THE WATER SUPPLY AND IRRIGATION DEVELOPMENT OF THE SOUTHERN HIGH PLAINS, NEW MEXICO

Sherman E. Galloway
Water Resource Engineering Specialist
New Mexico State Engineer Office
Roswell, New Mexico

INTRODUCTION

Like most of the southwestern United States, the Southern High Plains area of New Mexico has experienced a phenomenal rate of development since World War II. Hand in hand with this development has come an unprecedented demand for water. Foremost in this demand has been the need for additional water to supply the greater requirements of agriculture that have resulted from the transition from dry farming to irrigation farming that has occurred in this region during the past three decades.

The purpose of this paper is to review briefly the general conditions of ground-water occurrence and the growth of irrigation development in this area.

GEOGRAPHY

The Southern High Plains area of New Mexico occupies parts of Lea, Eddy, Chaves, Roosevelt, Curry, and Quay counties, and comprises the most westerly part of the Llano Estacado or Staked Plains. This in turn is a part of the High Plains Section of the Great Plains Physiographic Province and includes the Lea Plateau and those parts of the drainage basins of the Brazos and Red rivers of Texas that lie in New Mexico.

The Llano Estacado is a large, nearly flat plateau that occupies much of western Texas and eastern New Mexico. Characteristically, it is a grassy, treeless plain that is terminated to the north and west by erosion escarpments which face the valley of the Canadian River to the north and the valley of the Pecos River to the west. These escarpments are very bold and stand as steep faces that are cut by reentrants of short length. Except for a few localities where the edge is somewhat indefinite and marked only by a gradual slope, the escarpments reach heights of 100 to 400 feet.

In general the plain slopes gently to the east and southeast at a gradient of 10 to 15 feet per mile, and with few exceptions is remarkably smooth. The only irregularities in the topography are broad, shallow, nearly circular depressions that occur throughout the area and a few broad shallow valleys that are found for the most part in the northern part of the area.

The depressions range in size from some which are hardly discernable to those having diameters of 1 or 2 miles. In depth, they range from less than 1 foot to nearly 100 feet. In some localities, as a result of these depressions, short canyon-like stream channels have been formed by the headward erosion of drainage tributary to the depression.

In some parts of the area, notably the northern part, several valleys transverse the plain. In general these valleys are very shallow in relation to their width, and with the exception of some short ones on the edge which are tributary to the Pecos River drainage system, all follow the general slope of the plateau. Included among these are the Portales Valley and Blackwater, Running Water, and Frio draws, of which the Portales Valley is the most notable.

Sand dunes are found throughout the area, and several extensive areas of dune development exist that are worthy of mention. One strip of these dunes that is 2 to 5 miles in width lies between the Portales Valley and Blackwater Draw. It completely transverses the area and rises about 50 and 100 feet above Blackwater Draw and the Portales Valley, respectively. Other areas of dune development include a belt north of Blackwater Draw, a small area east of McDonald in Lea County, and large areas in southern Roosevelt County and northern Lea County.

Major centers of population within the area include Hobbs and Lovington in Lea County, Portales in Roosevelt County, and Clovis in Curry County. The major part of the income of the area is derived from stock grazing, irrigation farming, and oil production.

STRATIGRAPHY

Nearly all the Southern High Plains area of New Mexico is underlain by 25 to 500 feet of relatively unconsolidated sediments of Tertiary and Quaternary age. These consist chiefly of clay, sand and gravel that rest unconformably upon a thick sedimentary sequence of pre-Permian, Permian, Triassic and Cretaceous rocks. Triassic and Cretaceous rocks are exposed in the escarpments on the north and west sides of the Llano Estacado and locally in some of the deep arroyos and depressions of the region. Permian rocks are exposed in the valley of the Pecos River to the west.

Pre-Permian Rocks

Pre-Permian rocks are encountered only at relatively great depth throughout the region. These have little bearing on the water supply of the area, hence no further consideration will be given to them in this discussion.

Permian Series

Rocks of Permian age underlie all the Southern High Plains area. The uppermost strata of this series are chiefly brick-red shales and sandstones that are interbedded with gypsum, anhydrite and dolomitic limestone. Below these "red beds" is a thick section that consists chiefly of anhydrite which in turn is underlain by a thick salt series. Total thicknesses of Permian rocks in the area range from slightly less than 5,000 to slightly more than 5,500 feet.

The Permian rocks do not enter directly into the water-supply problems of the area, but when considered indirectly, they assume importance because of the role they have played in the development of the valley of the Pecos River to the west. The gradual removal of soluble strata, which comprise a major part of this series, from areas along and on either side of the Pecos River, over a period of many thousands of years, has been a major factor in the development of the present Pecos

Valley and the resulting complete isolation of the present Llano Estacado from contributory drainage from the mountains to the west.

Triassic System

Rocks of Triassic age in the Southern High Plains area have been assigned to the Dockum Group. They consist of as much as 1,400 feet of red shale and sandstone that rest unconformably upon the Permian Series.

The upper part of this series of rocks consists predominately of a thick shale sequence with minor amounts of sandstone that is unusually purplish-red in color. It attains a maximum thickness of about 1,200 feet. The interval between the base of this shale sequence and the top of the Permian Series is predominately sandstone and has been correlated with the Santa Rosa Sandstone of northern New Mexico.

Cretaceous System

The Cretaceous rocks of the region rest unconformably upon the Triassic "red beds." These rocks are usually present in the subsurface in extreme northern Lea County, and in southern and south-central Roosevelt County, but they are relatively rare throughout the remainder of the Southern High Plains area of New Mexico. Outcrops of these rocks are, in general, both poor and scattered, but when exposed they are seen to consist predominately of gray calcareous clay and sandstone with minor amounts of conglomerate and limestone, all of which change in character rapidly when traced laterally.

Logs of wells and seismic shot holes indicate a maximum thickness of about 125 feet for Cretaceous rocks in this region.

Tertiary System

The Ogallala Formation of late Tertiary age rests unconformably upon the rocks of the Cretaceous System and the Triassic "red beds," and is the principal formation exposed at the surface on the Southern High

Plains of New Mexico. This formation is composed of silt, sand, clay and gravel, and with the exception of the upper 10 to 40 feet, which is usually caliche, it is usually relatively unconsolidated. The upper caliche zone is particularly well exposed at the top of the escarpment on the north and west sides of the Llano Estacado where it is known as the "Caprock." Although the Ogallala Formation is lenticular and its lithology varies widely from place to place, sieve analyses of composite samples from test holes drilled in Lea County indicate that it is composed primarily of fine- to medium-grained sand. The basal part of this formation typically consists of very coarse sand and gravel that ranges from 5 to 20 feet in thickness.

The maximum known thickness of the Ogallala Formation in the Southern High Plains area of New Mexico is about 500 feet.

Quaternary System

Sediments deposited during Pleistocene and Recent times are found throughout the Southern High Plains area of New Mexico. Over much of this area these deposits are virtually inseparable from the underlying Ogallala Formation. In parts of Roosevelt and Curry Counties, however, these deposits assume great importance because of the bearing they have on the ground-water supply of the area.

Quaternary valley fill occurs to depths greater than 100 feet in the Portales Valley and consists of silt, sand and gravel, with the gravel usually being confined to the lowermost 5 to 10 feet of the deposit. The upper part of the valley fill consists of material ranging from silt to medium-sized sand. C. V. Theis, of the U.S. Geological Survey, on the basis of fossil evidence, has attributed these materials to a combination of lake and wind deposition. Logs of wells drilled in the vicinity of Running Water, Frio, and Tierra Blanca draws in Curry County further suggest that significant thicknesses of Quaternary valley fill may also underlie these draws.

Lake deposits are well exposed in the Big and Little Salt lakes in the Portales Valley, and notable occurrences of sand dunes are found on the north and south sides of the Portales Valley and Blackwater Draw, and in some areas of Lea County.

GEOLOGIC STRUCTURE

In general the rocks underlying the Southern High Plains of New Mexico dip gently to the east or east-southeast. This regional dip is interrupted by gentle folds, but these are noted only in the correlation of pre-Cenozoic rocks in the area. The overlying post-Mesozoic sediments apparently did not share in this deformation.

HYDROLOGY

There are no perennial streams on the New Mexico part of the Llano Estacado, and no contributing drainage, hence all of the water supply of the area must be derived from precipitation that falls on the area.

The major part of the precipitation comes during the summer, and typically occurs in the form of local thunder showers, which usually have a very irregular and spotty distribution. In general, annual precipitation decreases from about 18 inches to about 10 inches from north to south.

The rate of evaporation is relatively high throughout the year. During the summer there is in general a decrease in wind, but as the result of relatively high seasonal temperatures, the relative humidity is usually low, except during storms, and the air absorbs moisture readily. The fact that the wet season of the year coincides with the growing season is favorable for agriculture, but since it is also the season when potential evapotranspiration is greatest, it is certainly not favorable for ground-water recharge.

Well developed drainage systems are relatively rare on the New Mexico part of the Llano Estacado, and consist almost exclusively of Running Water, Frio, and Tierra Blanca draws in Curry County, Alamosa Creek in southwestern Quay County, Blackwater Draw in northern Roosevelt County, and two or three unnamed draws in southern Roosevelt County. During and following periods of heavy, sustained precipitation, flow may occur to varying degrees in all of these draws as well as in a few minor incipient draws that exist locally, but as a rule such flow diminishes rapidly due to infiltration and evaporation or drains into one of the numerous depressions in the land surface of the area.

This lack of well developed drainage systems is due to several factors: first, the slope of the surface of the Llano Estacado rarely exceeds 15 feet per mile and, secondly, the usual presence of a relatively well developed mat of vegetation, chiefly grass, tends to retard runoff and thereby protects the existing land surface from erosion. In addition, the usual patterns of precipitation are such that the ground ordinarily becomes relatively dry between periods of precipitation and therefore is usually capable of absorbing moisture readily. Consequently, it is only during periods of heavy sustained precipitation that there is any appreciable runoff.

Runoff that accumulates in the depressions in the land surface of the area is usually lost for the most part to evaporation rather than to seepage, due to the fact that a mantle of poorly permeable, extremely fine-grained sediment, that ranges from a few inches to several feet in thickness, is almost universally present within the perimeters of these natural catchment basins. As a result, the percentage of runoff which accumulates in depressions that becomes ground-water recharge is, for the most part, quite small.

C. V. Theis has presented evidence which indicates that the overall recharge to the ground-water supply of the region averages less than one-half inch per year.

Also to be recognized in considering the long term availability of ground water is the fact that the Llano Estacado extends eastward for 100 miles or more into Texas, and that ground water in amounts essentially equal to annual recharge in New Mexico, flows naturally across the state line into Texas each year.

SURFACE WATER AND SURFACE-WATER DEVELOPMENT

As previously noted, there are no perennial streams on the Southern Plains of New Mexico, hence there is little opportunity for the beneficial utilization of surface water. The only surface-water developments in the area are small retention works that impound runoff for stock, wildlife promulgation, and recreational purposes.

GROUND WATER AND GROUND-WATER DEVELOPMENT

The Southern High Plains of New Mexico, for purposes of discussing "Ground Water and Ground-Water Development," can be conveniently considered to consist of: (1) the Lea County Underground Water Basin, which includes all of central, and part of northern Lea County; (2) the Portales Underground Water Basin, which includes most of northeastern Roosevelt County and part of southwestern Curry County; (3) the Curry County area, which includes most of Curry County and parts of northern Roosevelt and southwestern Quay Counties; and (4) the Causey-Lingo area, in south-central Roosevelt County. The Lea County and Portales Basins are declared basins in which initiation of any new appropriation of ground water, or change in any existing right to appropriate ground water, requires prior approval by the State Engineer. The Curry County and Causey-Lingo areas, in contrast, have not been declared by the State Engineer.

Lea County Underground Water Basin

The Lea County Underground Water Basin, which was initially declared on August 21, 1931, and then extended to encompass additional areas to the south and west on October 1, 1952, occupies the southernmost sector of the Southern High Plains of New Mexico. It is bounded on the west and south sides by the escarpments of the Llano Estacado, and on the east by the Texas-New Mexico state line. Its northern boundary is roughly on an east-west line that might be projected across the Llano Estacado about 10 miles north of Tatum.

The geology and occurrence of ground water in the basin is rather simple. The Ogallala Formation outcrops on the surface over most of the area and is the principal water-bearing formation in the Basin. With only local exceptions, where erosional remnants of Cretaceous rocks existed prior to the deposition of the Ogallala Formation, it rests unconformably upon Triassic "red beds," which for all practical purposes form a barrier to the downward percolation of the ground water. The Cretaceous rocks contain water locally.

The depth to ground water in the basin ranges from about 20 to nearly 300 feet depending on where the well is located. In most of the irrigated area, however, water is obtained within 50 to 60 feet of the surface. The configuration of the water table is, in general, quite similar to the configuration of the land surface and slopes gently to the east-southeast.

The development of irrigation farming in Lea County had its beginning in the 1920s. By the end of 1929, 41 irrigation wells had been drilled. Of these, 17 had either been abandoned or were no longer in use, and 24 were still in use, although not every season. Development proceeded slowly until the end of 1946, at which time it was estimated that about 5,000 acres were being irrigated. The post-war years have brought a rapid increase in development and at the present time it is estimated that irrigation has been practiced on about 120,000 acres of land under rights to water that are recognized by the State Engineer. Approximately 55,000 acres of these lands are now fallow.

Present rates of water-level decline in wells in the Lea County Basin range from zero to slightly more than 2 feet per year. The average annual water-level decline in the vicinity of irrigated lands within the boundaries of this basin is slightly less than 1 foot.

A comparison of the calculated rate of annual flow of ground water from the Lea County Basin across the state line into Texas, under 1952 conditions, with a similarly calculated rate of flow, under 1976 conditions, shows an apparent net <u>decrease</u> in annual flow during this

24-year period of 2,200 acre-feet. Calculated annual rates of flow for the cited years across the subject reach of the state line are 34,260 acre-feet, and 32,040 acre-feet, respectively.

Portales Underground Water Basin

The Portales Underground Water Basin, which was initially declared on May 1, 1950, extended to encompass additional areas to the north, south and west on July 18, 1955, and then revised on November 3, 1955 to exclude part of the area encompassed by the extension of July 18, 1955, is located in northeastern Roosevelt County and southwestern Curry County, and occupies a part of the central portion of the Southern High Plains of New Mexico. The basin includes lands in Township 1 North, Ranges 30 through 37 East; Township 1 South, Ranges 31 through 37 East; Township 2 South, Ranges 32 through 37 East; and Township 3 South, Ranges 34 through 37 East.

Small quantities of water of relatively poor chemical quality are produced locally from the Triassic "red beds," and in some localities water may be derived from the Ogallala Formation or from Cretaceous rocks, but in general most of the water pumped in the area is shallow ground water that occurs in valley fill deposited by an ancient river, that was beheaded by the Pecos River in late Pleistocene time. Apparently this ancient river was a major stream that more or less followed the present course of the Pecos River above Fort Sumner and then continued east-southeastward across the plains, to the present course of the Double Mountain Fork of the Brazos River in Texas.

C. V. Theis, from his work in the area in the early 1930s, concluded that this valley must have had a topography similar to that of the present "Breaks in the Plains," with steep valley slopes facing a broad flat valley on either side, which was cut through the Ogallala Formation and into the underlying Cretaceous and Triassic rocks. He concluded that at least the lower part of the fill was the result of stream deposition, and he attributed the remainder of the fill to deposits of talus that resulted from waste and slump from the side slopes that the captured stream was unable to carry water. The accumulation of this talus and subsequent smoothing by local runoff and wind action have been postulated as the principal factors in the development of the present valley form.

In general, over most of the developed area the average depth to water is about 70 feet. Actual depths to ground water in the valley range from less than 10 feet to more than 170 feet depending on where the well is located. Depths to Triassic "red beds," which underly all of the area and form an effective barrier to the downward percolation of ground water, range from a few feet to slightly more than 300 feet.

Prior to 1910, many of the farmers in the area irrigated small tracts with water pumped by windmills and in a few cases centrifugal pumps powered by gasoline engines had been installed, but it was not until this date that large-scale irrigation was begun.

In 1910, the Portales Irrigation Company was organized by local irrigators who financed the project with mortgages on their irrigated land. An electric-power plant was constructed at Portales and 69 individual pumping plants were served in the present irrigated area. The electric-power plant had sufficient capacity to pump 30,000 acre-feet during the growing season and 10,000 acres were included in the project, but the capacity of the plant was never reached and the planned acreage was never irrigated. It is reported that an average of 4,000 acre-feet of water a year was pumped from 1910 to 1914.

The experiment was unsuccessful because of the lack of irrigation experience on the part of the people involved in the project. Attempts were made to irrigate too much land with one well, suitable crops were not ascertained, no markets were readily available for the produce, and a great deal of dissatisfaction developed among the people because of the restrictions that were imposed to distribute the load on the central power plant. As the result of these and other factors, the project failed and the electric-power plant was dismantled and sold during World War I.

In 1919, the pumping plants were too few to be reported separately by the U.S. Census. In about 1925, however, irrigation farming began to expand again in the area. Irrigation development grew slowly, and by

1929 the U.S. Census reported that 166 pumping plants were in operation and 4,823 acres were irrigated. About 300 irrigation wells were in use in 1931 and about 8,850 acres were under irrigation.

Irrigation development has grown from about 11,000 acres in 1938 to more than 110,000 acres at the present time.

Present rates of water-level decline in wells in the Portales Basin range from zero to more than 3.5 feet per year. The average annual water-level decline in the vicinity of irrigated lands within the boundaries of this basin is about 2 feet.

A comparison of the calculated rate of annual flow of ground water from the Portales Basin across the state line into Texas, under 1962 conditions, with a similarly calculated rate of flow, under 1972 conditions, shows an apparent net decrease in annual flow during this 10-year period of 2,990 acre-feet. Calculated annual rates of flow for the cited years across the subject reach of the state line are 11,270 acre-feet, and 8,280 acre-feet, respectively.

Curry County Area

The Curry County area includes most of Curry County and parts of northern Roosevelt and southwestern Quay counties. It is bounded on the north and west sides by the escarpments of the Llano Estacado, and on the east by the Texas-New Mexico state line. The southern boundary of the area follows roughly a line that might be drawn just north of, and parallel to Blackwater Draw from the Texas-New Mexico state line to the western escarpment of the Llano Estacado. The occurrence of ground water in this area is similar to its occurrence in the Lea County Underground Water Basin and with few exceptions all ground water pumped in the area is obtained from the Ogallala Formation. The saturated part of the Ogallala Formation in this area ranges from zero to slightly more than 200 feet in thickness and the best yields to wells are usually obtained from coarse sediments near the base of the formation. Depths to water in wells in this area range from less than 25 to more than 450 feet below the land surface with the depth to water in most wells being in excess of

250 feet. Pump discharges range from about 500 to nearly 1,000 gallons per minute.

The development of irrigation farming in the Curry County area began in the middle 1930s near the village of House in southwestern Quay County, and until the late 1940s was confined almost exclusively to the valley of Alamosa Creek in the vicinity of that community, where depths to pumping water levels in irrigation wells were ordinarily less than 50 feet. During the late 1940s and early 1950s, and particularly during 1953 and early 1954, however, numerous farmers drilled irrigation wells in southeastern Curry County, where pumping water levels were then, in most cases, in excess of 175 feet, and in some cases, in excess of 300 feet. An estimated 150 wells had been completed, and about 20 new wells were drilled per month in this area as of March 1954. Most of the acreage on which irrigation is now being practiced in the Curry County area was developed with water produced by wells drilled prior to 1960.

Recent cooperative surveys of irrigation in New Mexico by several federal and state agencies indicate that approximately 1,800 wells are now in existence in the Curry County area, and that the lands that have been irrigated with water produced by these wells total about 232,000 acres. During the past 10 years, however, drastic increases in pumping costs, arising in part from increased pumping lifts produced by declining water levels, and in part from rising fuel and/or power costs, have brought about a substantial reduction in the extent to which irrigaton continues to be practiced in this area. Many of the wells that were in use in the area as of the early 1970s now have either been abandoned or are simply no longer in use. Furthermore, many of the wells that are still in use are being pumped only to the extent necessary to sustain crops during extremely dry periods of the growing season.

Present rates of water-level decline in wells in the Curry County area range from zero to more than 6 feet per year. The average annual rate of water-level decline in the vicinity of irrigated lands in this area is about 3 feet.

A comparison of the calculated rate of annual flow of ground water from southeastern Curry County across the state line into Texas, under

1962 conditions, with a similarly calculated rate of flow, under 1972 conditions, shows an appaarent net <u>increase</u> in annual flow during this 10-year period of 6,500 acre-feet. Calculated annual rates of flow for the cited years across the subject reach of the state line are 38,230 acre-feet, and 44,730 acre-feet, respectively.

Causey-Lingo Area

The Causey-Lingo area consists of some 22,000 acres of irrigated land which are more or less confined within an area of less than 150 square miles in the vicinity of the communities of Causey and Lingo, and immediately adjacent to the Texas-New Mexico state line, in south-central Roosevelt County. Irrigation to supplement precipitation was begun on a small scale in this area in about 1945. Most of the wells in this area, however, have been drilled since 1954.

The principal water-bearing formation in the Causey-Lingo area is encountered below the base of the Ogallala Formation, and is composed of relatively unconsolidated sand and gravel of Cretaceous age, which occur for the most part in erosion channels cut into underlying Triassic "red beds."

Irrigation wells in the Causey-Lingo area range in depth from about 100 to about 275 feet and in yield from less than 100 to more than 1,000 gallons per minute. Known thicknesses of saturated material encountered by irrigation wells in the area range from 20 to 100 feet.

Present rates of water-level decline in wells in the Causey-Lingo area range from zero to more than 3 feet per year. The average annual water-level decline in the vicinity of irrigated lands in this area is about 1 foot.

Rates of annual flow of ground water from this area across the state line into Texas have not been calculated.

SUMMARY

Ground water provides the only dependable source of water supply in the Southern High Plains area of New Mexico, and as the result of extensive development of natural resources and irrigation farming during the past three decades, there is now an unprecedented demand for this important and necessary resource throughout the region.

To date, the principal areas of irrigation development have been confined to the Lea County Underground Water Basin in central and northern Lea County, the Portales Underground Water Basin in northeastern Roosevelt County and southwestern Curry County, the Curry County Area, and the Causey-Lingo area in south-central Roosevelt County.

While there are some slight differences in the occurrence of ground water in each of these areas, all are faced with the problem of having limited quantities of ground water in storage and annual withdrawal rates that are far in excess of annual recharge. Since ground water, in amounts essentially equal to annual recharge, flows naturally into Texas from each of these areas each year, it follows that most of the water now being pumped in all of these areas is being "mined" from transient storage. Under such conditions a reasonable approximation of the remaining life expectancy of large-scale irrigation at any particular locality in any of these areas can, in most instances, be obtained from:

$$LE = \frac{m_1 - m_2}{\Delta m}$$

where "LE" is the life expectancy of continued large-scale irrigation farming in years, "m_1" the present thickness of water-yielding materials in feet, "m_2" the thickness of water-yielding materials that will be needed to sustain future economic well yields in feet, and "Δm" the average annual water-level decline in feet.

Comparative analyses of historical changes in ground-water conditions in the vicinity of the Texas-New Mexico state line have shown, in general, that gradients on the regional water table have increased along this line. Further analyses of these data have shown, however, that the

magnitudes of these water-table-gradient increases, when considered in combination with the reductions of cross-sectional areas of the aquifers that occurred in consequence of regional water-level declines, were not sufficient to materially alter annual rates of ground-water movement across the state line.

Previously recited calculated rates of flow of ground water from New Mexico across the state line into Texas are as follows:

Lea County Underground Water Basin

1952 Flow Acre-Feet	1976 Flow Acre-Feet	Change in Flow Acre-Feet/Year
34,260	32,040	-2,220

Portales Underground Water Basin

1962 Flow Acre-Feet	1972 Flow Acre-Feet	Change in Flow Acre-Feet/Year
11,270	8,280	-2,990

Southeastern Curry County

1962 Flow Acre-Feet	1972 Flow Acre-Feet	Change in Flow Acre-Feet/Year
38,230	44,730	+6,500

It is quite interesting to note that the only listed area from which the annual flow of ground water increased across the state line into Texas, i.e., the Curry County area, is the only area of those listed that has not been designated as a declared underground water basin by the State Engineer.

SELECTED REFERENCES

Ash, S. R., 1961, Geology and ground-water resources of northern Lea County, New Mexico: Univ. N. Mex. M.S. thesis, 66 p.; U.S. Geol. Survey open-file rept., 153 p.

-----, 1961, Ground-water conditions in northern Lea County, New Mexico: U.S. Geol. Survey open-file rept., 48 p.; U.S. Geol. Survey Hydrol. Inv. Atlas HA-62, 2 sheets with text, 1963.

Baker, C. L., 1915, Geology and underground waters of the northern Llano Estacado: Tex. Univ. Bull. 57, 225 p.

Berkstresser, C. F., Jr., and Mourant, W. A., 1966, Geology and ground-water resources of Quay County, New Mexico: N. Mex. Bur. Mines and Min. Resources Ground-Water Rept. 9, 115 p.

Cooper, J. B., 1960, Ground water in the Causey-Lingo area, Roosevelt County, New Mexico: N. Mex. State Engineer Tech. Repr. 14, 51 p.

Cronin, J. G., 1969, Ground water in the Ogallala Formation in the Southern High Plains of Texas and New Mexico: U.S. Geol. Survey Hydrol. Inv. Atlas HA-330, 9 p., 4 sheets.

Dinwiddie, G. A., 1963, Municipal water supplies and uses, southeastern New Mexico: N. Mex. State Engineer Tech. Rept. 29A, 140 p.

-----, 1964, Municipal water supplies and uses, northeastern New Mexico: N. Mex. State Engineer Tech. Rept. 29B, 64 p.

Galloway, S. E., 1955, Feasibility report on the possibility of obtaining artesian irrigation water from the Triassic "Red Beds," Curry County, New Mexico: N. Mex. State Engineer open-file rept., 18 p.

-----, 1956, Geology and ground-water resources of the Portales Valley area, Roosevelt and Curry Counties, New Mexico: Univ. N. Mex. M.S. thesis, 119 p.

-----, 1963, Geology and hydrology of Ranger Lake area, Lea County, New Mexico: N. Mex. State Engineer open-file rept., 5 p.

-----, 1967, Saturated thickness of post-Mesozoic deposits, Portales Valley, Roosevelt County, New Mexico, January 1962: N. Mex. State Engineer Map RO 5, 1 sheet.

-----, 1969, Saturated thickness of post-Mesozoic deposits in part of Curry County, New Mexico, January 1962: N. Mex. State Engineer Map CU 2, 1 sheet.

-----, 1975, Records of municipal wells (as of July 1975) and measured depths to static water levels in wells (January 1942 to January 1975), east-central Lea County, New Mexico: N. Mex. State Engineer open-file rept., 61 unnumb. p.

-----, 1975, Records of municipal wells (as of July 1975) and measured depths to static water levels in wells (from beginning of record to January 1975), southeastern Curry and northeastern Roosevelt Counties, New Mexico: N. Mex. State Engineer open-file rept., 69 unnumb. p.

Havens, J. S., 1966, Recharge studies on the High Plains in northern Lea County, New Mexico: U.S. Geol. Survey Water-Supply Paper 1819-F, 52 p.; U.S. Geol. Survey open-file rept., 82 p., 1964.

Howard, J.W., Jr., 1954, Reconnaissance of ground-water conditions in Curry County, New Mexico: N. Mex. State Engineer Tech. Rept. 1, 35 p.; U.S. Geol. Survey open-file rept., 39 p.; (abs.) Am. Geol. Inst. Geol. Abs., v. 3, no. 3, p. 150, 1955.

Mourant, W. A., 1971, Saturated thickness of post-Mesozoic deposits in the central and northern parts of Lea County, New Mexico, January 1962: N. Mex. State Engineer Maps LC 4 and LN 4, 2 sheets.

Nye, S. S., 1930, Shallow ground-water supplies in northern Lea County, New Mexico: N. Mex. State Engineer 9th Bienn. Rept., 1928-30, p. 363-387; N. Mex. State Engineer Bull. 2, 26 p.

-----, 1932, Progress report on the ground-water supply of northern Lea County, New Mexico: N. Mex. State Engineer 10th Bienn. Rept., 1930-32, p. 229-251.

Theis, C. V., 1932, Report on the ground water in Curry and Roosevelt Counties, New Mexico: N. Mex. State Engineer 10th Bienn. Rept., 1930-32, p. 98-160.

-----, 1934, Progress report on the ground-water supply of Lea County, New Mexico: N. Mex. State Engineer 11th Bienn. Rept., 1932-34, p. 127-153.

-----, 1934, Progress report on the ground-water supply of Portales Valley, New Mexico: N. Mex. State Engineer 11th Bienn. Rept., 1932-34, p. 87-108.

-----, 1937, Amount of ground-water recharge in the Southern High Plains: Am. Geophys. Union Trans., 18th Ann. Mtg., p. 564-568.

Wright, J. I., 1963, Ground water development in the Curry County ground-water basin, Curry and Roosevelt Counties, New Mexico: N. Mex. State Engineer open-file rept., 25 p.

Yates, J. C., and Galloway, S. E., 1954, Two maps: (1) Approximate altitude and configuration of the base of the Ogallala Formation in part of Lea County, New Mexico, and (2) Approximate thickness of saturated sediments in the Ogallala Formation in part of Lea County, New Mexico: N. Mex. State Engineer open-file maps, 2 sheets.