27	178	150
C8-43-32ccb	12.2	29	157	190
C8-43-35cbb	22.0	53	165	330
C8-44-2acb	6.0	14	95	160
C8-44-14adb	26.0	63	132	480
C8-44-25ccd	15.7	38	166	230
C8-44-25dcd	20.0	49	170	290
C8-44-30caa	20.6	50	113	450
C8-44-35cbc	14.9	36	168	220
C8-44-35dac	7.3	17	181	100
C8-44-36abb	5.7	14	164	90
C8-44-36dab	23.1	56	161	350
C8-44-36dda	12.5	30	160	190

Table B-2 Continued

Well Location Number	Specific Capacity (gpm/ft)	Transmissibility (1000 gpd/ft)	Saturated Thickness (feet)	Hydraulic Conductivity (gpd/ft^2)
		Kit Carson County (Continued)		
C8-45-3bcd	59.0	144	101	1430
C8-45-34caa	8.4	20	76	270
C8-45-34ccd	11.4	27	66	420
C8-46-9bcc	27.8	67	57	1190
C8-47-26caa	16.5	40	33	1230
C8-47-26ccc	10.3	25	44	570
C8-51-35cda	16.6	40	22	1840
C9-42-11bbd	25.1	61	158	390
C9-42-31ccc	30.0	73	171	430
C9-43-3cca	7.0	17	151	110
C9-43-5bbb	17.4	42	160	270
C9-43-15dca	24.0	58	170	350
C9-43-18bbd	14.3	35	137	260
C9-43-18dbd	7.6	18	156	120
C9-43-22ccb	22.5	55	171	320
C9-44-1cac	3.9	9	157	60
C9-44-1cbb	9.5	23	157	150
C9-44-3dbb	32.7	80	169	470
C9-45-13dab	10.5	25	133	190
C9-45-21cdc	13.6	33	112	300
C9-48-2acc	24.0	58	54	1090
C9-51-2acc	16.7	40	11	3700
C9-51-2bbb	10.8	26	29	910
C10-42-6bbc	36.1	88	172	510
C10-42-10bcb	1.0	2	160	20
C10-42-16cba	27.0	66	149	440
C10-42-21baa	13.5	33	148	220
C10-42-26bbb	11.1	27	131	210
C10-42-27ccd	18.4	45	105	430
C10-42-28aad	14.3	35	112	310
C10-42-30bca	35.3	85	142	600
C10-42-30cba	36.2	88	128	690
C10-42-31aca	20.4	50	137	360
C10-42-31ddd	11.3	27	101	270
C10-43-11bab	20.4	49	177	280
C10-43-12bbb	17.2	41	173	240
C10-43-15dcc	29.0	71	158	450
C10-43-27ccb	23.4	57	161	360
C10-43-27dcb	22.0	53	174	310
C10-44-10bad	15.1	37	126	290
C10-44-23ccc	15.5	38	152	250
C10-44-26cdd	21.7	54	154	340
C11-42-4bcd	15.7	38	104	370
C11-42-28cad	15.0	37	36	1020
C11-43-11cad	20.2	50	126	390
C11-43-12ccb	24.5	60	161	370
C11-44-4add	28.6	70	113	620
C11-44-21abb	23.1	56	106	530
C11-44-27bbb	9.0	22	98	220
C11-44-28bcd	8.9	22	186	120
C11-46-25cdc	7.0	17	68	250
C11-46-30cca	3.3	8	73	110
C11-47-26bba	16.2	40	103	390
		Logan County		
B6-50-14dac	100.0	245	26	9300
		Phillips County		
B6-45-18abc	114.0	280	57	4900
B7-43-18abb	105.8	259	137	1900
B7-43-27bbb	74.2	182	145	1250
B7-43-33acd	72.7	178	177	1000

Table B-2 Continued

Well Location Number	Specific Capacity (gpm/ft)	Transmissibility (1000 gpd/ft)	Saturated Thickness (feet)	Hydraulic Conductivity (gpd/ft^2)
		Phillips County (Continued)		
B7-43-35abb	60.0	147	160	920
B7-43-35bcc	117.0	286	150	1900
B7-44-2ccd	103.0	253	89	2850
B7-44-7aca	90.0	220	42	5300
B7-44-17bcc	125.0	306	126	2400
B8-42-20dbd	6.0	15	55	270
B8-42-32bcc	115.3	282	144	2000
B8-44-36bbd	85.0	208	77	2700
B8-47-19bbd	9.1	22	125	180
B8-47-21ccc	31.4	77	83	930
B8-47-29aad	31.2	76	87	870
		Sedgwick County		
B10-43-3dcb	24.0	59	168	350
B10-44-35cad	26.4	65	119	550
		Yuma County		
B1-45-27bbb	105.0	258	174	1550
B1-45-28dbd	82.4	202	168	1200
B1-45-32aa	28.1	68	142	680
B1-47-4cad	85.2	209	212	990
B1-48-13dcd	47.8	117	156	750
B2-42-27bbc	13.3	32	111	290
B2-42-34ccc	37.5	92	11	8200
B2-46-26bcc	100.0	245	272	900
B2-46-30ddb	118.0	290	312	930
B2-47-17dda	44.4	109	319	340
B2-48-14bbd	56.3	138	320	430
B2-48-21dca	50.0	122	148	820
B2-48-22acc1	27.8	68	153	440
B2-48-22acc2	33.3	81	144	560
B2-48-22cdc	46.4	103	208	490
B2-48-25cdb	44.2	108	219	490
B2-48-28abd	58.3	143	144	990
B2-48-34bca	52.9	130	241	540
B3-43-33cda	13.0	31	81	380
B3-46-5bca	50.5	123	181	680
B3-46-7aa	18.9	46	268	170
B3-48-2ada	70.5	173	149	1150
B3-48-20ddb	68.4	168	158	1050
B4-44-18cdb	1.5	3	31	970
B4-44-34ddd	0.6	1	27	40
B4-47-23abc	26.6	65	124	510
B4-47-26aba	18.3	44	122	360
B4-47-32cbb	105.0	258	122	2100
B4-48-1bcc	16.9	41	196	210
B5-42-31aaa	61.0	149	317	470
B5-42-31bdc	29.2	71	197	360
B5-42-31cca	54.5	134	200	670
B5-43-24abb	66.6	163	242	670
B5-43-24dda	112.5	277	327	850
B5-47-22bdb	130.0	319	144	2200
B5-48-34dcd	53.5	131	149	880
C1-44-10acc	15.5	37	161	230
C1-44-23acc	24.1	58	284	200
C1-44-27bbb	46.4	113	150	750
C1-45-35bad	40.5	99	143	690
C2-45-10bba	53.4	131	93	1400
C3-42-31ccc	8.1	19	63	300
C3-42-34cbb	18.6	45	264	170
C3-43-28adc	9.5	22	286	80
C4-42-3bbb	4.4	10	74	135

Table B-2 Continued

Well Location Number	Specific Capacity (gpm/ft)	Transmissibility (1000 gpd/ft)	Saturated Thickness (feet)	Hydraulic Conductivity (gpd/ft^2)
		Yuma County (Continued)		
C4-42-32dac	19.5	47	61	770
C4-43-13aba	8.2	19	84	230
C4-43-24cab	8.0	19	72	270
C4-43-26cbb	15.7	38	89	430
C4-44-4bdc	35.2	86	95	910
C4-44-10ddd	27.6	67	118	570
C4-44-25abb	22.2	54	104	520
C4-44-27bbc	11.3	27	126	210
C4-44-31cbd	38.6	94	113	830
C4-44-35bbb	15.6	37	99	370
C4-45-33abb	35.6	87	148	590
C4-46-31cad	56.6	139	186	750
C4-47-25ddb	27.6	57	187	280
C4-47-27ddb	36.4	89	169	530
C4-47-31aba	45.4	111	91	1200
C4-48-35dab	82.8	203	172	1200
C5-43-12bda	23.5	57	58	980
C5-43-18cbb	32.0	78	78	1000
C5-44-5abb	16.9	41	16	2700
C5-44-9bab	35.4	86	101	850
C5-44-14caa	8.2	19	49	380
C5-44-16abc	14.3	34	97	350
C5-45-4bab	12.4	29	29	1050
C5-45-8aba	13.4	32	113	240
C5-47-2acc	65.6	161	296	550
C5-47-15cdb	30.4	74	178	420
C5-47-16adb	42.1	103	106	970
C5-47-20bab	30.0	73	167	440
C5-48-25abd	20.2	49	40	1200
		Washington County		
B2-50-9ddd	150.0	368	212	1750
B4-51-31bbc	0.9	2	13	160
C1-53-14add	1.5	4	10	400
C2-51-29cbb	0.5	1	10	100
C2-51-31cdc	40.0	98	39	3500
C4-51-23bbb	1.7	4	13	310

[a]Specific capacity was calculated from information obtained from Basic Data Reports of the Colorado Water Conservation Board and U.S. Geological Survey Water Supply Papers (6, 10, 11, 22, 33).

Table B-3. Transmissibility of the Ogallala Formation Calculated from Specific Capacity, Q/s, Using the Regression Equation T = 2.45 Q/s. (Specific capacity data from CSU efficiency studies (21)).

Well Location Number	Specific Capacity (gpm/ft)	Transmissibility (1000 gpd/ft)	Saturated Thickness (feet)	Hydraulic Conductivity (gpd/ft^2)
		Cheyenne County		
C13-45-25c	72.6	178	114	1550
C14-41-30b	46.3	113	208	540
C14-41-31b	72.0	176	252	700
C14-44-30b	84.4	207	128	1600
C14-45-24b	51.4	126	66	1900
		Kit Carson County		
C5½-42-33c	1.4	4	100	40
C6-42-33d	13.4	33	153	210
C6-42-34b	7.7	19	151	120
C6-44-24a	8.2	20	119	170
C6-44-29a	8.6	21	104	200
C6-44-35bd	48.2	118	117	1000
C6-46-2a	24.0	59	119	490
C7-45-21c	32.9	80	131	610
C7-45-29c	14.0	34	148	230
C7-45-31b	24.0	59	130	450
C7-45-31c	19.9	49	133	370
C7-45-33ccc	65.8	164	112	1460
C8-42-8a	12.6	31	174	180
C8-42-9b	17.3	42	161	260
C8-42-16b	4.2	10	121	80
C8-42-20ca	14.7	36	110	330
C8-42-29a	15.7	28	147	190
C8-42-29b	10.1	25	134	180
C8-43-25b	10.5	26	147	170
C8-43-27a	12.5	31	169	180
C8-43-32c	8.7	21	143	150
C8-43-34dbb	19.2	48	149	320
C8-43-35b	31.4	76	155	490
C8-44-2d	7.1	17	108	160
C8-44-10c	25.6	63	126	500
C8-44-19a	28.1	69	96	720
C8-44-21b	8.9	22	118	180
C8-44-22b	12.5	31	140	220
C8-44-24bb	11.1	27	135	200
C8-45-6a	41.1	101	103	980
C8-45-12d	22.3	54	112	490
C8-46-1b	20.9	51	105	490
C8-46-9bcc	27.2	67	57	1170
C8-46-20c	17.0	42	27	1540
C9-43-3c	6.7	16	145	110
C9-43-14ccc	10.6	26	150	170
C9-43-22dbb	21.6	53	171	310
C9-43-33b	8.9	22	157	140
C9-43-36b	11.4	28	181	150
C9-44-32b	5.9	15	134	110
C10-44-1a	18.3	45	159	280
C10-44-12b	14.2	35	132	260
C10-44-23c	17.8	44	139	310
C11-43-13bc	14.5	36	184	190
C11-43-14cb	17.6	43	113	380

Table B-3. Continued

Well Location Number	Specific Capacity (gpm/ft)	Transmissibility (1000 gpd/ft)	Saturated Thickness (feet)	Hydraulic Conductivity (gpd/ft^2)
		Phillips County		
B6-42-6b	33.6	82	116	710
B6-43-36a	46.7	114	154	740
B6-44-2a	175.8	431	175	2500
B6-44-4da	116.3	285	182	1550
B6-44-8b	109.3	268	134	2000
B6-45-29b	24.8	61	110	550
B7-42-17b	60.0	147	220	670
B7-43-14cb	78.3	198	193	1020
B7-43-18abb	130.2	318	142	2250
B7-43-33a	78.0	191	173	1100
B7-43-35cb	80.4	197	151	1300
B7-44-2c	75.9	186	88	2100
B7-44-15b	88.3	216	136	1600
B7-46-21a	6.2	15	43	340
B8-43-35d	200.2	490	173	2800
B8-44-35c	147.9	362	121	3000
B8-47-19b	11.0	27	124	220
B9-42-30c	31.2	76	188	410
B9-43-25a	26.8	66	43	1550
B9-46-28a	68.0	167	120	1390
B9-47-34a	35.9	88	146	600
		Sedgwick County		
B9-43-13a1	17.3	42	114	370
B9-43-13a2	30.8	76	65	1150
		Washington County		
B1-49-6ba	82.9	203	124	1650
B1-49-12a	45.1	110	159	690
B2-49-28a	93.2	228	107	2100
B3-49-5d	67.5	150	145	1030
		Yuma County		
B1-47-5b	40.8	100	216	460
B1-48-1bc	51.6	126	406	310
B1-48-2d	42.2	103	201	510
B1-48-13d	55.4	136	264	510
B2-47-5bb	33.4	81	245	300
B2-47-18c	28.8	70	221	320
B2-48-3dd	35.4	86	280	310
B2-48-25c	49.6	121	217	560
B3-47-25a	19.2	46	220	210
B3-47-30dc	48.3	118	202	580
B3-48-2a	87.0	213	148	1450
B3-48-20d	62.0	152	157	970
B4-43-15c	91.8	225	178	1250
B4-47-32c	88.3	217	123	1750
B4-48-15d	34.2	83	200	4200
B5-42-31c	52.4	128	243	530
B5-43-3b	61.5	151	170	890
B5-43-24d	75.2	184	318	580
B5-45-15c	49.7	122	137	890
B5-47-22b	98.4	241	165	1460
B5-47-26ca	72.9	179	176	1020
B5-47-32d	122.0	300	187	1600
B5-48-34d	9.3	22	136	160
C1-44-10a	20.7	50	161	310
C1-44-27bbb	27.0	66	149	440
C1-44-28	46.1	113	192	590
C1-45-2c	37.2	91	111	820
C1-45-3d	23.5	57	97	590

Table B-3. Continued

Well Location Number	Specific Capacity (gpm/ft)	Transmissibility (1000 gpd/ft)	Saturated Thickness (feet)	Hydraulic Conductivity (gpd/ft^2)
		Yuma County (Continued)		
C1-45-13a	27.7	57	146	390
C2-45-10a	48.3	118	97	1200
C2-45-10b	50.5	123	84	1450
C4-44-5d	32.6	80	98	820
C4-44-27b	11.8	28	126	220
C4-44-28b	11.9	28	100	280
C4-45-33a	50.6	124	127	980
C4-45-35bb	87.5	215	107	2000
C5-44-5ab	29.0	71	102	700
C5-47-4b	39.3	96	74	1300

APPENDIX C

Fortran IV Computer Program

```
10/26/66 *FORTRAN
                PROGRAM HPLAIN
000002          DIMENSION FK(600),DELY(600),DELX(600),H(600),Z(600),ST(600),TR(600
               1),A(600),B(600),C(600),D(600),QA(600),W(600),Q(600)
000002          READ (5,1) I,J
000011        1 FORMAT (2I5)
000011          IJ = I*J
000014       60 READ (5,61)(H(K),K=1,IJ)
000026       61 FORMAT (17F4.0)
000026       62 READ (5,61)(Z(K),K=1,IJ)
000040       63 READ (5,64)(DELX(K),K=1,IJ)
000052       64 FORMAT (17F4.1)
000052       65 READ (5,64)(DELY(K),K=1,IJ)
000064       66 READ (5,61)(FK(K),K=1,IJ)
000076          DO 67 K=1,IJ
000100          DELX(K)=DELX(K)*5280.0
000102       67 DELY(K)=DELY(K)*5280.0
000106          WRITE (6,6)
000111        6 FORMAT (1H1,42X,36HDELTA Y MAP, SPACING IN Y DIRECTION./)
000111          DO 7 K=1,IJ,J
000113        7 WRITE (6,8) DELY(K+16),DELY(K+15),DELY(K+14),DELY(K+13),
               1DELY(K+12),DELY(K+11),DELY(K+10),DELY(K+9),DELY(K+8),
               2DELY(K+7),DELY(K+6),DELY(K+5),DELY(K+4),DELY(K+3),
               3DELY(K+2),DELY(K+1),DELY(K), K
000165        8 FORMAT (1H0, 17F7.0, I13)
000165          WRITE (6,9)
000170        9 FORMAT (1H1, 42X, 36HDELTA X MAP, SPACING IN X DIRECTION./)
000170          DO 10 K=1,IJ,J
000172       10 WRITE (6,8) DELX(K+16),DELX(K+15),DELX(K+14),DELX(K+13),
               1DELX(K+12),DELX(K+11),DELX(K+10),DELX(K+9),DELX(K+8),
               2DELX(K+7),DELX(K+6),DELX(K+5),DELX(K+4),DELX(K+3),
               3DELX(K+2),DELX(K+1),DELX(K), K
000244          WRITE (6,11)
000247       11 FORMAT (1H1,47X,26HWATER TABLE ELEVATION MAP./)
000247          DO 12 K=1,IJ,J
000251       12 WRITE (6,8) H(K+16),H(K+15),H(K+14),H(K+13),H(K+12),H(K+11),
               1H(K+10),H(K+9),H(K+8),H(K+7),H(K+6),H(K+5),H(K+4),H(K+3),
               2H(K+2),H(K+1),H(K), K
000323          WRITE (6,13)
000326       13 FORMAT (1H1,49X,22HBEDROCK ELEVATION MAP./)
000326          DO 14 K=1,IJ,J
000330       14 WRITE (6,8) Z(K+16),Z(K+15),Z(K+14),Z(K+13),Z(K+12),Z(K+11),
               1Z(K+10),Z(K+9),Z(K+8),Z(K+7),Z(K+6),Z(K+5),Z(K+4),Z(K+3),
               2Z(K+2),Z(K+1),Z(K), K
000402          WRITE (6,15)
000405       15 FORMAT (1H1,47X,27HHYDRAULIC CONDUCTIVITY MAP./)
000405          DO 16 K=1,IJ,J
000407       16 WRITE (6,8) FK(K+16),FK(K+15),FK(K+14),FK(K+13),FK(K+12),FK(K+11),
               1FK(K+10),FK(K+9),FK(K+8),FK(K+7),FK(K+6),FK(K+5),FK(K+4),FK(K+3),
               2FK(K+2),FK(K+1),FK(K), K
000461          DO 17 K=1,IJ
000462          ST(K)=H(K)-Z(K)
000464       17 TR(K) = ST(K)*FK(K)
000471          JJ=IJ-32
000473          DO 18 K=19,JJ,J
000474          LL=K+14
000476          DO 18 L=K,LL
000477          IF(TR(L).GT.0.0.AND.TR(L+1).GT.0.0) GO TO 40
000507          A(L)=0.0
000510          GO TO 42
000510       40 A(L)=((TR(L)+TR(L+1))*(H(L+1)-H(L))*(DELY(L+1)))/(DELX(L)+DELX(
```

Hydraulic conductivities used in runs three and four.

```
                1L+1))
 000522     42 IF(TR(L).GT.0.0.AND.TR(L-1).GT.0.0) GO TO 44
 000533        H(L)=0.0
 000534        GO TO 46
 000534     44 H(L)=((TR(L)+TR(L-1))*(H(L)-H(L-1))*(DELY(L)))/(DELX(L)+DELX(
               1L-1))
 000546     46 IF(TR(L).GT.0.0.AND.TR(L-17).GT.0.0) GO TO 48
 000557        C(L)=0.0
 000560        GO TO 50
 000560     48 C(L)=((TR(L)+TR(L-17))*(H(L)-H(L-17))*(DELX(L-17)))/(DELY(L)+
               1DELY(L-17))
 000572     50 IF(TR(L).GT.0.0.AND.TR(L+17).GT.0.0) GO TO 52
 000603        D(L)=0.0
 000604        GO TO 54
 000604     52 D(L)=((TR(L)+TR(L+17))*(H(L+17)-H(L))*(DELX(L)))/(DELY(L)+
               1DELY(L+17))
 000616     54 QA(L)=(B(L)+C(L)-A(L)-D(L))*365.0*0.134
 000624        W(L)=(QA(L)/(DELY(L)*DELX(L)))*12.0
 000630     18 Q(L)=QA(L)/43560.0
 000636        WRITE (6,19)
 000641     19 FORMAT (1H1,48X,24HSATURATED THICKNESS MAP./)
 000641        DO 20 K=1,IJ,J
 000643     20 WRITE (6,8) ST(K+16),ST(K+15),ST(K+14),ST(K+13),ST(K+12),ST(K+11),
               1ST(K+10),ST(K+9),ST(K+8),ST(K+7),ST(K+6),ST(K+5),ST(K+4),ST(K+3),
               2ST(K+2),ST(K+1),ST(K), K
 000715        WRITE (6,21)
 000720     21 FORMAT (1H1,40X,41HVOLUME OF RECHARGE IN ACRE FEET PER YEAR./)
 000720        DO 22 K=19,JJ,J
 000722     22 WRITE (6,23) Q(K+14),Q(K+13),Q(K+12),Q(K+11),Q(K+10),Q(K+9),
               1Q(K+8),Q(K+7),Q(K+6),Q(K+5),Q(K+4),Q(K+3),Q(K+2),Q(K+1),Q(K), K
 000770     23 FORMAT (1H0, 15F8.2, I6)
 000770        WRITE (6,24)
 000773     24 FORMAT (1H1,42X,36HRATE OF RECHARGE IN INCHES PER YEAR./)
 000773        DO 25 K=19,JJ,J
 000775     25 WRITE (6,26) W(K+14),W(K+13),W(K+12),W(K+11),W(K+10),W(K+9),
               1W(K+8),W(K+7),W(K+6),W(K+5),W(K+4),W(K+3),W(K+2),W(K+1),W(K), K
 001043     26 FORMAT (1H0, 15F8.4, I6)
 001043        SUMQ=0.0
 001044        DO 27 K=19,JJ,J
 001045        LL=K+14
 001047        DO 27 L=K,LL
 001050     27 SUMQ=SUMQ+Q(L)
 001057        SUMO=0.0
 001060        DO 28 K=19,JJ,J
 001061     28 SUMO=SUMO+((B(K)*365.0*0.134)/43560.0)
 001067        DO 70 K=19,33
 001071     70 SUMO=SUMO+((C(K)*365.0*0.134)/43560.0)
 001077        LP=JJ+14
 001101        DO 71 K=JJ,LP
 001102     71 SUMO=SUMO-((D(K)*365.0*0.134)/43560.0)
 001110        JAK=IJ-18
 001112        DO 100 K=33,JAK,J
 001114    100 SUMO=SUMO-((A(K)*365.0*0.134)/43560.0)
 001122        WRITE (6,29)
 001125     29 FORMAT (1H1,7X,32HTHE TOTAL VOLUME OF RECHARGE IS./)
 001125        WRITE (6,30) SUMQ
 001132     30 FORMAT (1H0,15X,F15.8)
 001132        WRITE (6,31)
 001135     31 FORMAT (1H1,7X,31HTHE TOTAL VOLUME OF OUTFLOW IS./)
 001135        WRITE (6,32) SUMO
 001142     32 FORMAT (1H0,15X,F15.8)
 001142        END

 LENGTH OF ROUTINE  HPLAIN
 021663
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Hydraulic conductivities used in run five.

SYMBOLS USED IN FORTRAN IV PROGRAM

Symbol	Description
FK	Hydraulic conductivity of aquifer
H	Water table elevation
Z	Bedrock elevation
ST	Saturated thickness
TR	Transmissibility
DELY	Dimension of grid (y-direction)
DELX	Dimension of grid (x-direction)
I	Number of grids in model (y-direction)
J	Number of grids in model (x-direction)
IJ	Total number of grids in model
A,B,C,D	Flow across each grid face,respectively
QA	Volume of recharge in cubic feet per year
Q	Volume of recharge in acre-feet per year
W	Recharge rate in inches per year
SUMQ	Total volume of recharge for area in acre-feet per year
SUMD	Total volume of underflow from area in acre-feet per year
K,JJ,LL	Grid locations used in computations

APPENDIX D

INPUT DATA FOR COMPUTER

DELTA X MAP, SPACING IN X DIRECTION.

31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	14256	13200	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	2640	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	23232	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	15840	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	15840	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	7920	26400	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	10560	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	7920	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	26400	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	21120	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	3696	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	13200	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	15840	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	11616	27456	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	10032	24288	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	6336	29040	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	23760	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	24816	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	20064	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	8448	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	15840	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	17952	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	15840	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	13200	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	18480	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	7920	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	20064	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	19536	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	10032	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680

DELTA Y MAP. SPACING IN Y DIRECTION.

31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	13200	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	3696	5280	10560	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	2640	12672	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	21120	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	15840	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	7920	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	23760	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	15840	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	21120	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	14784	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	11616	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	10032	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	6336	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	22704	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	19536	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31630	20064	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	3696	4752	10560	17952	26400	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	10560	23760	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	11088	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680
31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680	31680

WATER TABLE ELEVATION MAP.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3400	3360
0	0	0	0	0	0	0	0	0	0	0	0	3612	3531	3474	3420	3380
0	0	0	0	0	0	0	0	0	0	3787	3751	3656	3568	3494	3445	3390
0	0	0	0	0	0	0	0	0	4015	3886	3793	3707	3611	3527	3464	3405
0	0	0	0	0	0	0	0	4174	4079	3945	3849	3745	3646	3558	3508	3440
0	0	0	0	0	0	0	4329	4222	4074	3955	3859	3749	3641	3586	3547	3465
0	0	0	0	0	0	4412	4360	4253	4089	3932	3775	3689	3637	3608	3562	3480
0	0	0	0	0	0	4405	4359	4231	4062	3858	3733	3688	3664	3635	3588	3505
0	0	0	0	0	0	4451	4296	4146	3964	3825	3768	3727	3700	3657	3603	3525
0	0	0	0	0	4554	4485	4283	4088	3946	3883	3825	3774	3731	3675	3608	3520
0	0	0	0	0	4593	4468	4239	4058	3985	3941	3881	3808	3728	3649	3570	3490
0	0	0	0	4672	4641	4473	4252	4094	4035	3984	3922	3833	3694	3598	3516	3440
0	0	0	0	4735	4655	4526	4284	4162	4096	4044	3978	3878	3768	3662	3527	3430
0	0	0	0	4780	4655	4501	4348	4246	4161	4089	4022	3940	3803	3610	3489	3390
0	0	0	0	4866	4779	4626	4459	4323	4251	4176	4057	3938	3756	3654	3575	3470
0	0	0	5005	4963	4840	4704	4560	4440	4313	4180	4049	3919	3803	3703	3584	3470
0	0	5234	5146	5009	4864	4727	4586	4440	4294	4175	4072	3922	3797	3686	3599	3500
0	5383	5316	5189	5036	4863	4738	4566	4413	4282	4176	4076	3946	3852	3775	3714	3650
0	5595	5452	5280	5089	4910	4786	4647	4456	4294	4182	4097	4019	3938	3862	3792	3715
0	5619	5510	5431	5222	5041	4896	4756	4563	4389	4260	4147	4075	4013	3934	3852	3760
0	0	0	5452	5270	5125	4951	4795	4622	4483	4351	4238	4141	4066	3989	3903	3815
0	0	0	0	5239	5113	4972	4852	4681	4532	4412	4301	4186	4102	4025	3942	3860
0	0	0	0	0	5127	5078	4869	4733	4571	4449	4344	4223	4133	4050	3948	3850
0	0	0	0	0	0	5046	4873	4725	4575	4474	4397	4296	4174	4030	3894	3800
0	0	0	0	0	0	0	0	0	0	0	4420	4279	4124	3895	3780	3775
0	0	0	0	0	0	0	0	0	0	0	4334	4158	4010	3826	3752	3700
0	0	0	0	0	0	0	0	0	0	0	4251	4148	3988	3870	3771	3710
0	0	0	0	0	0	0	0	0	0	0	0	4147	4052	3922	3782	3720
0	0	0	0	0	0	0	0	0	0	0	0	4148	4099	3995	3868	3800
0	0	0	0	0	0	0	0	0	0	0	0	0	4085	3993	3881	3875
0	0	0	0	0	0	0	0	0	0	0	0	0	4042	3929	3822	3810
0	0	0	0	0	0	0	0	0	0	0	0	0	3880	3810	3700	3745
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

BEDROCK ELEVATION MAP.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3250	3215
0	0	0	0	0	0	0	0	0	0	0	0	3575	3496	3361	3284	3245
0	0	0	0	0	0	0	0	0	0	3775	3701	3611	3517	3382	3307	3265
0	0	0	0	0	0	0	0	0	3886	3833	3721	3629	3526	3412	3322	3290
0	0	0	0	0	0	0	0	4170	4073	3897	3772	3682	3562	3466	3379	3310
0	0	0	0	0	0	0	4325	4219	4070	3919	3841	3742	3546	3432	3343	3240
0	0	0	0	0	0	4410	4359	4250	4080	3930	3759	3640	3478	3356	3273	3180
0	0	0	0	0	0	4400	4350	4225	4036	3834	3621	3486	3429	3336	3258	3170
0	0	0	0	0	0	4440	4289	4134	3936	3693	3596	3433	3383	3332	3263	3205
0	0	0	0	0	4540	4471	4281	4061	3866	3754	3616	3499	3385	3352	3289	3260
0	0	0	0	0	4580	4441	4206	3998	3829	3706	3577	3528	3474	3424	3388	3340
0	0	0	0	4660	4635	4436	4234	4035	3916	3841	3721	3611	3562	3538	3500	3435
0	0	0	0	4720	4640	4510	4270	4128	3959	3949	3846	3695	3636	3514	3480	3415
0	0	0	0	4765	4623	4479	4330	4185	4088	3965	3863	3816	3758	3607	3470	3375
0	0	0	0	4858	4775	4612	4385	4269	4209	4134	4013	3892	3750	3643	3540	3410
0	0	0	5000	4960	4828	4686	4532	4404	4252	4068	3918	3810	3705	3604	3514	3435
0	0	5219	5119	4982	4835	4692	4544	4343	4195	4074	3924	3806	3715	3606	3531	3425
0	5373	5296	5152	5019	4851	4709	4529	4359	4254	4143	3983	3855	3746	3676	3594	3515
0	5576	5445	5233	5062	4901	4784	4639	4450	4290	4180	4015	3897	3833	3747	3647	3550
0	5610	5486	5420	5189	5029	4884	4753	4552	4378	4254	4089	4008	3898	3775	3684	3625
0	0	0	5412	5235	5103	4940	4774	4619	4470	4316	4166	4052	3920	3828	3732	3680
0	0	0	0	5199	5110	4970	4850	4662	4505	4367	4219	4090	3986	3871	3803	3725
0	0	0	0	0	5120	5074	4860	4732	4570	4372	4268	4166	4035	3930	3894	3775
0	0	0	0	0	0	5030	4860	4719	4552	4448	4384	4292	4149	3991	3871	3780
0	0	0	0	0	0	0	0	0	0	0	4396	4242	4059	3874	3696	3700
0	0	0	0	0	0	0	0	0	0	0	4325	4136	3960	3798	3672	3600
0	0	0	0	0	0	0	0	0	0	0	4242	4132	3978	3856	3745	3680
0	0	0	0	0	0	0	0	0	0	0	0	4132	4040	3909	3759	3700
0	0	0	0	0	0	0	0	0	0	0	0	4125	4084	3986	3859	3780
0	0	0	0	0	0	0	0	0	0	0	0	0	4084	3972	3865	3850
0	0	0	0	0	0	0	0	0	0	0	0	0	4035	3920	3795	3780
0	0	0	0	0	0	0	0	0	0	0	0	0	3870	3800	3675	3720
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

SATURATED THICKNESS MAP.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	150	145
0	0	0	0	0	0	0	0	0	0	0	0	37	35	113	136	135
0	0	0	0	0	0	0	0	0	0	12	50	45	51	112	138	125
0	0	0	0	0	0	0	0	0	129	53	72	78	85	115	142	115
0	0	0	0	0	0	0	0	4	6	48	77	63	84	92	129	130
0	0	0	0	0	0	0	4	3	4	36	18	7	95	154	204	225
0	0	0	0	0	0	2	1	3	9	2	16	49	159	252	289	300
0	0	0	0	0	0	5	9	6	26	24	112	202	235	299	330	335
0	0	0	0	0	0	11	7	12	28	132	172	294	317	325	340	320
0	0	0	0	0	14	14	2	27	80	129	209	275	346	323	319	260
0	0	0	0	0	13	27	33	60	156	235	304	280	254	225	182	150
0	0	0	0	12	6	37	18	59	119	143	201	222	132	60	16	5
0	0	0	0	15	15	16	14	34	137	95	132	183	132	148	47	15
0	0	0	0	15	32	22	18	61	73	124	159	124	45	3	19	15
0	0	0	0	8	4	14	74	54	42	42	44	46	6	11	35	60
0	0	0	5	3	12	18	28	36	61	112	131	109	98	99	70	35
0	0	15	27	27	29	35	42	97	99	101	148	116	82	80	68	75
0	10	20	37	17	12	29	37	54	28	33	93	91	106	99	120	135
0	19	7	47	27	9	2	8	6	4	2	82	122	105	115	145	165
0	9	24	11	33	12	12	3	11	11	6	58	67	115	159	168	135
0	0	0	40	35	22	11	21	3	13	35	72	89	146	161	171	135
0	0	0	0	40	3	2	2	19	27	45	82	96	116	154	139	135
0	0	0	0	0	7	4	9	1	1	77	76	57	98	120	54	75
0	0	0	0	0	0	16	13	6	23	26	13	4	25	39	23	20
0	0	0	0	0	0	0	0	0	0	0	24	37	65	21	84	75
0	0	0	0	0	0	0	0	0	0	0	9	22	50	28	80	100
0	0	0	0	0	0	0	0	0	0	0	9	16	10	14	26	30
0	0	0	0	0	0	0	0	0	0	0	0	15	12	13	23	20
0	0	0	0	0	0	0	0	0	0	0	0	23	15	9	9	20
0	0	0	0	0	0	0	0	0	0	0	0	0	1	21	16	25
0	0	0	0	0	0	0	0	0	0	0	0	0	7	9	27	30
0	0	0	0	0	0	0	0	0	0	0	0	0	10	10	25	25
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Saturated thicknesses used in runs one, three and five.

SATURATED THICKNESS MAP.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	150	145
0	0	0	0	0	0	0	0	0	0	0	0	70	80	113	136	135
0	0	0	0	0	0	0	0	0	0	20	50	75	85	112	138	125
0	0	0	0	0	0	0	0	0	40	43	72	78	85	115	142	115
0	0	0	0	0	0	0	0	20	30	70	50	40	84	130	150	130
0	0	0	0	0	0	0	10	20	30	36	25	25	95	154	204	225
0	0	0	0	0	0	10	15	25	35	40	45	49	159	252	289	300
0	0	0	0	0	0	10	20	30	40	50	140	202	235	299	330	335
0	0	0	0	0	0	11	20	30	40	132	172	294	317	325	340	320
0	0	0	0	0	14	20	30	40	100	160	209	290	346	323	319	260
0	0	0	0	0	20	30	40	60	156	235	304	280	254	225	182	150
0	0	0	0	12	30	40	50	75	119	143	201	222	132	60	16	10
0	0	0	0	10	20	30	40	50	137	110	132	183	160	130	25	15
0	0	0	0	20	40	35	30	61	73	124	159	124	45	20	19	15
0	0	0	0	20	30	40	74	60	50	50	60	55	10	20	35	60
0	0	0	10	10	20	30	35	40	61	112	131	109	110	80	50	35
0	0	10	15	20	29	35	42	80	90	101	148	116	72	70	90	75
0	10	15	20	25	30	35	45	54	35	40	93	91	106	99	120	135
0	19	25	30	25	20	25	30	35	40	45	82	122	105	125	145	165
0	20	30	35	40	35	35	30	35	35	30	58	67	115	159	168	135
0	0	0	40	63	35	30	35	25	35	45	72	89	146	161	171	135
0	0	0	0	40	35	30	30	35	40	45	90	110	120	154	139	135
0	0	0	0	0	20	25	35	30	35	85	76	57	98	120	70	75
0	0	0	0	0	0	16	13	10	23	26	13	10	25	39	23	20
0	0	0	0	0	0	0	0	0	0	0	24	37	65	35	84	75
0	0	0	0	0	0	0	0	0	0	0	9	22	40	50	110	120
0	0	0	0	0	0	0	0	0	0	0	9	16	10	25	26	30
0	0	0	0	0	0	0	0	0	0	0	0	15	12	13	23	20
0	0	0	0	0	0	0	0	0	0	0	0	10	15	9	9	20
0	0	0	0	0	0	0	0	0	0	0	0	0	10	21	16	25
0	0	0	0	0	0	0	0	0	0	0	0	0	7	9	27	30
0	0	0	0	0	0	0	0	0	0	0	0	0	10	30	60	25
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Saturated thickness used in runs two and four.

HYDRAULIC CONDUCTIVITY MAP.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	500	500	375	300	225
-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	700	750	750	600	500	375	400
-0	-0	-0	-0	-0	-0	-0	-0	-0	200	500	1000	875	800	900	850	500
-0	-0	-0	-0	-0	-0	-0	-0	150	200	375	600	500	700	1100	1300	1000
-0	-0	-0	-0	-0	-0	-0	100	150	200	375	500	500	1100	2000	1250	750
-0	-0	-0	-0	-0	-0	100	100	150	200	375	625	1250	1750	1750	1000	900
-0	-0	-0	-0	-0	-0	100	100	150	200	625	900	1250	1000	1500	900	800
-0	-0	-0	-0	-0	-0	100	150	200	500	900	900	1000	900	1300	750	750
-0	-0	-0	-0	-0	350	300	250	750	1100	1100	375	750	875	1000	625	600
-0	-0	-0	-0	-0	400	500	500	1000	1100	400	400	875	500	500	375	375
-0	-0	-0	-0	100	150	200	500	900	800	625	800	600	500	200	200	200
-0	-0	-0	-0	100	150	200	600	500	625	750	700	600	375	250	200	200
-0	-0	-0	-0	100	150	200	250	375	500	625	750	800	800	600	150	200
-0	-0	-0	-0	100	100	150	150	150	300	250	400	400	250	200	200	200
-0	-0	-0	100	100	150	180	200	200	300	500	375	500	600	300	300	375
-0	-0	100	200	150	150	200	100	200	400	700	500	625	1000	800	750	250
100	100	50	250	300	400	300	300	375	600	400	400	600	500	450	300	250
-0	100	150	100	250	400	500	600	500	600	875	600	500	400	250	300	375
-0	200	500	400	300	600	750	800	600	500	700	700	900	400	250	250	375
-0	-0	-0	500	500	600	500	450	500	600	700	300	200	300	250	300	375
0	0	0	0	100	100	150	250	200	150	200	200	250	250	350	300	200
-0	-0	-0	-0	-0	150	200	250	300	300	300	200	350	500	250	350	250
0	0	0	0	0	0	150	200	250	300	250	200	375	375	250	200	200
-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	750	900	900	875	375	250
-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	625	900	1500	1100	625	500
0	0	0	0	0	0	0	0	0	0	0	250	500	500	450	400	400
-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	200	250	200	250	450
0	0	0	0	0	0	0	0	0	0	0	0	100	150	200	250	300
-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	100	150	150	300
0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	250	250
-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	100	200	300	400
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Hydraulic conductivities used in runs three and four.

HYDRAULIC CONDUCTIVITY MAP.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
0	0	0	0	0	0	0	0	0	0	0	0	875	500	375	200	225
0	0	0	0	0	0	0	0	0	0	1300	1100	850	400	400	375	400
0	0	0	0	0	0	0	0	0	200	500	1000	875	500	700	750	400
0	0	0	0	0	0	0	0	150	200	375	600	500	700	1250	1300	875
0	0	0	0	0	0	0	100	150	200	375	500	500	1300	2500	1250	750
0	0	0	0	0	0	100	100	150	200	375	625	1250	1750	1750	875	625
0	0	0	0	0	0	100	100	150	200	625	1000	1250	1000	1500	750	500
0	0	0	0	0	0	100	150	200	500	1500	900	1100	1300	1600	750	500
0	0	0	0	0	350	300	250	750	1400	1100	375	750	875	1000	625	450
0	0	0	0	0	400	500	500	1400	1100	400	400	875	500	375	375	375
0	0	0	0	100	150	200	500	900	800	625	800	900	500	200	200	200
0	0	0	0	100	150	200	500	625	625	750	800	900	375	250	200	200
0	0	0	0	100	150	200	250	375	400	625	750	875	800	500	150	200
0	0	0	0	100	100	150	150	200	200	250	400	400	250	200	150	200
0	0	0	100	100	150	150	200	200	300	500	375	500	800	250	250	375
0	0	100	100	150	150	200	200	300	750	1100	400	625	1000	800	750	250
0	100	100	50	200	150	200	200	300	375	500	400	400	400	200	200	250
0	100	150	150	200	250	375	450	500	750	875	600	400	625	150	250	375
0	200	750	800	1000	1250	1300	1700	1500	1000	625	1000	900	300	250	250	300
0	0	0	1100	750	600	500	450	400	500	800	400	350	300	250	400	375
0	0	0	0	100	100	150	150	200	150	200	200	250	250	350	300	200
0	0	0	0	0	150	200	200	250	250	300	200	350	500	250	350	250
0	0	0	0	0	0	150	200	250	300	250	200	375	375	250	200	200
0	0	0	0	0	0	0	0	0	0	0	750	1100	1100	875	375	250
0	0	0	0	0	0	0	0	0	0	0	625	1100	1500	1100	625	500
0	0	0	0	0	0	0	0	0	0	0	250	500	500	450	400	400
0	0	0	0	0	0	0	0	0	0	0	0	200	250	300	375	375
0	0	0	0	0	0	0	0	0	0	0	0	100	150	200	250	300
0	0	0	0	0	0	0	0	0	0	0	0	0	100	150	200	200
0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	250	250
0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	300	300
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Hydraulic conductivities used in run five.

APPENDIX E

COMPUTER RESULTS

First Run

RATE OF RECHARGE IN INCHES PER YEAR.

0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.4408
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-4.8431	-5.0853	-2.4249	1.4413
0.	0.	0.	0.	0.	0.	0.	0.	0.	-17.6970	-1.9260	.2799	.0074	-.1051	.7118
0.	0.	0.	0.	0.	0.	0.	0.	4.0652	-2.1675	.0477	.6962	.2062	.0884	-1.4505
0.	0.	0.	0.	0.	0.	0.	.3112	2.7095	1.8784	1.8919	.9638	1.4720	-.9330	1.0451
0.	0.	0.	0.	0.	0.	.3502	.0143	.6612	.4063	.2608	2.2629	.5322	-.3377	5.0951
0.	0.	0.	0.	0.	.2935	.1096	.3583	.1709	.4084	1.0043	.4024	-2.0053	1.3346	2.7964
0.	0.	0.	0.	0.	.2337	.4172	.9161	1.7370	1.9052	-3.4564	-4.4164	-.8051	2.8939	6.0204
0.	0.	0.	0.	0.	.2487	.1072	.9811	2.2070	-4.7891	-1.9004	-1.9021	1.9820	1.9705	4.2431
0.	0.	0.	0.	1.9898	.5705	.7310	1.8791	-2.5040	.0880	-.3670	1.8801	6.2937	5.9797	5.7533
0.	0.	0.	0.	1.1427	1.3814	.1692	-1.5127	-.5911	3.8001	3.4810	1.2179	1.2249	-1.0265	-2.6493
0.	0.	0.	-.7538	1.4022	.4641	-.0665	-.7040	.1889	1.8892	3.4926	1.1183	-12.0563	-7.6114	-3.0450
0.	0.	0.	9.2652	-.0010	1.3342	-.4615	.7173	.5215	1.3956	4.2501	.4449	1.5910	3.3848	-3.2519
0.	0.	0.	3.4792	-.8443	-1.4532	-1.1833	.4670	1.1582	.0361	1.8900	3.6722	-1.0068	-2.8642	-1.2255
0.	0.	0.	.6396	.9218	2.6506	.4983	-2.3132	.6371	3.3755	1.7069	.2583	-2.8538	-.5462	1.9082
0.	0.	-3.1402	.2444	.3982	.7262	1.8128	2.8830	3.8233	1.9966	-1.6060	-2.0542	.3147	1.6809	-1.7611
0.	1.4788	1.6177	-.0470	.3180	.4949	2.4398	2.3566	-1.2035	.1232	3.6883	-3.6383	-3.4568	-4.5767	-3.4722
-6.3163	1.0052	-.9172	-.8342	-.1749	1.0345	-.5044	-1.8698	-1.1753	1.1514	1.6362	-3.0377	-2.0030	-.9718	.7433
1.4473	1.2557	.7093	-2.5350	-1.3008	-.0049	.7089	-.0557	-.3780	1.1506	1.0353	1.4141	-.0040	.0703	1.4369
.9224	.4872	2.5712	.6966	-.9066	-.2100	.1644	.4027	-.4687	.3672	-.5820	.4888	2.4763	1.3867	.4852
0.	0.	3.0027	1.1325	.1203	.0460	-.2309	-.4561	.8378	.8754	1.0746	.7563	1.9795	2.1235	.6795
0.	0.	0.	.6419	-.7482	-.1118	.8049	.6692	.5044	1.1067	1.7640	.0004	1.0985	1.5241	1.7259
0.	0.	0.	0.	.7063	.6934	-.2515	.0167	1.9313	1.5687	.4001	-.1777	1.0900	1.8405	.0399
0.	0.	0.	0.	0.	-1.1920	-.2605	.5384	.4954	.5718	.5855	1.3249	2.8929	.7861	.6937
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	4.5075	2.1424	2.3746	-2.3450	-3.5895
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.4379	-.6420	-1.5383	-2.2026	-.9955
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.3175	.0334	-.7709	.2988	.1769
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0347	-.0061	.3018	-.8718
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.3407	.6935	.3953	.4016
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.6713	.9763	-.1969
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.1133	.3718	.1214
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.2571	-.1022	-2.3651

Run made with constant hydraulic conductivity of 650 gpd/ft^2 and saturated thickness from page 123.

Second Run

RATE OF RECHARGE IN INCHES PER YEAR.

0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.4408
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-6.7732	-13.8031	-2.7691	1.4413
0.	0.	0.	0.	0.	0.	0.	0.	0.	-15.6507	-1.4054	1.2675	-.4659	-.5833	.7118
0.	0.	0.	0.	0.	0.	0.	0.	1.6692	-.6174	.5118	1.1531	.4841	-.1355	-1.6262
0.	0.	0.	0.	0.	0.	0.	1.4343	2.7513	.7084	.7454	1.3570	2.5403	-.9862	.7758
0.	0.	0.	0.	0.	0.	1.4796	.5711	-.1560	.1539	1.1924	2.3111	.1627	-.1355	5.2508
0.	0.	0.	0.	0.	2.0374	1.0231	1.4779	.9379	1.2320	-.6407	-.2769	-2.0053	1.3346	2.7964
0.	0.	0.	0.	0.	.7354	1.3947	1.7714	2.3463	.9001	-5.1411	-4.6559	-.8051	2.8939	6.0204
0.	0.	0.	0.	0.	.5749	.6134	.7983	1.1115	-5.6110	-1.7142	-2.0361	1.9820	1.9705	4.2431
0.	0.	0.	0.	2.4000	1.8727	1.1366	.9826	-3.0417	-.1809	-.5633	1.8943	6.1711	5.9797	5.7533
0.	0.	0.	0.	1.1896	1.5227	-.4143	-1.9371	-.4428	4.1418	3.4810	1.3148	1.2249	-1.0265	-2.6493
0.	0.	0.	-.3243	2.3436	.9066	-.3516	-2.2701	.0095	1.7181	3.4926	1.1183	-12.4501	-7.3924	-2.9267
0.	0.	0.	8.7987	.5420	3.0077	-1.4369	.1023	.4691	1.4783	4.0620	1.0303	1.4146	1.9282	-2.8361
0.	0.	0.	4.2478	-1.4669	-2.3957	-1.4686	.4020	1.0214	.0321	1.7835	3.6756	-.1612	-3.3044	-1.4576
0.	0.	0.	2.1965	2.0032	2.3269	-.0530	-2.4113	.7161	3.8164	1.8603	.1716	-3.2301	-.3526	1.8073
0.	0.	-1.9678	.6143	.8972	1.2401	1.6435	2.9511	3.7885	2.0027	-1.6303	-1.8221	.0623	.7450	-1.3523
0.	.5687	1.2097	.3151	.5508	.5348	2.0331	2.0196	-.6576	.3254	3.6883	-3.8759	-3.5389	-3.6934	-3.7318
-6.8865	.0078	-.2185	.2271	-.7220	.6700	-1.2217	-2.0779	-1.1611	.9467	1.5032	-3.0377	-2.1076	-1.3063	1.2242
2.1343	.7727	-.8021	-1.6051	-1.3931	-.3146	.8182	-.7466	-1.6830	-.7726	.3406	1.4141	.1405	.0874	1.3038
1.3786	1.1085	3.3798	1.2439	-.3991	.3754	1.4160	.6814	-.6177	.1110	-1.0974	.4888	2.4763	1.5235	.4852
0.	0.	.6005	0.	3.4268	.2176	-.1768	-.3877	.9741	.7595	.7640	.6365	1.9521	2.1235	.6795
0.	0.	0.	3.4725	.0430	-1.2420	1.2382	.0418	-.0428	1.0387	2.1064	-.1718	.8735	1.4656	1.7077
0.	0.	0.	0.	3.0302	3.2763	-.5567	1.0548	1.2808	.7693	.3058	-.1625	1.1136	2.1507	.2102
0.	0.	0.	0.	0.	-5.1135	.0812	.3760	.4865	.6216	.7007	1.4515	2.7538	1.1453	.5295
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	4.5075	2.1230	2.7673	-2.5354	-3.7358
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.4379	-.9233	-.6626	-2.6390	-1.5007
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.3175	.0334	-.4824	.4263	.0783
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0384	-.0061	.4105	-.8718
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.5400	.8376	.3953	.4016
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0905	.9088	-.1969
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0014	.8242	.9330
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.5334	.1912	-4.6259

Run made with constant hydraulic conductivity of 650 gpd/ft^2 and saturated thickness from page 124.

Third Run

RATE OF RECHARGE IN INCHES PER YEAR.

0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-.4433
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-7.8914	-5.4159	-1.9000	.2023
0.	0.	0.	0.	0.	0.	0.	0.	0.	-10.5349	-3.2658	-.3828	-.5963	-.4718	-.0490
0.	0.	0.	0.	0.	0.	0.	0.	2.1945	.5808	1.1409	.0618	-.3336	-.1394	-3.4625
0.	0.	0.	0.	0.	0.	0.	.0940	1.1665	1.7254	2.3348	1.3186	3.1613	-2.6605	.1705
0.	0.	0.	0.	0.	0.	.0664	.0203	.4292	.3219	.3985	4.7854	4.3705	-2.0993	5.4546
0.	0.	0.	0.	0.	.0451	.0230	.1060	.0758	.6214	2.3298	2.3261	-3.5850	1.5250	-.3506
0.	0.	0.	0.	0.	.0360	.0819	.3074	1.3984	5.1514	-4.0745	-8.0341	-.3849	4.5615	2.1068
0.	0.	0.	0.	0.	-.0201	.0726	1.0235	7.8567	-10.5561	-1.3030	-.6378	6.2448	2.3108	-1.2323
0.	0.	0.	0.	.9677	.2400	1.1183	4.8384	-4.7112	.8223	1.1206	4.9481	10.7032	7.5214	1.5449
0.	0.	0.	0.	.8506	1.1446	2.9945	-2.2207	-2.7053	2.0605	3.9316	2.1113	-2.2774	-3.0170	-2.4587
0.	0.	0.	-.1111	.4555	.5183	1.7564	-.3457	.8694	1.2705	3.8721	-.1256	-13.0315	-4.1792	-1.4398
0.	0.	0.	1.6948	.0614	.7360	.2205	1.4493	1.3656	1.8884	5.9600	-1.1707	-2.5844	.6529	-1.3033
0.	0.	0.	.7334	-.0993	-.3092	.1272	.8034	2.1449	1.3268	3.0985	5.3548	-2.2819	-2.5953	-.3244
0.	0.	0.	.0984	.2204	.6608	.2394	-.3243	.5157	2.7241	1.8315	.1372	-2.5621	-.2768	.5013
0.	0.	-.4831	.0461	.0941	.2148	.4864	1.1136	2.9407	1.4594	-.9723	.0524	-.1122	-.7187	-.6898
0.	.2275	.3520	.0419	.1435	.2043	1.1648	3.1688	1.8205	-1.6020	1.2632	-.7822	-3.1904	-4.4351	-3.1279
-.9717	.0625	-.1073	-.0494	-.0427	.3353	.0390	-.6321	-.5306	.7386	.8097	-1.6862	-1.4813	.6191	1.4473
.2376	.0545	-.1751	-1.6519	-.8967	-.3659	.1750	-.4531	-.4702	1.0173	-.0679	.5071	-.3477	-1.0041	1.1155
.7394	.6513	2.1589	.6477	-1.2749	-.2635	.4829	.4849	-.9349	.7646	-.2921	-.7503	.9788	.1584	-.0143
0.	0.	4.3889	.5345	.0188	.0342	-.1398	-.0067	1.3485	.7300	1.3006	.9825	.6958	1.1353	.7213
0.	0.	0.	-.5308	-.1510	-.0022	.3360	.1617	.2180	.6792	.9694	.1935	.6240	.8314	.4763
0.	0.	0.	0.	.1777	.2048	-.0759	.0099	.8476	.4542	.1892	.5885	.1100	.3869	.0978
0.	0.	0.	0.	0.	-.2449	-.0252	.2702	.1979	.2190	.0877	.9345	2.2995	.6431	.4980
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	6.2906	4.0821	4.6339	-4.4590	-2.1397
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	3.6108	.0444	-2.9694	-5.4134	-1.2307
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.8166	.0814	-.8826	.4158	.1905
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.3531	.1190	.2839	-.4327
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.4335	.2101	.1826	.2664
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.1327	.2602	-.0012
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.2309	.2049	.1192
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.1377	.0801	-1.0113

Run made with hydraulic conductivities from page 125 and saturated thickness from page 123.

Fourth Run

RATE OF RECHARGE IN INCHES PER YEAR.

0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-.4433
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-12.3911	-12.8799	-2.1647	.2023
0.	0.	0.	0.	0.	0.	0.	0.	0.	-11.5726	-2.5995	.5235	-1.2002	-.7661	-.0490
0.	0.	0.	0.	0.	0.	0.	0.	1.2792	1.0744	1.5421	.5699	-.1626	-.5699	-3.8137
0.	0.	0.	0.	0.	0.	0.	.4421	1.3450	1.0229	1.4874	1.7031	4.7165	-2.7475	-.3404
0.	0.	0.	0.	0.	0.	.3111	.2176	.2145	.3592	1.1964	4.8226	4.0863	-1.7104	5.7660
0.	0.	0.	0.	0.	.3135	.2086	.4506	.6699	1.7789	1.3346	1.7124	-3.5850	1.5250	-.3506
0.	0.	0.	0.	0.	.1131	.2891	.5823	2.4075	5.1293	-6.1764	-8.4025	-.3849	4.5615	2.1068
0.	0.	0.	0.	0.	.0277	.2496	1.3385	7.5165	-11.5351	-1.0165	-.7924	6.2448	2.3108	-1.2323
0.	0.	0.	0.	1.1427	.7613	1.6547	5.3099	-5.6329	.2567	.7100	4.9645	10.5618	7.5214	1.5449
0.	0.	0.	0.	.9780	1.2885	2.6357	-2.6431	-2.3860	2.6388	3.9316	2.2232	-2.2774	-3.0170	-2.4587
0.	0.	0.	-.0254	.7006	1.3351	1.8910	-1.8353	.6210	1.0732	3.8721	-.1256	-13.2587	-4.0950	-1.4034
0.	0.	0.	1.7128	.2026	1.8123	-.1051	1.0613	1.3437	1.9838	5.7429	-.8330	-2.6164	.0923	-1.1398
0.	0.	0.	.9012	-.1537	-.5069	.1682	.9325	2.1028	1.4239	3.0330	5.3569	-1.6810	-2.9676	-.5762
0.	0.	0.	.3379	.4523	.6680	.1528	-.3545	.5488	2.9860	1.9676	.0519	-2.8828	-.1439	.4729
0.	0.	-.3027	.1563	.1996	.3481	.4596	1.1345	2.9025	1.4617	-.9873	.3580	-.1510	-1.3054	-.5809
0.	.0875	.2453	.1009	.1972	.2126	.9671	2.8404	2.1146	-1.3682	1.2632	-1.1477	-3.2475	-3.3631	-3.3709
-1.0595	-.0485	-.0176	.0778	-.1301	.1996	-.3120	-.7452	-.5308	.5800	.7074	-1.6862	-1.6421	.3727	2.0021
.3917	-.1089	-1.1464	-1.6216	-1.7390	-1.1267	-.7212	-1.2476	-1.6323	-1.2920	-1.0031	.5071	-.3144	-1.0002	1.0848
.9977	1.3718	3.7354	2.0268	-.3714	.9583	3.1850	-.2772	-2.0618	.3773	-.7877	-.7503	.9788	.1900	-.0143
0.	0.	.8869	0.	3.5079	.4243	.3236	.6001	2.0535	.7303	1.0068	.9364	.6853	1.1353	.7213
0.	0.	0.	.5342	.0030	-.1887	.5396	.0642	.1284	.7794	1.0983	.1407	.5375	.8089	.4665
0.	0.	0.	0.	.7785	.9708	-.1191	.4487	.5969	.1458	.1356	.5783	.1190	.5540	.1895
0.	0.	0.	0.	0.	-1.4515	.0886	.2077	.1945	.2420	.1541	1.0075	2.2193	1.1267	.4096
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	6.2906	4.0709	4.9541	-4.6155	-2.3981
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	3.6108	-.6048	-1.4218	-6.0894	-1.9805
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.8166	.0814	-.6154	.6880	.1514
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.3536	.1190	.3591	-.4327
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.3103	.2322	.1826	.2664
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.1972	.2498	-.0012
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.2137	.3441	.4937
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.5305	.2829	-1.9904

Run made with hydraulic conductivities from page 125 and saturated thickness from page 124.

Fifth Run

RATE OF RECHARGE IN INCHES PER YEAR.

0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-.7128
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-5.9474	-5.2769	-1.9800	.3027
0.	0.	0.	0.	0.	0.	0.	0.	0.	-11.6775	-3.0093	-.1151	-.6500	-1.0061	-.1890
0.	0.	0.	0.	0.	0.	0.	0.	2.1945	.5488	.8339	.7105	.3298	-.3987	-3.8082
0.	0.	0.	0.	0.	0.	0.	.0940	1.1665	1.7254	2.3348	1.3186	3.0394	-1.6804	.8781
0.	0.	0.	0.	0.	0.	.0664	.0203	.4292	.3219	.3985	4.1854	3.4322	-1.6816	6.1743
0.	0.	0.	0.	0.	.0451	.0230	.1060	.0758	.6214	2.1922	2.3261	-3.5628	1.5156	1.5152
0.	0.	0.	0.	0.	.0360	.0819	.3074	1.3984	3.9778	-3.5603	-7.5515	.9498	5.8689	5.5008
0.	0.	0.	0.	0.	-.0201	.0726	1.0235	4.5114	-6.5498	-.4501	-1.4497	4.4724	3.4774	2.3489
0.	0.	0.	0.	.9677	.2400	1.1183	3.6313	-3.7568	-.0788	1.1206	4.5440	9.5538	7.2220	2.5484
0.	0.	0.	0.	.8506	1.1446	1.7243	-.9997	-2.4667	2.0605	3.9316	2.5982	-1.6277	-2.8114	-3.1084
0.	0.	0.	-.1111	.4555	.5183	1.7433	-.5138	.8694	1.2705	2.3551	.0125	-10.3246	-4.5986	-1.4398
0.	0.	0.	1.6948	.0614	.8351	.0067	1.4888	1.3089	1.6337	4.1772	-1.3801	-.8186	.6575	-1.3033
0.	0.	0.	.7334	-.0993	-.3092	.1534	.9413	1.9533	1.1731	2.7057	4.0359	-1.8924	-2.6101	-.3790
0.	0.	0.	.0984	.2204	.6608	.1321	.1538	.8027	2.6320	1.8315	.1426	-2.2927	-.3034	.5448
0.	0.	-.9274	.0461	.0941	.2148	.5183	1.0212	2.8244	1.4003	-1.0719	-.6124	-.1795	.0992	-.8687
0.	.7476	.4096	-.0939	.1444	.0218	.7097	1.8243	1.1955	.3102	2.7655	-1.5591	-3.3264	-5.1038	-3.5160
1.1472	.3679	.0148	-.2526	-.1255	.4167	.0593	.5887	.7546	.5422	1.6153	-2.1076	-.9790	.2006	.9808
.2376	.0016	.3197	-.5616	-.6732	-.1166	.3470	-.1879	-.2720	1.0209	.4647	.4074	-.4082	.3291	1.2068
.5249	.3736	.6655	.2941	-.3055	-.1317	.1356	.2683	-.3959	.4864	.3018	.2819	.5919	.1349	.6403
0.	0.	2.2962	.6942	.1982	-.0719	-.1587	-.1276	1.0645	.4427	.5493	1.1906	1.1668	.7053	.6513
0.	0.	0.	-.2886	-.1510	.0049	.3391	.1561	.2361	.6167	.8368	.0178	.6240	.8314	.2813
0.	0.	0.	0.	.1777	.2323	-.0812	-.0043	.8452	.4524	.1892	.5885	.1100	.3869	.0978
0.	0.	0.	0.	0.	-.2449	-.0191	.2696	.1980	.2190	.0877	.8977	2.1095	.6431	.4980
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	5.6033	3.1663	4.4447	-3.5885	-2.1397
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	3.0070	.5605	-2.3457	-5.4134	-1.2307
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.8166	.0943	-.8826	.4355	.1997
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.3511	.0696	.1704	.2236
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.4335	.2101	.1548	.1971
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.1327	.2340	.0111
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.2309	.2049	.1330
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	.1377	.0801	1.0442

Run made with hydraulic conductivities from page 126 and saturated thickness from page 123. This data was used in preparing recharge map of Figure 18.