An Appraisal of Potential Ground-Water Salvage Along the Pecos River Between Acme and Artesia New Mexico

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1659

Prepared in cooperation with the New Mexico State Engineer Office

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By R. W. MOWER, J. W. HOOD, R. L. CUSHMAN, U.S. GEOLOGICAL SURVEY, R. L. BORTON, *and* S. E. GALLOWAY, NEW MEXICO STATE ENGINEER OFFICE

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Typical vertical view of a reach of the Pecos River, bottom-land vegetation, and cultivated land in the Acme-Artesia area, Roswell basin, Chaves and Eddy Counties, N. Mex. Photograph by Pacific Air Industries, September 27, 1952.

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By R. W. Mower, J. W. Hood, R. L. Cushman, U.S. Geological Survey, and R. L. Borton, and S. E. Galloway, New Mexico State Engineer Office

ABSTRACT

Phreatophytes, such as saltcedar, grasses (saltgrass and sacaton), and mesquite, all of which grow in the bottom land of the Acme-Artesia reach of the Pecos River, Chaves and Eddy Counties, N. Mex., consume tens of thousands of acre-feet of water each year. The spread and increase in growth density of this vegetation, particularly saltcedar, are continuing uncontrolled, and the amount of water used by these phreatophytes increases yearly. The water used by saltcedar is considered as wasted because saltcedar has no known beneficial use. The water used by the phreatophyte grasses is beneficial where the grasses provide forage for livestock. The amount of water used by mesquite is small compared to that used by saltcedar and grasses because the volume of mesquite is small. The continued large-scale waste of water by nonbeneficial phreatophytes in the Roswell basin should be stopped, because the water is needed for beneficial use. The annual draft on the ground-water reservoir for irrigation alone exceeds the annual recharge to the acquifers.

Phreatophytes draw water directly from the water of the Quaternary alluvium, but the major source of recharge to the alluvium is artesian water from the San Andres limestone and Grayburg formation, either as seepage from artesian water pumped for irrigation or as upward leakage from the artesian system. The rate of recharge to the alluvium, as upward leakage per unit area of alluvium, is largest in the vicinity of Roswell and diminishes progressively southward to Artesia as the thickness of the confining bed separating the artesian and nonartesian water becomes greater.

The general movement of water in both ground-water reservoirs is eastward toward the river; the river and adjacent bottom land are the principal areas of natural discharge of ground water in the Acme-Artesia area. In general, water moving eastward toward the river which is not intercepted by wells will reach the bottom land. Ground water not discharged by evapotranspiration or by the few irrigation wells in the bottom land will discharge to the Pecos River or its tributaries.

Water levels in the artesian and nonartesian wells in the Acme-Artesia area have trended downward since 1943, because of drought, heavy pumping for irrigation, and discharge of water in the bottom land by evapotranspiration. The decline in nonartesian water levels by 1958 was not sufficient to cause a shortage of ground water to the phreatophytes; thus, conditions still were favorable for

additional phreatophyte growth. In time, pumping in the cultivated area may reverse the movement of ground water between the bottom land and the cultivated area. If this occurs, the nonartesian water levels in parts of the phreatophyte area should decline to a level that would cause a shortage of water to the phreatophytes. However, it is not anticipated that pumping will reduce appreciably the ground-water levels in the phreatophyte area in the immediate future.

The ground water in the bottom land, in general, is suitable for irrigation. Use of water by the phreatophytes causes some deterioraton in the chemical quality of the water in the bottom land. Evapotranspiration discharges chemically pure water and leaves a residue of mineral salts removed from the water. The rejected salts eventually are leached downward to the water table and increase the dissolved salts content of the ground water. Reducing the amount of evapotranspiration in the bottom land would reduce the chemical deterioration of the ground water reaching the Pecos River.

Phreatophytes in the Acme-Artesia area were mapped in 1956 and 1958 according to species, areal density, and vertical density. About 41,000 acres were either wholly or partly infested with phreatophytes. There was no appreciable increase in total phreatophyte acreage between 1956 and 1958; however, saltcedar increased in areal and vertical density and encroached on about 5,000 acres of grassland during that period. Results of the 1958 phreatophyte survey showed that if each species were reduced to an area of 100 percent volume density, saltcedar would cover about 8,700 acres, grass about 17,000 acres, and mesquite about 170 acres .

The results, in acre-feet, of computing water use by four methods for years 1956 and 1958 respectively were: (a) by extrapolation of water-use rates from other areas, 62,000 and 73,000; (b) by the inflow-outflow method, 62,000 and 88,000; (c) by the pumping-well analogy method, 54,000 and 55,000; and (d) by the transpiration-well method, 88,000 and 107,000. The average of these rates for each year probably would approximate the magnitude of the water use for the respective years.

It was concluded that if the saltcedar were eradicated, phreatophyte grasses encouraged to grow, and nonartesian water levels controlled, the use of water by evapotranspiration in the phreatophyte area would be about 45,000 acre-feet per year. If the saltcedar growth continues uncontrolled and the water levels in the phreatophyte area remain at about the 1958 level, the rate of water use by evapotranspiration might rise to about 170,000 acre-feet annually in just a few years.

The means for eradicating the phreatophyte growth were not studied during the investigation. Information from other sources indicate that mechanical clearing, burning, and spraying with chemicals might effect a measure of control on saltcedar.

INTRODUCTION

A large amount of water is wasted annually through evapotranspiration in the bottom land of the Pecos River between Acme, in Chaves County, and Artesia, in Eddy County, N. Mex. Most of this waste is water transpired by nonbeneficial vegetation. This loss of water is in an agricultural area where the use of water for irrigation alone exceeds the average annual recharge to the area. Aerial photographs of the Pecos River bottom land and recorded field observations made in the years 1939–58 show a progressive increase in the areal extent and density of the nonbeneficial vegetation, particularly saltcedar. Saltcedar was introduced in the area in about 1912 (Eakin and Brown, revised 1939) and has become the dominant phreatophyte in terms of total amount of water wasted. The loss of water from the valley increases yearly as larger quantities of water are used by these nonbeneficial plants.

In the water-deficient Pecos Valley, and particularly in the Roswell basin, reducing or eliminating the loss of water by nonbeneficial uses is important. During the 1950's, water levels, artesian pressures, and surface flows declined throughout the Roswell basin because discharge exceeded recharge. The decline can be attributed to reduced recharge due to drought, an increase in ground-water pumpage, and an increase in consumptive waste of water resulting from the spread of nonbeneficial vegetation in the bottom land of the Pecos River and its tributaries.

The surface-water supply of the Pecos River and its tributaries is fully appropriated. That part of the Roswell hydrologic basin in which irrigation wells could be developed has been declared a groundwater basin, subject to the administrative jurisdiction of the State Engineer, and is closed to new appropriations of water from both nonartesian and artesian sources. Considerable effort has been expended to reduce irrigation water requirements through improved irrigation practices and lining of irrigation ditches. It is impractical to take large tracts of irrigated lands out of cultivation to reduce the overdevelopment of the ground-water reservoir. Adjudication is in progress, however, to eliminate the irrigated acreage having no water rights. Reducing the amount of water wasted by nonbeneficial vegetation in the bottom land of the valley would increase the amount of water available for beneficial use.

PURPOSE AND SCOPE

In 1956, the State Engineer of New Mexico requested the U.S. Geological Survey to conduct an investigation in the Roswell basin to prepare an estimate of the amount of water used annually by nonbeneficial vegetation in the Acme-Artesia sector of the Roswell basin to detemine the quantity of ground water that might be salvaged, and to determine the hydrologic effects of a salvage program. The investigation of evapotranspiration in the Acme-Artesia sector of the Pecos Valley was begun in July 1956, and was made cooperatively by the Ground Water Branch of the U.S. Geological Survey, the New Mexico State Engineer Office, and the New Mexico Interstate Stream Commission.

The investigation was limited to the bottom land of the Pecos River and its tributaries between Acme and Artesia because this area was close to Roswell and contained many observation wells, gaging stations, and weather stations that would have to be constructed if a different reach of river were used. Of prime importance were the river gaging stations near Acme and Artesia, whose records were essential to some of the proposed methods of determining water use by bottom-land vegetation.

The initial phase of the investigation was devoted to a review of previously collected data and some field studies to evolve a program of investigation that would be commensurate with the time and funds available. The second phase, begun in December 1956, consisted of mapping the bottom-land vegetation in the Acme-Artesia sector to determine the volume of transpiring vegetation; making seepage investigations in the Pecos River to determine gains and losses in flow and relating these to use of water by vegetation; collecting samples of water for analysis to determine changes in quality of water; making tests of the transmissibility of the alluvial fill in the bottom land to evaluate the rate of ground-water movement in the bottom land; and measuring ground-water levels to determine the configuration of the water table in and adjacent to the bottom land.

In this report, estimates were made of the amount of water used annually by bottom-land vegetation in the Acme-Artesia sector of the Roswell basin and the amount of water that might be salvaged by eradicating nonbeneficial vegetation and replacing that vegetation with forage grasses.

LOCATION AND EXTENT OF THE AREA

The area of investigation is in the Roswell basin in south-central Chaves County and north-central Eddy County, N. Mex. It includes the bottom land of the Pecos River and the lower reaches of its tributaries lying south of U.S. Highway 70, about 15 miles northeast of Roswell near Acme, and north of State Highway 83 near Artesia. The eastern boundary of the area is a westward facing bedrock escarpment east of the Pecos River, and the western boundary is the eastern limit of the irrigated farmland (pl. 1). The area is about 51 miles long, about 0.1 to 4 miles wide, and includes about 41,000 acres.

PREVIOUS INVESTIGATIONS

The first important study of the geology and ground-water resources of the Roswell basin was made by Fisher (1906) in 1905. During 1925–28, Fiedler and Nye (1933) made the first comprehensive investigation, in which they described the artesian aquifer and the principal intake area and concluded that the average annual recharge to the artesian aquifer was about 235,000 acre-feet. Although the 1925–28 study was limited mainly to the artesian aquifer, the basic data and interpretations were useful in the present investigation.

Morgan (1938) estimated that recharge to the valley fill from precipitation was not more than 0.5 inch per year, and total recharge to the valley fill from all sources was about 142,000 acre-feet. Morgan apparently did not consider the saltcedars to be important users of water because no mention was made of them. Evapotranspiration by phreatophytes was mentioned, but no attempt was made to evaluate it.

The report of the Pecos River joint investigation prepared in 1942 under the authority of the National Resources Planning Board includes a study of the water resources of the entire Pecos River drainage basin. Several sections of the report deal exclusively with the water regimen in the Roswell basin and a detailed study was made of base flow in the Acme-Artesia reach of the Pecos River. The average annual gain in the Pecos River between gaging stations near Acme and Dayton was 75,000 acre-feet during the period 1905–39. The highest average monthly inflow was 10,600 acre-feet for January, and the lowest average monthly inflow was 2,800 acre-feet for July.

It was concluded that evapotranspiration was 30,000 acre-feet per year from 20,000 acres in the Roswell basin in 1940. Experiments with growing saltcedars in tanks at Carlsbad indicated that the optimum evapotranspiration by saltcedar in that area was equivalent to a 6-foot depth of water per year. Field studies indicated that the average annual evapotranspiration for the Roswell basin was 5 feet of water, the rate having diminished from 6 feet near the river to 4 feet at the edges of the bottom land.

Most of the data reported in the Pecos River Compact (1949) are from the Pecos River joint investigation. The report shows that the base flow of the Pecos River decreased 30 cfs (cubic feet per second) from 1927 to 1947, due principally to the pumping of nonartesian water in the Roswell basin, and states that at some future date, probably in 40 to 50 years, ground-water pumpage in the Roswell basin will cause cessation of gain to this reach of the river. It was recognized that saltcedars were using an appreciable quantity of ground water and that the waste of water by them would increase. No estimates were made of the evapotranspiration in the Acme-Artesia reach of the river; however, it was estimated that 55,000 acre-feet of water per year was wasted by saltcedar between Artesia and Lake McMillan.

A report was prepared by the Pecos River Commission (1955) outlining programs for water salvage and salinity alleviation in the Roswell basin. The serious depletion of base flow in the Acme-Artesia reach of the river and of the surface-water supply of the Hagerman Canal was attributed to ground-water pumpage in the Roswell basin. The principal problems of the area were recognized as encroachment of saltcedar, channel deterioration by filling with silt and choking with saltcedar, depletion of normal streamflow, increased sedimentation, and increased flood hazards. The report lists a series of remedial measures but points out that there is no simple solution to the water problems of the basin.

A quantitative study of the Roswell ground-water reservoir was made by M. S. Hantush (1955) in 1954 and 1955. Coefficients of transmissibility and storage were computed for the shallow and artesian aquifers from 16 pumping tests. Hantush proposed that "coefficient of leakage" be used in evaluating the hydraulic characteristics of leaky artesian aquifers. He defined the coefficient of leakage (1955, p. 17) as, "the quantity of flow that crosses a unit area of the interface between the main aquifer and its semiconfining bed per unit head difference between the heads at the top and the bottom of the semiconfining bed." The coefficient of leakage was also computed. Using these coefficients and data from previous studies, Hantush evaluated recharge, natural discharge, and effects of pumping in the Roswell basin. He concluded that a redistribution of the irrigation wells would make more efficient use of the ground-water reservoir, especially in reducing the loss of water by evapotranspiration. With an idealized distribution pattern of pumping, it was estimated that the safe yield would be 130,000 acre-feet per year from the artesian aquifer and 86,000 acre-feet per year from the nonartesian aquifer.

During 1950–53, upward leakage from the artesian to the shallow aquifer was about 80,000 acre-feet per year, according to Hantush (1955, p. 58), and pumpage of ground water for irrigation was about 257,000 acre-feet per year. Hantush (1955, p. 66) estimated that the loss of water by evapotranspiration in the Roswell basin was about 30,000 acre-feet annually. The rate of natural discharge from the nonartesian aquifer for the immediate future may be 116,000 acre-feet per year. Hantush states, "Thus, it appears that under the present well-field distribution the shallow storage probably will be exhausted before an appreciable amount of losses will be recovered."

The report "Use of water by bottom-land vegetation in lower Safford Valley, Arizona," by J. S. Gatewood and others (1950), describes the theory and methods employed in collecting and analyzing basic data in determining water use by phreatophytes. Some of these methods were used in the Roswell basin study. The rate of water use by saltcedar in the Safford Valley was extrapolated to compute water use by saltcedar in the Roswell basin.

ACKNOWLEDGMENTS

The investigation was done through the combined efforts of personnel of the Ground Water Branch, U.S. Geological Survey, and the Technical Division, New Mexico State Engineer Office. The study was under the direct supervision of W. E. Hale, district engineer, U.S. Geological Survey, who coordinated the work of both agencies, and J. C. Yates, Chief, Water Resources and Development Section, Technical Division, New Mexico State Engineer Office. R. W. Mower, hydraulic engineer, Geological Survey, was project chief. R. L. Borton and S. E. Galloway, geologists, New Mexico State Engineer Office, assisted in drilling test holes, analyzed drill cuttings, mapped some of the phreatophytes, and prepared parts of the text on the geology and climate of the area.

W. L. Garner and E. H. Banta, of the State Engineer Office, aided in the collection of streamflow and seepage-investigation data and provided records of streamflow, surface-water diversions, and other surface-water data. J. I. Wright, engineer, and R. J. Garvey, assistant engineer, Water Rights Division, New Mexico State Engineer Office, assisted in the collection of seepage-investigation data. S. O. Decker, hydraulic engineer, Geological Survey, supervised and assisted in the seepage investigations and provided surface-water records. Chemical analyses of the ground- and surface-water supplies were made under the supervision of J. M. Stow, district chemist, Geological Survey.

Some of the small-diameter observation wells near the Pecos River were drilled by Joe Smith and L. L. Hanke, assisted by G. C. Shaw, all of the Technical Division, New Mexico State Engineer Office. The Board of Directors of the Pecos Valley Artesian Conservancy District and Superintendent, R. E. Crawford, furnished their drilling rig for drilling three observation wells.

The cooperation of land owners who allowed access to their wells and some who granted permission to drill shallow observation wells on their land is also acknowledged.

LOCATION-NUMBERING SYSTEM

The system used in this report for numbering wells, seeps, and springs and for sampling or measuring points on canals, drains, and streams is based on the Federal system of subdivision of the public lands. A number assigned to a given well or point locates its position to the nearest 10-acre tract in the land net as shown in figure 1. The location number is divided by periods into four segments. In this report the first segment denotes the township south of the New Mexico base line, and the second segment denotes the range east of the New

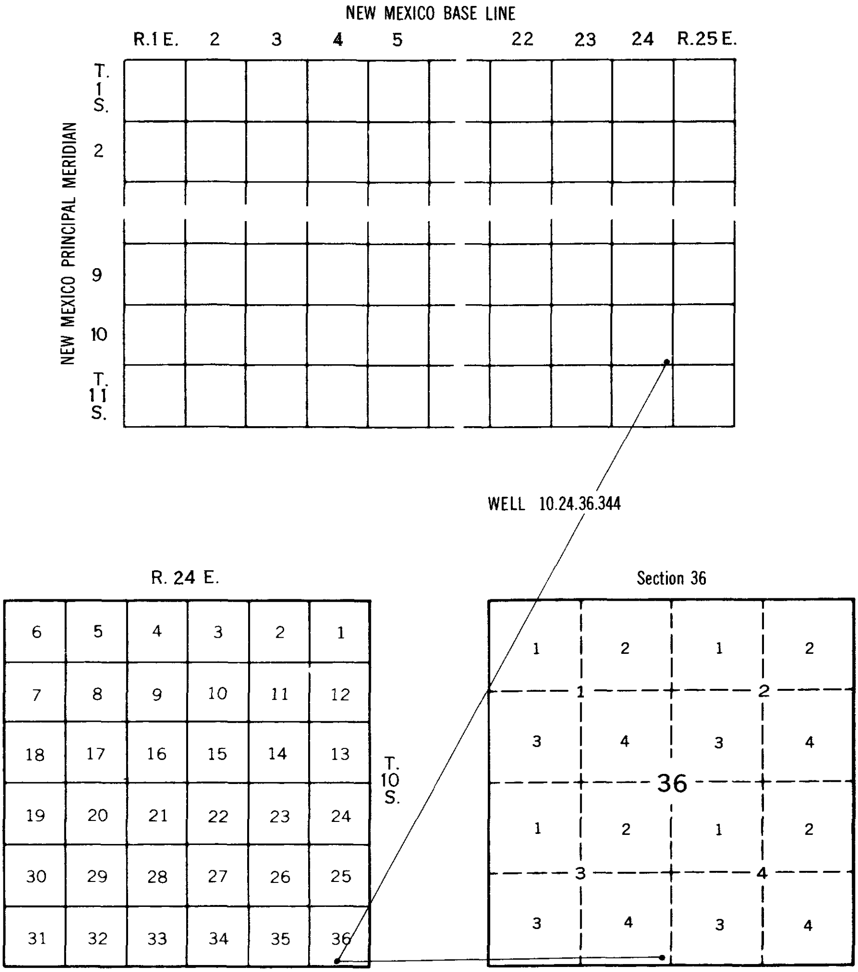

FIGURE 1.—System of numbering wells and locations in New Mexico.

Mexico principal meridian. The third segment denotes the number of the section within the township. The fourth segment denotes the particular 10-acre tract of the section in which the point is located. For this purpose the section is divided into four quarters, numbered 1, 2, 3, and 4, for the northwest, northeast, southwest, and southeast quarters, respectively. The first digit of the fourth segment gives the quarter section, which is a tract of 160 acres. Similarly, the quarter section is divided into four 40-acre tracts numbered in the same manner, and the second digit denotes the 40-acre tract. The 40-acre tract is divided into 10-acre tracts which are numbered in the same manner. Thus a point numbered 10.24.36.344 is located in the SE¼SE¼SW¼ sec. 36, T. 10 S., R. 24 E.

If a point cannot be located accurately within a 10-acre tract, a zero is used as the third digit, and if it cannot be located accurately within a 40-acre tract, zeros are used for both the second and third digits. If a point cannot be located more closely than the section, the fourth segment of the location number is omitted. When it becomes possible to locate more accurately a point in whose number zeros have been used, the proper digit or digits are substituted for the zeros. The letters a, b, c, and so forth, are added to the last segment to designate the second, third, fourth, and succeeding wells or points in the same 10-acre tract.

Wells are numbered on maps in this report by using the numerals of the fourth segment of the complete number. Township, range, and section numbers appear elsewhere on the map to aid the reader in identifying a location when the complete location number is mentioned in the text.

TOPOGRAPHY AND DRAINAGE

The area studied ranges in altitude form 3,520 feet near Acme to about 3,290 feet near Artesia. Physiographically, the area consists of a subdued alluvial terrace and a flood plain, immediately adjacent to the Pecos River, bounded by red-bed bluffs to the east and terraces to the west. The monotonous topography of the terraces is broken by ephemeral and water-table lakes and by the channels of eastward flowing tributaries to the Pecos River.

The Pecos River, the master stream of the Roswell basin and of southeastern New Mexico, flows southward through the area. From the gaging station near Acme to the gaging station near Artesia, a distance of 82 river miles, the Pecos River descends approximately 220 feet or about 2.7 feet per mile. This low gradient, together with the wide floodplains, oxbow lakes, and meander scars, indicate that the river is in a stage of late maturity or old age. Between Acme and Artesia, the principal tributaries to the Pecos River enter from the west and include, from north to south, the Rio Hondo, the Rio Felix, and Cottonwood Creek.

CLIMATE

Climatological records have been collected by the U.S. Weather Bureau at six meteorological stations in, and adjacent to, the area investigated for this report.

The records collected at the Roswell Weather Bureau station (Roswell WB AP) comprise the most complete set of climatological records within the general area of study. Records collected at this station include data on precipitation, temperature, relative humidity, and wind movement. Evaporation data are not collected at the Roswell

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WB AP station; however, records of evaporation and wind movement are available for stations at Lake Avalon and Bitter Lake National Wildlife Refuge (Bitter Lake WL Ref.).

The climate of the Acme-Artesia area is characterized by hot summers and cool winters. Daytime temperatures in the summer frequently rise above 100° F, but the mean summer temperature is about 80° F. Winter temperatures frequently drop below freezing at night, but rarely go below 0° F. The mean winter temperature is about 45° F. The mean annual temperature is about 60° F.

Thunderstorms during June through September contribute more than one-half of the annual precipitation. Summer rains are of high intensity and of short duration. Occasionally snow falls in the winter, but it melts quickly.

The growing season is about 6 months long and extends from mid-April to late in October. About 70 percent of the days in the year are sunny.

Monthly and annual mean values of the climatological data collected at and near Roswell through 1958 are given in table 1. Climatological data obtained during 1956, 1957, and 1958 at active stations in or near the area investigated are given in tables 2, 3, and 4.

NATIVE VEGETATION

The phrase "native vegetation" is used in this report to denote those species of plants which thrive and propagate naturally within the project area. Although the plants in this general category vary greatly in their individual characteristics, each species can be classified into one of three distinctive groups depending on the relation of the root system of that species to its water supply. The terms "phreatophyte," "xerophyte," and "hydrophyte" are used to designate these three distinctive groups of plants.

The term "phreatophyte" is derived from two Greek words meaning "well" and "plant." Phreatophytes are plants that extend their root systems to the water table, or to the capillary zone above it. Thus, these plants are able to secure a continuous supply of water that is largely independent of the short-term changes in soil moisture. Phreatophytes can thrive whether the water table is inches or tens of feet below the land surface. Phreatophytes infest thousands of acres of land within the project area and consume large quantities of water. Most of the phreatophytes in the project area have no economic value. Phreatophytes in greatest abundance are saltcedar, mesquite, saltgrass, and sacaton; others are present in small numbers.

TABLE 1.—*Mean monthly values for climatological data at and near Roswell, Chaves County, N. Mex.*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Temperature [1] ° F	39.9	44.0	51.1	59.3	67.7	76.4	78.7	77.6	70.9	59.9	47.9	40.1	59.5
Precipitation [1] inches	.42	.47	.56	.81	1.16	1.38	1.99	1.69	1.88	1.18	.62	.51	12.67
Evaporation [2] do	2.86	3.96	6.55	8.93	10.86	12.72	11.31	9.94	7.87	5.45	3.62	2.91	86.98
Wind movement [3] miles	1,393	1,535	2,260	2,579	2,099	2,363	1,931	1,749	1,186	1,186	1,199	1,412	20,892
Relative humidity [4] (percent):													
Time of measurement:													
5:00 a.m. m.s.t	65	64	54	52	59	60	71	71	68	71	63	64	64
11:00 a.m. do	42	40	28	27	29	30	38	37	38	39	34	36	35
5:00 p.m. do	38	33	22	20	23	22	32	32	33	36	33	28	29
11:00 p.m. do	56	52	41	38	44	44	54	56	55	57	53	54	50

[1] U.S. Weather Bureau, 1900–59.
[2] U.S. Weather Bureau, composite record for Roswell no. 2, 1940–59, Roswell WB AP, 1950, and Bitter Lakes Wild Life Refuge 1941–58.
[3] U.S. Weather Bureau, 1947–58, composite record for Roswell no. 2, 1947–49, Roswell WB AP, 1950, and Bitter Lakes Wild Life Refuge, 1951–58.
[4] U.S. Weather Bureau, 1948–58.

TABLE 2.—*Climatological data for 1956 from selected stations in the Roswell basin, Chaves and Eddy Counties, N. Mex.*

[Compiled from U.S. Weather Bureau records, 1956]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Precipitation (inches):													
Bitter Lakes W L Ref	0.02	1.30	T	T	0.15	T	0.53	0.57	0.00	0.54	0.00	T	3.11
Roswell WB AP	.02	1.42	0.03	0.03	.40	0.04	.54	1.13	.16	.54	T	0.04	4.35
Hagerman	.06	.76	.00	.08	.23	1.36	1.34	1.34	.29	.65	.00	.03	6.14
Artesia	.05	.45	T	.04	.91	2.08	.81	1.68	.12	.87	.00	T	7.01
Lake Avalon	.02	.27	.00	.07	.67	1.32	.91	2.26	.04	.53	T	.20	6.29
Temperature (°F):													
Bitter Lakes W L Ref	42.4	37.8	53.1	58.6	70.4	80.2	79.6	77.0	73.0	63.2	45.3	41.6	60.2
Roswell WB AP	42.1	37.4	52.5	57.7	71.5	81.1	80.5	78.3	73.5	63.1	44.6	41.7	60.3
Hagerman	42.3	38.1	51.1	56.7	70.2	79.5	79.6	76.7	71.7	62.8	43.6	40.9	59.4
Artesia	43.8	40.4	54.3	59.9	73.2	81.6	81.7	78.6	74.5	65.8	----------	45.2	----------
Lake Avalon	46.1	43.4	56.9	60.9	75.3	83.3	83.2	80.8	76.1	66.2	48.7	46.3	63.9
Wind movement (miles):													
Bitter Lakes W L Ref	1,352	1,811	1,970	2,322	2,366	2,257	2,037	2,838	1,846	1,881	1,451	1,404	23,535
Lake Avalon	2,196	2,891	3,083	3,180	3,031	2,391	2,282	2,231	2,166	2,122	1,973	2,351	29,897
Evaporation (inches):													
Bitter Lakes W L Ref	2.79	----------	7.77	9.84	13.10	13.54	13.27	11.60	11.10	7.82	3.84	3.04	----------
Lake Avalon	4.23	5.33	10.52	11.83	15.41	15.17	14.38	13.32	12.24	9.21	4.98	4.62	121.24
Relative humidity (percent):													
Roswell WB AP.													
5:00 a.m. m.s.t.	58	70	43	46	55	62	64	68	58	62	47	62	58
11:00 a.m. do	36	49	19	23	25	27	32	33	29	30	25	35	30
5:00 p.m. do	32	48	13	19	19	21	28	30	23	29	26	34	27
11:00 p.m. do	50	60	31	33	34	44	47	51	42	48	43	47	44

Frost and temperature extremes, 1956

	Temperature (°F)				Last frost in spring	First frost in fall	Frost-free Period
	Highest	*Date*	*Lowest*	*Date*	*Date*	*Date*	*(days)*
Bitter Lakes W L Ref	104	June 14	0	Feb. 5	Apr. 22	Oct. 27	188
Roswell WB AP	104	July 16	3	6	10	26	199
Hagerman	102	17	3	10	10	21	194
Artesia	104	17	8	10	10	27	200
Lake Avalon	105	16	12	2	10	25	198

TABLE 3.—*Climatological data for 1957 from selected stations in the Roswell basin, Chaves and Eddy Counties, N. Mex.*

[Compiled from U.S. Weather Bureau records, 1957]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Precipitation (inches):													
Bitter Lakes W L Ref	0.09	0.35	0.97	0.02	0.30	0.38	0.51	1.43	T	3.02	0.61	0	7.68
Roswell WB AP	.09	.64	.80	.31	.43	.06	.87	1.23	1.18	2.91	.80	0	9.32
Hagerman	.37	.34	.53	.05	1.58	.07	1.11	1.63	1.19	3.51	.98	T	11.36
Artesia	.15	.28	.26	.06	.88	.07	.60	.47	.07	2.48	.64	0	5.96
Lake Avalon	.04	.35	.75	.01	3.30	.02	.86	1.27	.05	4.06	.94	0	11.65
Temperature (° F):													
Bitter Lakes W L Ref	43.0	53.5	51.9	59.0	65.9	77.3	81.1	78.1	70.1	58.0	45.1	42.4	60.4
Roswell WB AP	41.6	52.3	51.5	57.0	66.6	77.9	82.6	79.4	70.4	58.1	44.8	43.7	60.5
Hagerman	42.3	51.8	50.7	57.1	65.3	75.4	80.5	78.8	70.0	57.9	44.8	43.8	59.8
Artesia	44.2	53.5	53.8	59.4	67.9	79.4	83.6	81.4	72.1	59.9	46.3	45.4	62.2
Lake Avalon	47.0	56.3	56.0	63.2	69.4	80.4	84.6	82.4	74.5	60.9	47.8	47.3	64.1
Wind movement (miles):													
Bitter Lakes W L Ref	1,700	1,699	2,855	3,542	2,412	2,066	2,161	1,657	1,228	1,242	1,475	1,768	23,805
Lake Avalon	3,125	2,477	3,508	3,510	3,133	2,710	2,499	2,120	2,057	2,365	2,355	1,933	31,792
Evaporation (inches):													
Bitter Lakes W L Ref	2.88	3.82	7.32	9.10	11.39	14.70	15.02	11.94	8.91	5.09	2.24	3.32	95.73
Lake Avalon	4.87	5.24	9.15	11.51	13.59	14.73	15.77	13.38	10.47	5.73	3.33	4.04	111.81
Relative humidity (percent):													
Roswell WB AP.													
5:00 a.m. m.s.t.	64	70	62	59	69	55	64	71	69	82	83	64	68
11:00 a.m. do	48	48	31	33	33	27	35	41	38	58	61	32	40
5:00 p.m. do	43	42	29	23	28	20	27	34	26	56	57	29	35
11:00 p.m. do	55	62	50	44	53	41	48	56	50	75	74	50	55

Frost and temperature extremes, 1957

	Temperature (°F) Highest	Date	Lowest	Date	Last frost in spring Date	First frost in fall Date	Frost-free Period (days)
Bitter Lakes W L Ref	109	June 29	0	Jan. 17	Apr. 14	Oct. 24	193
Roswell WB AP	108	29	6	18	12	26	197
Hagerman	107	July 2	3	Nov. 23	24	26	185
Artesia	110	2	4	23	8	26	201
Lake Avalon	108	June 27	−3	23	Mar. 7	Nov. 22	260

TABLE 4.—*Climatological data for 1958 from selected stations in the Roswell basin, Chaves and Eddy Counties, N. Mex.*

[Compiled from U.S. Weather Bureau, 1958]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Precipitation (inches):													
Bitter Lakes W L Ref	1.43	0.79	2.27	0.91	0.37	0.03	0.51	1.83	3.36	1.29	0.39	0.02	13.20
Rosewell WB AP	1.57	.84	1.93	.84	.77	.20	.66	1.27	3.56	.98	.19	.25	13.06
Hagerman	.86	.97	1.69	1.33	.16	2.28	.60	1.05	6.98	1.64	.18	T	17.74
Artesia	1.44	1.14	2.67	1.19	.14	2.97	1.34	2.06	4.76	1.79	.70	.01	20.21
Lake Avalon	1.35	.82	.95	1.05	.40	.58	1.11	4.03	5.97	2.98	.83	T	20.07
Temperature (°F):													
Bitter Lakes W L Ref	39.5	45.8	46.5	58.6	70.0	80.5	82.2	79.4	71.3	58.1	47.3	39.9	59.9
Roswell WB AP	39.5	45.0	46.3	58.3	70.3	81.3	83.1	80.5	71.3	58.6	49.1	40.5	60.3
Hagerman	38.5	44.6	46.2	56.3	68.7	80.1	----------	78.4	70.9	58.9	49.4	40.7	----------
Artesia	39.7	45.6	46.6	59.2	71.7	81.6	83.1	80.9	72.7	59.1	50.4	42.1	61.1
Lake Avalon	40.8	47.2	49.7	60.9	72.8	82.5	84.6	81.5	73.1	60.7	52.1	44.5	62.6
Wind movement (miles):													
Bitter Lakes W L Ref	1,965	2,497	2,141	3,262	2,413	2,707	2,475	1,778	1,737	1,144	1,363	1,278	24,760
Lake Avalon	2,045	2,785	3,287	3,355	2,352	2,809	2,533	1,667	1,822	1,416	1,915	1,735	27,721
Evaporation (inches):													
Bitter Lakes W L Ref	2.26	3.74	3.61	9.54	10.66	13.50	13.78	11.69	7.97	3.77	3.24	2.38	86.15
Lake Avalon	3.20	4.88	5.37	11.25	12.26	14.72	14.36	12.65	7.48	4.77	4.10	3.37	98.41
Relative humidity (percent):													
Roswell WB AP													
5:00 a.m. m.s.t.	77	74	82	64	70	64	69	72	82	86	77	77	75
11:00 a.m. do	52	53	63	40	38	36	37	42	56	56	44	51	47
5:00 p.m. do	42	40	50	30	20	27	28	33	50	53	41	40	39
11:00 p.m. do	68	63	72	52	52	45	50	57	68	77	66	68	62

Frost and temperature extremes, 1958

	Temperature (°F)				Last frost in spring	First frost in fall	Frost-free Period
	Highest	*Date*	*Lowest*	*Date*	*Date*	*Date*	*(days)*
Bitter Lakes W L Ref	112	July 14	3	Dec. 29	Apr. 14	Oct. 23	192
Roswell WB AP	110	14	11	31	14	31	200
Hagerman	107	15	7	20	13	31	201
Artesia	111	15	10	Jan. 1	14	Nov. 1	201
Lake Avalon	110	14	15	Dec. 31	Mar. 15	18	248

Saltcedar is not indigenous to the project area. It first appeared in the lower end of the Roswell basin in about 1912 and has spread upstream. Photographs of vegetation, including saltcedar, in the bottom land along the Acme-Artesia reach of the Pecos River are shown in the frontispiece and in figures 2 and 3.

The term "xerophyte" is derived from two Greek words meaning "dry" and "plant." Xerophytes do not extend their roots below the belt of soil water, and thrive in upland areas where the water table is at a considerable depth below the land surface. These plants depend on infrequent rains for their moisture requirements and are able to maintain themselves during prolonged periods of drought by becoming nearly dormant or by drawing upon moisture stored within the plant system. Some plants normally classified as xerophytes can be phreatophytes when the water table or capillary zone is within the reach of their root system. Mesquite is an example of a plant that can be either a xerophyte or a phreatophyte depending upon its environment. Mesquite, creosote bush, and cactus are but three of the many xerophytes growing in the area of investigation.

FIGURE 2.—View looking south from a point above NW¼ sec. 24, T. 11 S., R. 25 E., Chaves County, N. Mex. The areal density of most of the saltcedar in this view is greater than 75 percent. The relatively tall trees on the near bank of the river in the right-central part of the photograph are cottonwoods.

The term "hydrophyte" is a combination of the two Greek words for "water" and "plant." A hydrophyte grows only in water or in saturated soil where the water table either is at or no more than a few inches below the land surface. Hydrophytes are noted for their large water requirements; however, consumptive-use studies for these plants were not made because the volume of hydrophytes in the area studied was relatively small. Cattails, rushes (tules), and watercress are a few of the hydrophytes growing in the area.

AGRICULTURE AND DEVELOPMENT

The Acme-Artesia section of the Roswell basin consists of a highly productive cultivated area, generally west of and parallel to the Pecos River, and an area of native vegetation in the bottom land or flood plain of the Pecos River and its tributaries.

The cultivated area west of the Pecos River is devoted almost exclusively to irrigation farming. The soils are well suited for cultivation and irrigation water is obtained from the nonartesian and artesian ground-water reservoirs and from surface streams. The major crops

FIGURE 3.—View looking north-northeast from a point above NE¼ sec. 13, T. 17 S., R. 26 E., Eddy County, N. Mex. New Mexico Highway 83 bridge near center of photograph. The areal density of the saltcedar north of the highway is about 90 to 100 percent; the vertical density is about 100 percent.

are cotton, alfalfa, grain sorghum, and small grains; a small acreage is used for growing vegetables, broom corn, castor beans, and other minor crops. In 1958, the 105,000 acres of irrigated land in Chaves County produced crops worth approximately $20 million.

The bottom land of the valley is used mostly for pasture, and very little land is cultivated. The paucity of irrigation farming in the bottom land is due to: the lack of arable soils, particularly on the east side of the river; a saturated soil profile in parts of the area; the poor chemical quality of the water in both the shallow and artesian ground-water reservoirs in parts of the bottom land; the susceptibility of the bottom land to flooding; the expense involved in clearing, leveling, and maintaining these lands; the availability of more suitable farm land in other parts of the valley; the lack of water rights for these lands; and the difficulties encountered in developing satisfactory irrigation wells in the fine-grained sediments of the nonartesian ground-water reservoir beneath the bottom land.

Most of the population in the Acme-Artesia sector of the Roswell basin is concentrated in the vicinity of Roswell and Artesia. Roswell with a population of about 39,500 in 1960 is the largest city in the basin and is the second largest city in the State. It is the principal business center for southeastern New Mexico. Artesia, 39 miles south of Roswell, had a population of about 11,900 in 1960 and is the 11th largest city in New Mexico. Other towns in the area are Dexter, Hagerman, and Lake Arthur, which are 16, 23, and 29 miles south-southeast of Roswell, respectively.

Rail and truck services are available to all of these communities, and there is a commercial airport at Roswell. Rail service is by a branch line of the Atchison, Topeka, and Santa Fe Railway extending from the main line at Clovis, New Mexico, to the Texas and Pacific Railroad at Pecos, Texas.

U.S. Highway 285 traverses the Acme-Artesia area from north to south and passes through or near all of the principal communities. Highway connections to the east and west are provided by U.S. Highways 70 and 380, which intersect U.S. Highway 285 at Roswell, and New Mexico Highways 31 and 83, which intersect U.S. Highway 285 at Hagerman and Artesia, respectively. With the exception of the bottom land adjacent to the Pecos River, all the land in the valley may be reached from these highways by county and private roads. Some roads provide access to the margins of the bottom land, but few penetrate the dense thickets of bottom-land vegetation for any significant distance.

GEOLOGY

The Roswell basin is in the northwestern shelf area of the Delaware basin, a large structural depression centered in the extreme southeastern corner of New Mexico. The consolidated rocks exposed in and near the study area are Permian in age. They form the uplands from about 12 miles west of the Pecos River to the Sierra Blanca and Sacramento Mountains about 75 miles west of the river. The Permian strata form conspicuous westward-facing bluffs east of the Pecos River; farther east, they dip beneath Triassic shales and sandstones and Recent drifting sand. Surficial sediments in the project area are Recent alluvium and gently terraced Quaternary valley fill.

The geology of the Roswell basin was studied in detail by Fiedler and Nye (1933), Morgan (1938), and Bean (1949). The discussion of the geology of the area in this report was drawn largely from these sources. A stratigraphic section of the rocks in the Acme-Artesia area is given in figure 4.

STRATIGRAPHY

PERMIAN SYSTEM

Rocks of Permian age within the confines of the area, from lower to upper, include the Abo formation, Yeso formation, Glorieta sandstone, San Andres limestone, and the Chalk Bluff formation or its equivalent, the Grayburg formation. The San Andres limestone and Chalk Bluff formation compose the bedrock aquifers that yield water of quantity and quality suitable for irrigation. Rocks of the Abo and Yeso formations and the Glorieta sandstone underlie the project area at great depth and will not be discussed because of their remote relation to use of water in the bottom land.

SAN ANDRES LIMESTONE

The San Andres limestone is composed mostly of limestone and dolomite but includes minor quantities of interbedded limy shale, anhydrite, and gypsum. The San Andres is underlain conformably by the Glorieta sandstone and is overlain unconformably by the Chalk Bluff formation, and in places by Quaternary valley fill where erosion has removed the Chalk Bluff. Owing to these unconformities, the thickness of the San Andres limestone ranges from approximately 500 feet near Roswell to about 1,300 feet near Artesia; its average thickness is about 1,000 feet. From its outcrop about 12 miles west of the Pecos River the formation dips gently southeastward beneath younger sediments. Near the Pecos River the San Andres is covered by about 400 feet to about 950 feet of the Chalk Bluff formation and Quaternary valley fill. These overlying beds are thinnest in the northern part of the basin and become progressively thicker southward. The porosity and permeability are erratic throughout the San Andres. Vermiculate porosity and cavernous zones occur in the upper part of the limestone and to a lesser extent in the lower part; thus, the limestone is more permeable in the upper part.

Time Units			Rock Units
Era	Period	Epoch	
CENEZOIC	Quaternary	Recent	Recent alluvium
			Lakewood terrace deposits
		Pleistocene	Orchard Park terrace deposits
			Blackdom terrace deposits
			Quartzose conglomerate
PALEOZOIC	Permian	Guadalupe	Chalk Bluff formation
			Grayburg formation
		Guadalupe / Leonard	San Andres limestone
		Leonard	Glorieta sandstone
			Yeso formation
		Wolfcamp	Abo formation

FIGURE 4.—Stratigraphic section of rock units in the Acme-Artesia area, Chaves and Eddy Counties, N. Mex.

CHALK BLUFF FORMATION

RED BED-GYPSUM FACIES

The Chalk Bluff formation overlies the San Andres limestone unconformably. In the northern two-thirds of the area investigated, the Chalk Bluff is composed mostly of orange-red, limy, anhydritic siltstone and fine-grained sandstone intercalated with thick beds of white and gray gypsum and anhydrite, and minor amounts of gypsiferous limestone and blue shale. The red bed-gypsum facies of the Chalk Bluff formation is well exposed in the bluffs east of the Pecos River between Roswell and Artesia. Owing to erosion, the red bed-gypsum facies ranges in thickness (pl. 2) from 0 near Roswell to about 1,000 feet between Dexter and Lake Arthur.

GRAYBURG FORMATION

From Lake Arthur southward, the basal part of the Chalk Bluff formation grades into gray interbedded dolomitic sandstone and porous dolomite of the Grayburg formation. The dolomite of the Grayburg formation is not easily distinguished from the brown dolomite of the underlying San Andres limestone. The Grayburg formation increases in thickness southward from Lake Arthur at the expense of the red bed-gypsum facies. South of Artesia, the Grayburg is between 200 and 300 feet thick and is the principal artesian aquifer, the confining beds being the red bed-gypsum facies of the Chalk Bluff formation.

QUATERNARY SYSTEM

VALLEY FILL

Alluvial deposits of Quaternary age overlie the Permian rocks unconformably in the study area. The Quaternary sediments are principally along the west side of the Pecos River in a belt ranging from about 12 miles to 25 miles in width. They consist of lenticular deposits of clay, silt, sand, and gravel. The alluvial sediments were deposited by the Pecos River and its tributaries during at least four stages, each stage consisting of erosion followed by deposition. The sediments deposited during the three latest stages underlie the erosional terrace surfaces named, from oldest to youngest, Blackdom, Orchard Park, and Lakewood terraces. Deposits laid down during the earliest stage of deposition are called the "quartzose conglomerate." The quartzose conglomerate and the deposits underlying the Blackdom and Orchard Park terraces are considered to be of Pleistocene age; however, the quartzose conglomerate may be equivalent, in part, to the Tertiary Ogallala formation of the High Plains to the east. The deposits underlying the Lakewood terrace and the river alluvium are of Recent age.

The thickness of the Quaternary deposits ranges from 0 to about 350 feet. An alluvium-thickness map compiled by Morgan (1938, pl. 1) shows that the thickest accumulation is in a narrow belt parallel to and about 4 miles west of the present course of the Pecos River, from north of Roswell to just south of Lakewood. This probably is an ancient channel of the Pecos River. The quartzose conglomerate is the thickest and most consolidated of the alluvial deposits and is the principal unit of the nonartesian aquifer. Only the sediments underlying the Orchard Park and Lakewood terraces are exposed in the project area. They are red and blue clay, gray silt, and fine sand, and are thin and impermeable compared to the quartzose conglomerate.

Erosion has been active since the development of the Lakewood terrace, so that streams have become entrenched about 20 feet in the valley fill. A thin deposit of silt, sand, and gravel derived from older alluvium and from the limestone uplands to the west occupies the channels of the Pecos River and its larger tributaries.

WATER RESOURCES

GROUND WATER

The San Andres limestone, the limestone facies of the Clark Bluff formation, and the Quaternary alluvium contain the principal aquifers in the Acme-Artesia reach of the Roswell basin. Water in the limestone reservoir and limestone facies of the Chalk Bluff formation is under artesian pressure in the project area, but is nonartesian in these rocks in most of the Roswell basin west and northwest of the project area. Water in the valley fill is under water-table conditions. The red bed-gypsum facies of the Chalk Bluff formation is the overlying confining bed for the artesian system. The confining bed allows some upward movement of water, and where pressure is sufficient, water will move upward through the Chalk Bluff formation (fig. 5). Most of this water discharges into the Quaternary valley fill, but some is discharged directly to the land surface from the Chalk Bluff formation by springs, particularly in the Pecos River and its tributaries where their channels have cut into the Chalk Bluff formation. The general movement of water in the valley fill is toward the Pecos River.

ARTESIAN AQUIFERS

The principal artesian aquifers in the Roswell basin are in the San Andres limestone, and they yield more than one-half of all the water consumed in the basin. Water is under artesian pressure in only a small part of the San Andres limestone in the Roswell basin. In the Acme-Artesia area of the Roswell basin, the artesian aquifer in this

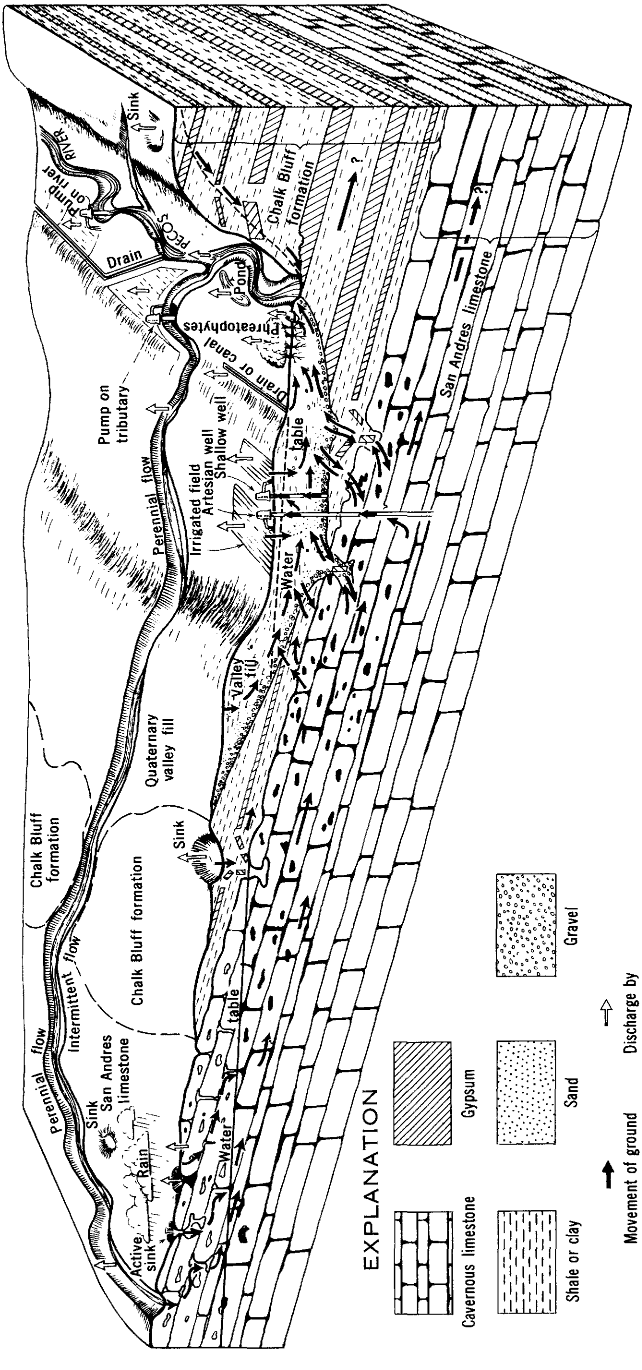

FIGURE 5.—Generalized diagram showing sources of recharge to the aquifers, movement of ground water, and points of discharge of ground water in the Roswell basin, Chaves and Eddy Counties, N. Mex.

formation extends from the bluffs east of the Pecos River westward to about 12 miles west of the river. Plate 3 shows the height to which water in tightly cased artesian wells will rise above the water table in the valley fill.

The exact limits of the ground-water reservoir (artesian and nonartesian) of the San Andres limestone are not pertinent to this report, but a generalized description of its limits is given to show that the reservoir is large in comparison to the Acme-Artesia area. The western limit of the reservoir is about 25 to 50 miles west of the Pecos River, in the area of outcrop of the San Andres limestone where the water table intersects the bottom of the limestone. A ground-water divide, north of Vaughn and about 100 miles north of Roswell, forms the northern limit of the reservoir in the Roswell basin. The limestone is relatively impervious east of the Pecos River, and movement of ground water eastward beyond the river is restricted. The bluffs east of the Pecos River are considered to mark the eastern limit of the reservoir. The Seven Rivers Hills mark the southern limit of the reservoir.

The San Andres limestone is not a single homogeneous aquifer, for the permeability of the limestone varies both laterally and vertically. If the full section of the San Andres limestone were present, it would be about 1,300 feet thick, but as much as 700 feet of the limestone was removed in local areas west of the Pecos River prior to the deposition of the Chalk Bluff formation. Artesian wells tap aquifers in the upper 500 feet of the limestone, but most commonly in the upper 300 feet. A few wells tap aquifers at greater depth.

HYDRAULIC COEFFICIENTS

A knowledge of the ability of an aquifer to store and transmit water enables the prediction of the ground-water regimen under a given set of conditions. The coefficient of transmissibility, the field coefficient of permeability, and the coefficient of storage are the three coefficients most often used for evaluating an aquifer. The coefficient of leakage, as defined by Hantush (1955), is given on page 6 of this report and is a fourth property that is used in the quantitative evaluation of leaky artesian aquifers in the Roswell basin.

The coefficients of transmissibility and permeability can be defined in several units of measurement. For the purpose of this report they are defined as follows: the coefficient of transmissibility is the rate of flow of water in gallons per day through a section of the aquifer 1 mile in width and the full thickness of the aquifer, under a hydraulic gradient of 1 foot per mile at the prevailing temperature. The field coefficient of permeability is the rate of flow of water, in gallons per day, through a section of aquifer 1 mile wide and 1 foot thick under a hydraulic gradient of 1 foot per mile. The coefficient of transmissibility is the product of the field coefficient of permeability and the thickness of the aquifer, in feet. The coefficient of storage of an aquifer is the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. The coefficient of storage is dimensionless.

Hantush (1955) conducted a series of pumping tests of the San Andres limestone. From four pumping tests he concluded that the average coefficient of transmissibility (Hantush, 1955, table 5) ranged from 1,400,000 gpd per ft (gallons per day per foot) in the vicinity of Rowell, to 66,000 gpd per ft in the vicinity of Lakewood; the average storage coefficient ranged from about 0.00001 to about 0.0001 in those same areas. Although these values were determined for relatively small areas, they probably represent near-maximum and near-minimum values for the areas where the San Andres limestone is tapped by irrigation wells. The values are too high for areas where the aquifer is not capable of supplying the quantities of water needed for irrigation.

RECHARGE

The high permeability of the San Andres limestone in its outcrop makes it very receptive to recharge. Fiedler and Nye (1933, p. 148-152) concluded that, although recharge occurs throughout the part of the basin west and north of the area covered by alluvium, most of the recharge to the San Andres limestone occurs in the principal intake area (Fiedler and Nye, 1933, pl. 2). The principal intake area includes about 1,200 square miles. The minor intake area includes about 5,800 square miles to the west and north of the principal intake area.

The quantity of recharge to the San Andres limestone has been estimated by several hydrologists. Fiedler and Nye (1933, p. 250–254) estimated that the average annual recharge was about 235,000 acre-feet. This estimate was based on the hypothesis that the discharge from all springs in the Roswell basin, prior to the construction of wells, reflected the average annual recharge to the San Andres limestone. Complete records of the flow of all springs along the Pecos River between Acme and Major Johnson Springs, which is below Lake McMillan (pl. 1), were not available to them; hence, they state that their estimate may contain considerable error.

Hantush (1955, p. 55) computed that the average annual recharge to the San Andres limestone from 1941 through 1953 was about 264,000 acre-feet. This figure was based on an inventory of all water available in the Roswell basin during this period. He assumed that the algebraic sum of the change in storage in the San

Andres limestone, the pumpage from this aquifer, and the upward leakage from it for a given period of time was a measure of recharge. The figures for the net change in storage and the quantity of upward leakage used by Hantush have not been confirmed; however, the yearly figures for pumpage he used for 1952 and 1953 probably were about 10 percent too high, and for 1941–51 were about 3 to 35 percent too low, according to Mower (1960, table 11). If the average yearly pumpage were 8.5 percent more than that assumed by Hantush, and the figures for upward leakage and net change in storage were correct, the average annual recharge for the period 1941–53 would have been about 280,000 acre-feet.

The amount of annual recharge computed by Fiedler and Nye, and by Hantush, are in reasonable agreement. Therefore, it is assumed that these figures represent the general magnitude of the average annual recharge to the San Andres limestone, although their figures may be conservative.

MOVEMENT OF WATER

The general movement of water in the San Andres limestone is eastward toward the Pecos River. The gradient of the water table in the recharge area of the San Andres limestone is eastward and in places is as much as 100 feet per mile. The gradient of the piezometric surface is east-southeastward across the cultivated part of the basin (a strip 3 to 7 miles wide west of and parallel to the Pecos River) at about 1 to 20 feet per mile and averages about 10 feet per mile (pl. 4).

East of the Pecos River, the movement of water in the limestone aquifer is more sluggish than west of the river. East of the river the major component of water movement in the limestone is southward. Lowering of the artesian pressure in the vicinity of Roswell by pumping of artesian wells has caused saline water in the limestone east of the river to move toward Roswell (Hood and others, 1959). Pumping has not reversed the hydraulic gradient; however, a decrease in pressure in the fresh-water part of the aquifer had caused the denser saline water to move upgradient. Encroachment of saline water will continue until a new point of equilibrium is established between the fresh water and saline water. Although the principal area of the saline-water encroachment in 1958 was near Roswell, other pumped areas toward which saline-water is encroaching have been detected between Roswell and Artesia.

The transmissibility of the San Andres limestone is not constant between the recharge area and the Pecos River. In general, the more permeable zones in the limestone are beneath and parallel to the principal surface drainage systems where the opportunity for solution activity of percolating ground water is greatest. Five such areas are indicated by Fiedler and Nye (1933, pl. 41).

DISCHARGE

Prior to the use of irrigation wells tapping the artesian aquifer, the discharge of the artesian aquifers was chiefly by upward seepage of water through the Chalk Bluff formation and the Quaternary valley fill. This seepage appeared at the land surface as springs and seeps along the Pecos River and its tributaries. The largest spring area was in the vicinity of Roswell where the Chalk Bluff formation is thin or absent. The Chalk Bluff formation thickens, and the rate of leakage per unit area diminishes, from Roswell southward and eastward; therefore, the quantity of upward leakage is less per unit area elsewhere in the basin than it is in the vicinity of Roswell.

The pattern of ground-water movement and points of discharge changed when irrigation wells were constructed to tap the artesian aquifers. The use of these wells lowered the artesian pressure in the spring area near Roswell, and the springs ceased to flow at the land surface. However, the artesian water continued to discharge into the valley fill below the land surface throughout the artesian area. Hantush (1955, p. 58) estimated that the upward leakage from the artesian aquifers to the valley fill is about 80,000 acre-feet per year under normal climatic conditions. Wells that tap the artesian aquifers discharged more than 250,000 acre-feet annually in the period 1953–58, and the discharge has been in excess of 200,000 acre-feet per year since 1944.

THE CONFINING BED

The Chalk Bluff formation is not considered to be a reliable source of water to wells. Although the entire formation probably is saturated with water in the area investigated, the rate of water yield to wells generally is small.

The Chalk Bluff is more important in a major part of the area as an aquiclude (confining bed) rather than an aquifer. The red bed-gypsum facies of the Chalk Bluff formation has a low permeability, and confines water in the San Andres limestone and the Grayburg formation.

Hantush (1955), on the basis of pumping tests, computed average coefficients of leakage for the red bed-gypsum facies of the Chalk Bluff formation which ranged from 0.00114 gpd per sq ft per ft in the Roswell area to 0.000061 gpd per sq ft per ft in the Dexter area. This range of values probably is representative of the leakage through the formation in the vicinity of the tests but may not be applicable in other areas, especially where the permeability of the San Andres limestone is low. In these latter areas there has been little circulation of water, and consequently, there has been little solution activity in either the San Andres limestone or the Chalk Bluff formation. The minimum value for coefficient of leakage in the Roswell basin probably is much lower than the lowest value computed from the aquifer tests, and the upper computed value of 0.00114 gpd per sq ft per ft probably is close to the maximum value.

Nearly all the recharge to the Chalk Bluff formation is derived from the underlying San Andres limestone. Water moving into the Chalk Bluff formation is not being stored in the formation but is moving through it. Little or none of the Chalk Bluff is dewatered during the pumping season; therefore, the formation contains approximately the same amount of water at all times.

NONARTESIAN AQUIFER

Water in the Quaternary valley fill is unconfined and in this report is called nonartesian water to differentiate it from the artesian water in the limestone aquifers. The nonartesian aquifer is second in importance to the artesian aquifers as a source of water for wells in the Roswell basin. Prior to 1930, only about 3 percent of all irrigation water used in the basin was from wells completed in the nonartesian aquifer; however, shallow-water development increased rapidly in the next decade. Since 1938, 30 to 40 percent of all irrigation water used in the Roswell basin was pumped from the nonartesian aquifer. In addition, nearly all ground-water seepage into the Pecos River discharges from the valley fill.

The nonartesian aquifer is composed of irregular beds of sand and gravel intercalated with beds of silt and clay, all of which were deposited by the Pecos River and its tributaries. The proportion of permeable beds of sand and gravel to relatively impermeable beds of silt and clay is variable. Most of the permeable beds are interconnected, but the degree of interconnection is variable. In some areas the aquifer may be highly permeable and in others it may be relatively impermeable.

The nonartesian aquifer ranges in width from about 3 to 10 miles and is about 65 miles long. It is parallel to and mostly west of the Pecos River and extends from about 6 miles northeast of Roswell, in Chaves County, to about 2 miles southwest of Lakewood in Eddy County. The west edge of the main part of the nonartesian aquifer is approximately 5 to 8 miles west of the Pecos River. Although the average thickness of the valley fill west of the Pecos River is about 150 feet, its average saturated thickness is only about 75 feet. The eastern edge of the valley fill is at the bluffs formed by the Chalk

Bluff formation east of the Pecos River. Between the bluffs and the Pecos River the alluvium is thin and probably averages less than 40 feet in thickness; its average saturated thickness is about 25 feet.

HYDRAULIC COEFFICIENTS

The hydraulic properties of the nonartesian aquifer have not been determined for the entire project area. Hantush (1955) made four pumping tests in shallow wells in Chaves County. These wells were a considerable distance west of the Pecos River, and the data from the tests probably are not representative of the aquifer characteristics in the bottom land. The tests were made in areas where the valley fill is coarse grained, whereas the valley fill in the bottom land consists principally of fine-grained sediments.

During the present investigation, 12 pumping tests were made at 6 locations in the bottom land, and coefficients of transmissibility were computed. The wells used for the tests penetrated thin, lenticular beds of Recent river deposits of fine sand, silt, and clay. The wells were drilled with a small rotary rig and were cased with 2-inch diameter plastic pipe. The casings were perforated with several hundred 1/8-inch holes. The bottoms of the casings were sealed to prevent sand from entering. A 1- to 2-inch envelope of 1/4-inch gravel was placed opposite the perforated part of the casing, after the casing was set in the hole. The wells were developed for several hours by pumping and surging.

The description of the test at well 11.25.36.143 is typical of the 12 tests. Well 11.25.36.143 is on a low mound in a natural clearing in a moderate to dense growth of saltcedar. The water level in the well was 14.36 feet below the land surface at the beginning of the test. The well was pumped steadily for 120 minutes at an average rate of 9.8 gpm; the discharge was determined frequently by measuring with a stop watch the time required to fill a 5-gallon bucket. The pumped water was discharged onto the land surface about 50 feet from the well and flowed another 50 feet. All of the water had percolated into the ground about 7 hours after pumping ceased, but it is believed that none of the water reached the water table during the test. There were no other observation wells, and it was not possible to measure the water level in the pumped well until the pump was removed. When pumping ceased, the pump was removed quickly from the well and the water-level recovery was measured. At the end of 7 hours of recovery, the water level was within 0.06 foot of the prepumping level.

The coefficient of transmissibility and the field coeffcient of permeability were computed to be 11,600 gpd per ft and 410 gpd per ft per ft respectively. The results of all 12 tests are given in table 5.

TABLE 5.—*Data from pumping tests in valley fill of the bottom land, Acme-Artesia area, Roswell basin, N. Mex.*

[Coefficient of transmissibility: representative of the aquifer to the depth drilled. Field coefficient of permeability: computed by dividing the coefficient of transmissibility by the depth drilled in alluvium]

Well	Depth drilled in alluvium (ft)	Depth cased (ft)	Perforated (ft)	Estimated thickness of alluvium (ft)	Static water level below land surface (ft)	Discharge (gpm)	Elapsed pumping time (min)	Coefficient of transmissibility *T* (gpd per ft)	Field coefficient of permeability *Pf* (gpd per ft²)
10.25.33.341	47	44	14–44	90	4.20	3.0	120	1,000	23
11.25.25.114	47	45	20–45	90	9.06	4.4	127	5,800	150
11.25.25.144	47	45	15–45	90	9.85	4.0	104	11,700	320
11.25.36.142	42	37	7–37	80	11.10	11.4	120	12,900	420
11.25.36.143	42	35	15–35	80	14.36	9.8	120	11,600	410
11.25.36.242	70	63	48–63	80	4.20	27.6	120	23,500	360
13.26.3.343	22	21	11–21	22	11.65	4.0	116	4,700	470
13.26.10.123	19	17	5–17	19	9.95	3.0	120	13,200	1,470
14.26.25.331	35	28	8–28	35	15.70	2.6	120	6,200	330
14.26.26.423	42	42	16–42	42	17.66	3.3	14	20,400	850
14.26.26.424	47	41	11–41	47	15.90	4.0	115	21,900	700
15.26.27.211	32	28	12–28	32	13.47	3.8	116	10,600	590

Pumping tests of 30 nonartesian wells outside of the bottom land, including the tests made by Hantush (1955), indicated that the coefficient of transmissibility averaged about 102,000 gpd per ft, and the field coefficient of permeability averaged about 850 gpd per ft per ft.

In addition to the tests described above, the approximate values for the coefficient of transmissibility were estimated from the specific-capacity tests of 11 shallow irrigation wells by the use of an equation (Theis, 1954) relating specific capacity and coefficient of transmissibility. The average coefficient of transmissibility computed for the 11 selected wells was 49,600 gpd per ft, and the average field coefficient of permeability was 485 gpd per ft per ft. The field coefficient of permeability computed by this method was about the same as the average coefficient computed for the 12 tests in the bottom land.

The coefficient of transmissibility in a narrow belt of the nonartesian aquifer between the cultivated land and the bottom land was computed to be the quotient of the quantity of ground water moving across the belt per day divided by the sum of the slope of the water table across the belt and the length of the belt. This belt is shown on plate 5 by a heavy line drawn parallel to and west of the Pecos River.

The rate of ground-water movement across the belt could not be measured directly, but it was assumed to be about equal to the rate of ground-water inflow to the Pecos River and tributaries during times of minimum evaportranspiration, pumping from wells, change in ground-water storage in the bottom land, and change in river stage, and during a time when the Pecos River was in low-flow stage.

The maximum rate of ground-water inflow to the river was computed using data obtained during seepage investigations of that reach of the Pecos River between the gaging stations near Acme and Artesia. A seepage investigation, as referred to in this report, consists of measurements of flow in the Pecos River at selected sites throughout the reach, flow to the river from tributaries and drains, and diversions from the river. A summary of the quantities of inflow and diversions, either measured or computed for seepage investigations made between January 4, 1956 and March 6, 1959, are shown in table 15.

The rate of ground-water inflow to the Pecos River is at a maximum sometime during the winter months, probably in January and February. The chances were small that a seepage investigation would be made when the ground-water inflow to the river was at a maximum; therefore, an attempt was made to extrapolate data from a seepage investigation to compute maximum ground-water inflow to the river. The river stage at the gaging stations near Acme and Artesia, diversions of river flow, and ground-water levels were studied to determine the approximate time of maximum ground-water inflow to the river. The calendar year 1956 was selected for the study because the seepage investigation data were more complete for that year. Graphs showing the river stages at the gaging stations near Acme and Artesia were inspected for 1956, and all stages representing flood flows were deleted from the record of each station, the deleted record being replaced by an interpolated record representing low flow only. After this was done, the graph in figure 6 was prepared to show the daily difference between the low flow at the gaging station near Acme and that at the gaging station near Artesia, allowance being made for time of water travel between the two stations. The narrow valleys in the graph are attributed to diversions and some peaks in the graph reflect spill from the Hagerman Canal, both of which are not corrected for on the graph. The general February high of the graph was interpreted as probably representing the net gain in flow in the reach at the time of maximum ground-water inflow to the river. One of the highest points on the graph was on February 18, a date when no water was being spilled from Hagerman Canal and no river diversions were being made. This date was selected for computing the maximum ground-water inflow to the river. The net gain in the reach on that date was about 95 cfs (cubic feet per second), but was less than the total gain in the reach by the rate that was being evaporated from the surfaces of the Pecos River, tributaries, and lakes and ponds that discharge to the river and tributaries. An evaporation pan near Bitter Lake registered 0.11 inch of evaporation on February 18, a rate equivalent to about 7 cfs of evaporation from the river and lake surfaces in the reach. The total gain probably was about 102 cfs.

Not all of the 102 cfs of flow represents ground water moving across the belt between the cultivated land and the bottom land, because some of the gain was inflow to the bottom land through tributaries and drains (see inflow to the Acme-Artesia reach of the Pecos River from sources outside the bottom land in table 15). Data from the seepage investigations of February 26 and 27 were extrapolated to the February 18 date to compute the gain in river flow that is derived from ground water crossing the belt in the nonartesian aquifer. The apparent net gain in flow to the Pecos River on February 26 and 27 averaged about 80 cfs, and the apparent gain in flow attributed to ground-water sources within the bottom land (ground water that moved across the belt) averaged about 73 cfs (table 15). Evaporation from a pan near Bitter Lake was 0.28 and 0.58 inch respectively on February 26 and 27. The lower evaporation rate was used in computing evaporation, and the equivalent evaporation from the surface-water bodies in the reach was about 18 cfs. The total gain in riverflow on February 26 and 27 was about 98 cfs. The relation of apparent gain in the river (80 cfs) to total gain (98 cfs) should be equal to the relation of apparent gain from ground water (73 cfs) to the total gain in ground water (89 cfs). If 89 cfs of ground water entered the river when the total gain was 98 cfs on February 26 and 27, then about 91 cfs of ground water probably entered the reach when the total gain was 102 cfs on February 18. Therefore, the rate at which ground water moved across the belt in the nonartesian aquifer is about 6.0×10^7 gpd or 67,000 acre-feet per year.

The length of the belt of nonartesian aquifer in the Acme-Artesia reach is about 60 miles; therefore, about 9.8×10^5 gpd would have moved across each mile of the belt if the flow were uniform throughout the reach.

The slope of the water table across the belt was measured from a water-table contour map for January 1957 (fig. 6). A water-table contour map for February 1956 was not available; however, a study of the February 1956 and January 1957 water levels in wells near the belt indicated that probably there would be little difference between the two maps if the February 1956 had been available. The slope of the water table across the belt averaged about 23.6 feet per mile in the Acme-Artesia reach; therefore, the coefficient of transmissibility averaged about 42,000 gpd per ft. The saturated thickness of the nonartesian aquifer averaged about 96 feet along the belt; therefore, the field coefficient of permeability of the nonartesian aquifer averaged about 440 gpd per ft per ft.

The aquifer coefficients computed by this method may be too low because the quantity of ground water moving across the belt may

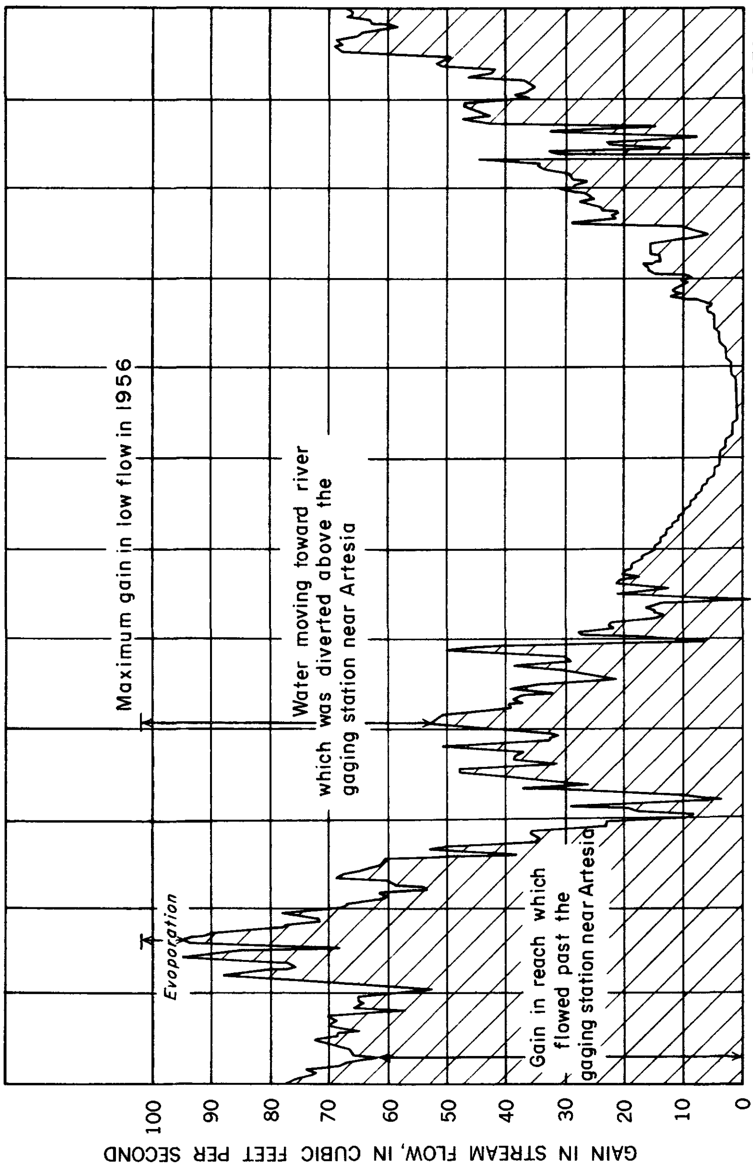

FIGURE 6.—Hydrograph showing net gain in the low flow of the Pecos River in the Acme-Artesia reach, Chaves and Eddy Counties, N. Mex.

exceed 91 cfs by the rate at which water was entering ground-water storage and by the rate that ground water was being lost by evaporation from the land surface in the bottom land. On the other hand, the coefficients may be too large, because the 91 cfs probably included some water entering the nonartesian aquifer from the artesian system beneath the bottom land. The coefficients will be larger or smaller than those computed, depending on the direction of adjustment needed to compensate for the unbalance among these other factors.

The field coefficient of permeability of the nonartesian aquifer within the belt between the cultivated land and the bottom land should be less than the field coefficient of permeability of the nonartesian aquifer beneath the cultivated area, but more than that of the nonartesian aquifer beneath the bottom land. A simple average of the two permeability coefficients (table 6) for tests in the cultivated area is about 670 gpd per ft per ft. This, averaged with the 510 gpd per ft per ft for test of wells in the bottom land, gives an average of 590 gpd per ft per ft for the belt area. This is considerably more than the 440 gpd per ft per ft indicated on page 31. It is believed that a field coefficient of permeability of about 500 gpd per ft per ft may be closer to the true value for the belt area than either the 440 or 590 gpd per ft per ft.

TABLE 6.—*Summary of hydraulic coefficients for the nonartesian aquifer in the Acme-Artesia area, Roswell basin, N. Mex.*

Determined by	Average coefficient of transmissibility *T* (gpd per ft)	Average field coefficient of permeability *Pf* (gpd per ft²)
Tests of 30 irrigation wells outside of bottom land	102, 000	850
Tests of 12 small-diameter wells in bottom land	12, 000	510
Tests of specific capacity of 11 irrigation wells	49, 600	485
Computation of movement of water eastward across belt between cultivated land and bottom land in the Acme-Artesia area	42, 000	440

RECHARGE

Ground water in the Quaternary valley fill is derived from five sources: infiltration from streams flowing across it, infiltration of precipitation, upward leakage through confining beds from underlying artesian aquifers, infiltration of irrigation water, and leakage from artesian wells. The first three are natural sources and the other two are the result of activities of man. The amount contributed by each source varies with locality and time.

The amount of annual recharge from streams crossing the valley fill varies widely, and data from which to estimate recharge are insufficient.

Recharge from precipitation was estimated by Morgan (1938, p. 28) as not more than one-half inch per year; this amounts to about 4 percent of the average annual precipitation. In the phreatophyte areas, all of the precipitation during the growing season and most of that during the rest of the year is transpired or evaporated and does not recharge the shallow aquifer. For the purposes of computation in this report, all of the precipitation on the phreatophyte area in 1956–57 and most of the precipitation in 1958 was considered to have been consumed by evapotranspiration.

Recharge to the nonartesian aquifer as upward leakage from the artesian system is not uniform at all points between Acme and Artesia. The amount of water percolating upward through a unit area of the confining bed (red bed-gypsum facies of the Chalk Bluff formation) varies with the difference in head across the confining bed. Upward leakage of artesian water in the bottom land is about one eighth of the total upward leakage in the Acme-Artesia area of the Roswell basin. This figure was obtained by comparing the average annual difference in head across the Chalk Bluff and the thickness and areas of the Chalk Bluff west of the project area to the thickness and areas of the Chalk Bluff formation in the project area and by using the coefficients of leakage derived by Hantush (1955, p. 29). Hantush (1955, p. 51) concluded that the average annual leakage was 80,000 acre-feet in the entire Roswell basin; therefore, the average annual leakage in the bottom land presumably is about 10,000 feet per year. In general, the amount of recharge from the artesian system per unit area of valley fill increases from west to east.

Recharge to the valley fill as infiltration of irrigation water probably averages about one fifth of the total irrigation water used. This recharge was about 100,000 acre-feet per year during 1956–58. Less than 1,200 acre-feet per year was recharge from irrigation water used in the bottom land.

Recharge from underground leaks through defectively cased artesian wells is negligible in the bottom land. The law requires that artesian wells known to leak underground into the shallow aquifer be repaired or plugged. The Pecos Valley Artesian Conservancy District plugged 1,129 leaky artesian wells from September 1931 to December 1958. The testing for leaks in all artesian wells is not complete, but the amount of recharge to the valley fill from this source probably is relatively small compared with recharge from other sources.

There is a small quantity of ground-water inflow to the basin from the north at the gaging station near Acme. The water-table contour maps (pls. 5 and 6) do not show the water-table configuration at that gaging station. However, it was assumed that if the water table near the gaging station slopes toward the river as it does in the mapped area, the principal component of ground-water movement would be toward the river in the vicinity of the gaging station rather than parallel to the river. Therefore, the ground-water inflow at the gaging station near Acme probably is small because the water-table gradient and cross sectional area of the fill are small. It is estimated that the inflow at Acme probably is counterbalanced by an equivalent quantity of ground-water outflow from the basin past the gaging station near Artesia, because the water-table contours (pl. 5) indicate that the movement of ground water in the vicinity of Artesia also is toward the river rather than southward.

Morgan (1938, p. 66) estimated that the total recharge to the nonartesian aquifer was about 142,000 acre-feet per year. Hantush (1955, p. 58) estimated that, under normal weather conditions, the annual recharge would be about 154,000 acre-feet. Below-normal precipitation, below-normal streamflow, less upward leakage of artesian water as a result of heavier pumping from the artesian system, and the repair and plugging of leaky artesian wells have caused some reduction in recharge in the period 1938–58. This reduction was offset, in part, by an increase in recharge from infiltration of irrigation water, because more artesian water was used to make up for a deficiency of precipitation. It is estimated that the annual recharge during 1956–58 was in the order of about 150,000 acre-feet.

MOVEMENT OF WATER

The direction of ground-water movement in the valley fill was interpreted from water-table contour maps prepared as of January 1957 and August 1958 (pls. 5 and 6).

The general movement of water in the nonartesian aquifer is toward the Pecos River. Unless the shallow ground water is intercepted by wells, drains, evapotranspiration, or tributaries of the Pecos River, it will discharge directly to the Pecos River. Most of the shallow ground water moving toward the river moves eastward from west of the river; some ground water enters the river from the east, but the amount is relatively small.

The movement of water in the valley fill is influenced by the large-scale pumping of shallow wells for irrigation use. In Tps. 10 and 11 S., where the annual pumpage from shallow wells is relatively small, the movement of water is toward the river, except near the stream channels that intersect the water table (pl. 5). In contrast, the annual pumpage from the shallow aquifer is large in Tps. 12, 13, and 14 S., and pumping of wells has created large depressions in the water table, toward which the shallow ground water converges from all sides. Along the eastern side of these water-table depressions, ground-water divides exist, and there some of the water moves toward the depressions and some toward the river. These depressions have been enlarging in area and depth each year, and the eastern parts of the depressions probably will reach the bottom land and the Pecos River soon in some areas. When this happens, water will move from the river and bottom land toward the pumped area.

Southeast of Hagerman, near sec. 24, T. 14 S., R. 26 E., the water table was almost horizontal between the cultivated area and the river in August 1958 (pl. 6). From the vicinity of sec. 24 to south of Lake Arthur the movement of ground water in the bottom land was southward approximately parallel to the river and at a low gradient. In this area of low gradient, the use of water by phreatophytes probably caused some movement of water from the river to the phreatophyte area. If the downward trend of the nonartesian water levels in the cultivated area continues, most, if not all, of the recharge to the aquifer in the phreatophyte area in this subreach will be from seepage from the river. Provided the rate of seepage from the river is insufficient to maintain the volume of phreatophyte growth that existed in 1958, some of the phreatophytes would die and the water use by this vegetation would decrease. Several years probably would elapse before substantial decreases in phreatophyte growth would be effected, and in the meantime, the phreatophyte growth might increase before it begins to recede.

The amount of water moving through the valley fill toward the Pecos River, per unit length of river, probably is larger in the vicinity of Roswell than elsewhere in the Acme-Artesia reach. Pumpage from the valley fill is smaller in the vicinity of Roswell because most of the irrigation water used in that area is pumped from artesian wells. The Chalk Bluff formation is thin in that area, and there is a large amount of upward leakage from the artesian system. Recharge from the irrigation water and upward leakage from the artesian system combine to make a high recharge rate per unit area of valley fill. These waters move eastward through the valley fill and maintain the water table at a shallow depth in the bottom land, a condition that is favorable for the growth of phreatophytes.

DISCHARGE

The Quaternary valley fill is the source of water for most of the phreatophytes in the Acme-Artesia area, but all the water in the fill is not available for use by those plants. Irrigation wells in the cultivated area pump 150,000 to 200,000 acre-feet of water each year from the nonartesian aquifer. Studies of the recharge to and discharge from the valley fill reveal that pumpage each year by nonartesian irrigation wells exceeds the average annual recharge to the valley fill. Other sources of nonartesian water discharge, such as drains, transpiration by phreatophytes, and seepage to the Pecos River and its tributaries increase the annual overdraft.

The distribution of large-scale pumping is not uniform throughout the nonartesian aquifer. The unevenness of the pumping pattern and recharge pattern have greatly lowered the water table in some areas, and in other areas the land has been waterlogged. Ground-water levels in the valley fill rose rapidly following the large-scale development of the artesian water for irrigation. Large tracts of low-lying lands were waterlogged by 1910, and drains (open and tile) were installed in the Roswell, East Grand Plains, Dexter and Greenfield, Hagerman, and the Lake Arthur to Artesia areas. The open drains were used principally to carry effluent from the tile drains to natural channels. Of the 347 miles of drains constructed, only 166 miles were active by 1957. Deterioration of the drains and lowering of the shallow-water levels by wells in the valley fill caused 181 miles of drains to dry up. The active drains discharged about 6,500 acre-feet of water in 1956, about 6,000 acre-feet in 1957, and about 7,000 acre-feet in 1958. About 3,200 acre-feet of drain discharge was used to irrigate fields in 1956, about 2,900 acre-feet in 1957, and about 2,500 acre-feet in 1958; the remainder of the drainage water discharged to the Pecos River and its tributaries.

Evapotranspiration consumes large quantities of nonartesian ground water each year. An estimate of this discharge will be given later in this report.

Some nonartesian ground water discharges directly to the Pecos River. The rate of discharge varies seasonally, and estimates of the annual discharge are developed in this report (p. 30–31 and table 9) as a means of determining the total water use in the bottom land. The fact that water passes through the bottom land and discharges into the river indicates that the phreatophytes are not using all of the water available to them; therefore, there is water available to support additional phreatophyte growth.

WATER-LEVEL FLUCTUATIONS IN WELLS

A systematic and prolonged series of measurements of the water level or artesian pressure in a well can reveal trends in the change of ground-water storage in the aquifer tapped by the well. A change in storage indicates an unbalance between recharge and discharge. The unbalance may be short-termed, long-termed, or a combination of the two, and may be local or basin-wide. Water-level fluctuations in wells can be classed roughly into four categories with respect to time: secular; seasonal; diurnal; and sporadic.

Secular fluctuations are long-termed fluctuations extending over a period of years and represent a prolonged trend in net difference between recharge and discharge. In the Acme-Artesia area, the dominant secular fluctuation in the period 1956–58 was a continuation of a trend starting after 1943, and is one in which artesian pressure and nonartesian water levels have trended downward because discharge was in excess of recharge. General drought conditions and increased pumpage of ground water to meet irrigation requirements have created the unbalance between recharge and discharge. Factors promoting this condition probably also have slowed the spread of phreatophytes, particularly saltcedar. The below-normal precipitation probably has retarded the spread of saltcedar more than the declining water levels have, because the soil moisture was too low to nurture seedlings outside the areas of high water table. If similar climatic conditions persist, the decline in nonartesian water levels will start to control the spread or intensification of saltcedar growth by lowering ground-water levels to depths beyond the reach of the roots in areas where saltcedar is growing or is becoming established.

Fluctuations of ground-water levels caused by differences between recharge and discharge and identifiable with the seasons of the year are referred to as seasonal water-level fluctuations. In the Acme-Artesia area the dominant seasonal fluctuation is cyclical in character. Artesian pressure and nonartesian water levels fluctuate through a cycle ranging from a high in January and February, to a low in August and September, and back to another high level the following January and February. Figures 7 to 10 show hydrographs of the mean monthly water levels in selected artesian wells. Figures 11 and 12 show hydrographs of water levels in selected nonartesian wells.

The dominant seasonal fluctuation in the cultivated area is attributed to the pumping of irrigation wells during the summer months. The rate of pumping from these wells temporarily exceeds the replenishment to the aquifer in the area of pumping, and the water levels decline. After pumping ceases, the replenishment exceeds the discharge and the water levels rise. The amplitude of the cycle is greatest in the centers of heavy pumping, and decreases with distance from the pumped areas. The ground-water levels in the phreatophyte areas declined because of pumping of irrigation wells and the draft by phreatophytes. The phreatophytes function as pumps, and their pumping and nonpumping season coincides with that of the irrigation wells; therefore, in the bottom land the amplitude of the seasonal fluctuations caused by the pumping of the irrigation wells is accentuated by the withdrawal of ground water by the phreatophytes.

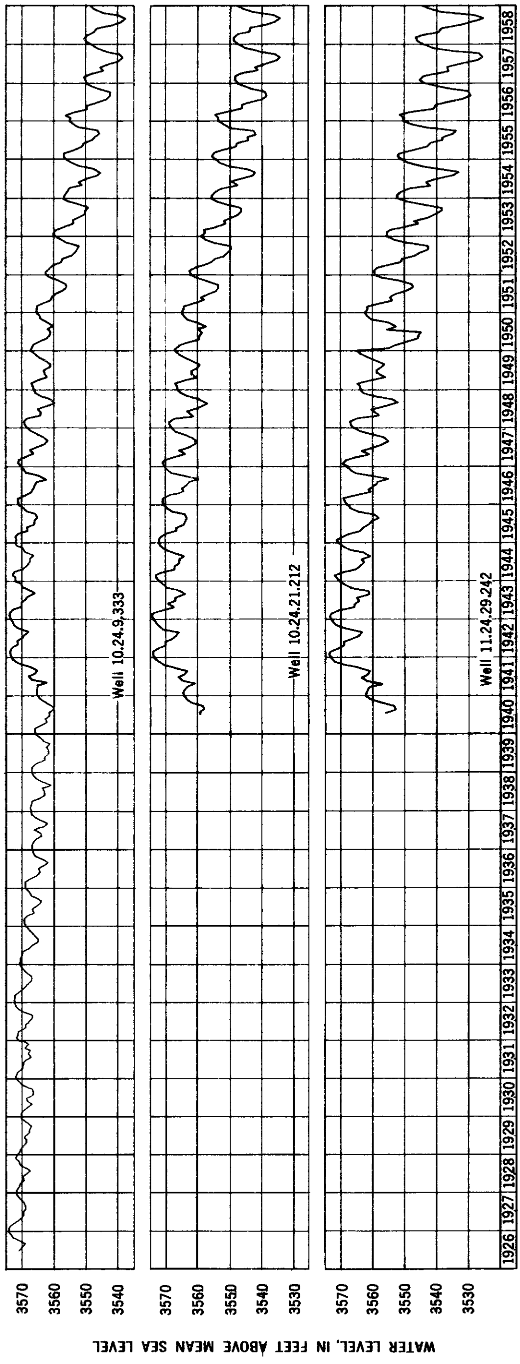

FIGURE 7.—Hydrographs of mean monthly artesian water levels in wells 10.24.9.333, 10.24.21.212, and 11.24.29.242 in the Roswell basin, Chaves County, N. Mex.

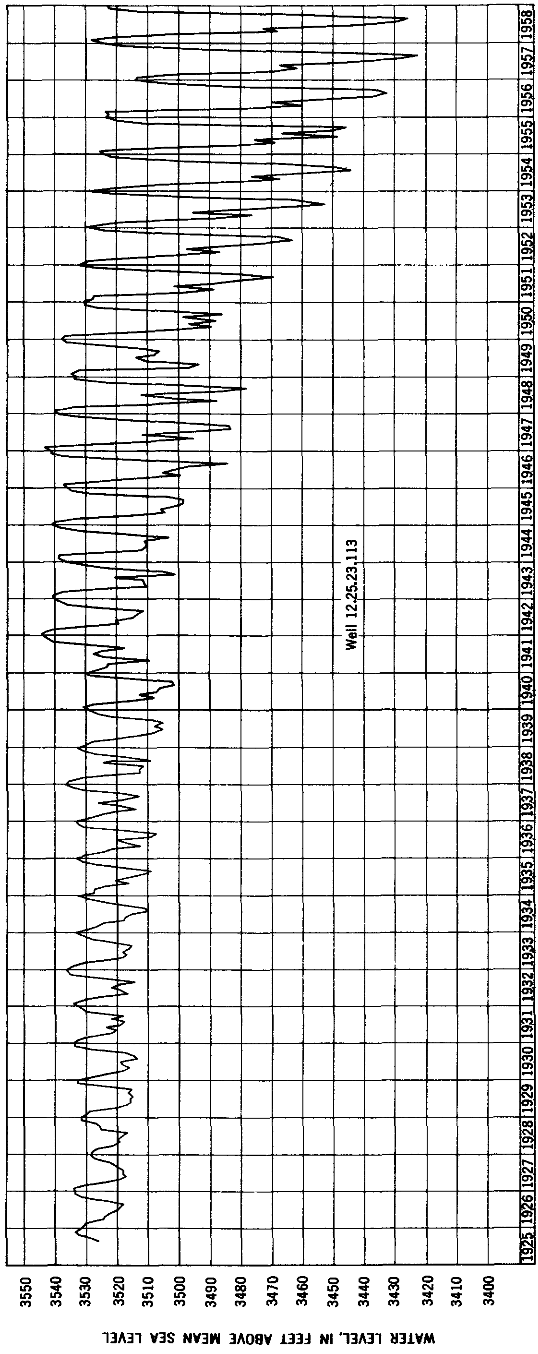

FIGURE 8.—Hydrograph of mean monthly artesian water level in well 12.25.23.113 in the Roswell basin, Chaves County, N. Mex.

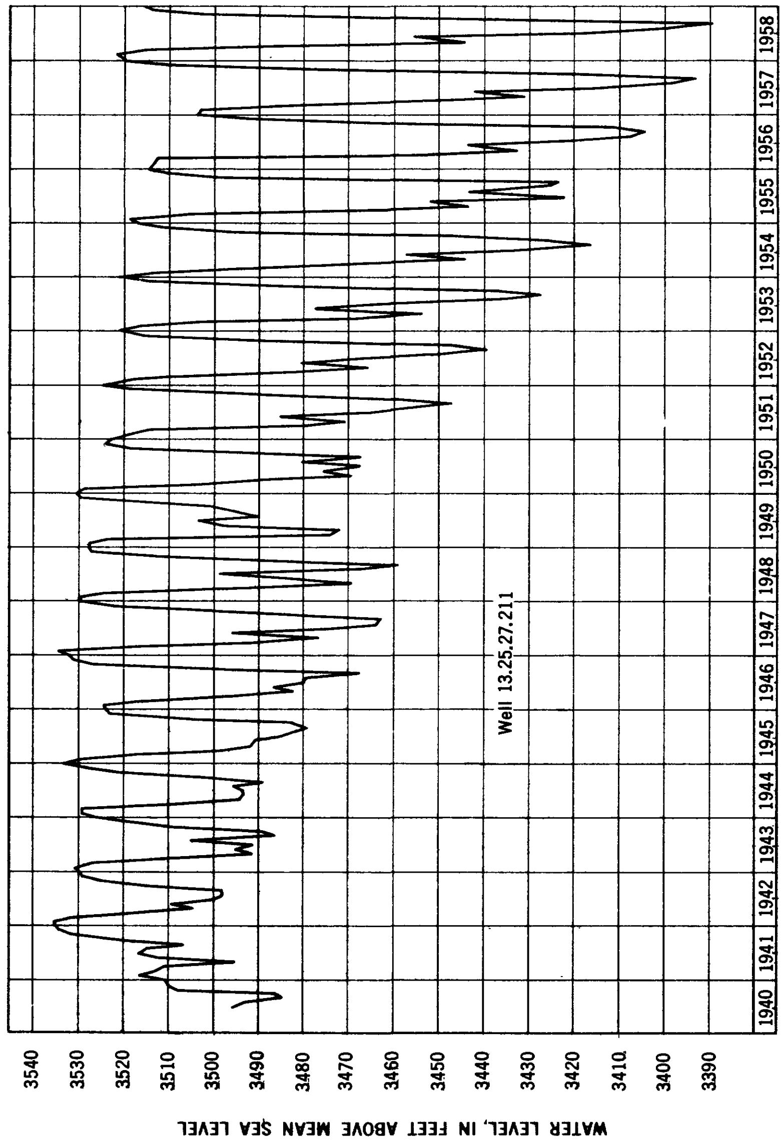

FIGURE 9.—Hydrograph of mean monthly artesian water level in well 13.25.27.211 in the Roswell basin, Chaves County, N. Mex.

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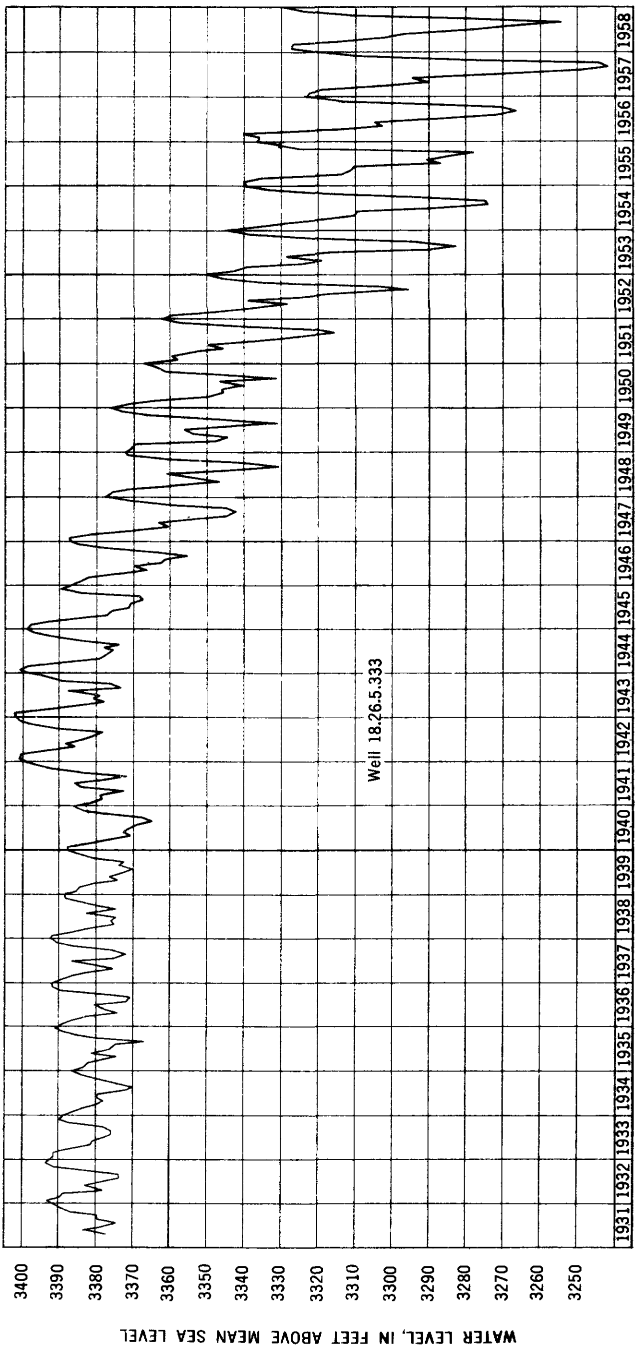

FIGURE 10.—Hydrograph of mean monthly artesian water level in well 18.26.5.333 in the Roswell basin, Eddy County, N. Mex.

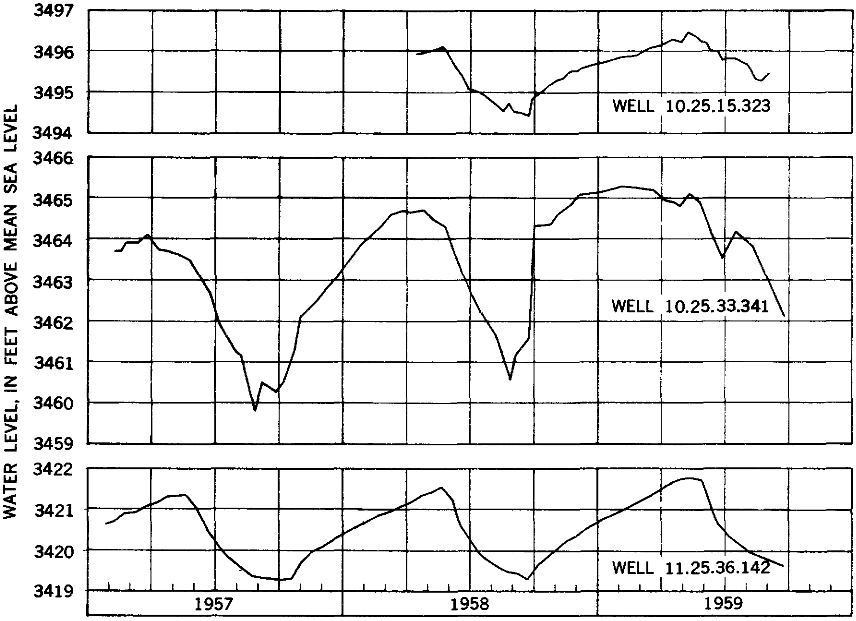

Figure 11.—Hydrographs of nonartesian water levels in wells 10.25.15.323, 10.25.33.341, and 11.25.36.142 in the Roswell basin, Chaves County, N. Mex.

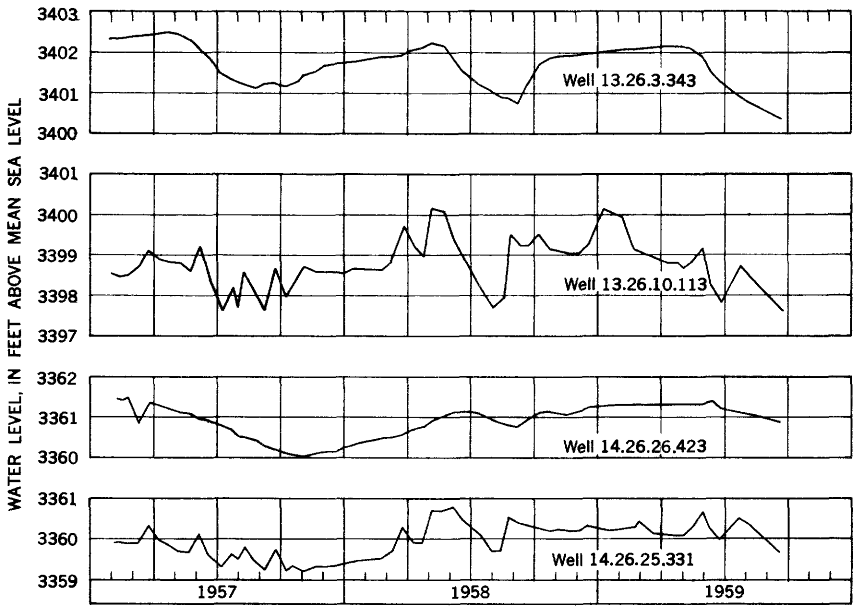

Figure 12.—Hydrographs of nonartesian water levels in wells 13.26.3.343, 13.26.10.113, 14.26.25.331, and 14.26.26.423 in the Roswell basin, Chaves County, N. Mex.

The amplitude of the seasonal cycle in the phreatophyte area probably will increase when seasonal water-level fluctuations, caused by pumping of nonartesian irrigation wells, reach the phreatophyte area. Where seasonal drawdown lowers nonartesian water levels faster and to greater depths than phreatophyte roots can follow, the phreatophytes eventually may die. The amplitude of the seasonal water-level fluctuation in the bottom land in 1958 was too small to affect the phreatophytes.

Diurnal water-level fluctuations are those fluctuations that occur with daily regularity, but not necessarily with the same magnitude each day. The principal diurnal fluctuation relating to the phreatophytes is that caused by changes in the rate of evapotranspiration during the day. When the rate of water movement to the phreatophyte area is uniform, the water-level fluctuation is cyclical in form and ranges from a high water level in midmorning to a low water level in mid or late afternoon. The decline in water level is caused by the withdrawal of ground water by the phreatophytes during the daylight hours when water use by the plants is at a maximum rate; the rise in water level is the result of a reduction in withdrawals of water during the night when water use by the plants is at a minimum rate. More details of these diurnal fluctuations are given later in this report in the discussion of the transpiration-well method for determining the use of water by phreatophytes.

Sporadic water-level fluctuations are those caused by a local fluctuation in recharge or discharge of relatively short duration. Intermittent pumping of a well and the rise and fall of stage in the Pecos River and its tributaries are two causes of sporadic water-level fluctuations in the Acme-Artesia area.

Sporadic water-level fluctuations in the phreatophyte area as the result of intermittent pumping of irrigation wells are localized around the few irrigation wells in the bottom lands; therefore the effects on the overall phreatophyte growth and water use in the bottom land are relatively small.

Changes in stage in the Pecos River and tributaries cause fluctuations in ground-water levels in the phreatophyte area. Hydrographs of figures 11 and 12 depict water-level fluctuations in nonartesian wells near the Pecos River. Water levels in wells 13.26.10.113 and 14.26.25.-331 responded readily to changes in stages of the nearby river, while their companion wells showed relatively little response. The sporadic water-level fluctuations near the river are caused by pressure effects in response to the river stage and by the movement of river water into and out of bank storage. Recharge from the river probably does not move more than a few tens of feet into the nonartesian aquifer unless the high river stage is sustained for a relatively long period of time. Phreatophytes growing within the first few tens of feet from the river receive some of their water as seepage from floodflows; the amount received decreases with distance from the river. Data are insufficient to make an estimate of the total amount of water the phreatophytes receive each year from floodflows.

All the water-level fluctuations that occur in the Acme-Artesia area and all the causes of fluctuations of water levels have not been discussed. Many of the fluctuations are minor, and some do not represent changes in water storage. The discussion has been limited to those fluctuations that could affect the growth of phreatophytes.

SURFACE WATER

The Roswell basin is drained by the Pecos River which traverses the basin from north to south. The principal tributaries in the Acme-Artesia reach originate west of the Pecos River. Berrendo Creek, North Spring River, Rio Hondo, South Spring Creek (formerly called the South Spring River), Rio Felix, Walnut Creek, Cottonwood Creek, and Eagle Creek are the larger tributaries to the Pecos River from the west between Acme and Artesia. Comanche Draw and Long Arroyo are the principal tributaries to this reach of the Pecos River from the east.

Streamflow records for most streams in the Roswell basin are meager prior to 1932 and consist only of spot measurements or of continuous records for short periods of time. The gaging station on the Pecos River near Artesia is the one exception. This station was originally established near Dayton, N. Mex., in March 1905 and was moved to near Artesia in February 1936. In March 1932, gaging stations were established on Cottonwood Creek near Lake Arthur and on Rio Felix near Hagerman. The gaging station near Acme was established on the Pecos River in July 1937 and the station near Lake Arthur in August 1938.

Records of streamflow measurements dating back to 1888 have been published in annual Water-Supply Papers of the U.S. Geological Survey. Streamflow records for the period 1888 through 1931 also have been published in a series of surface-water reports by the New Mexico State Engineer.

FLOW IN THE PECOS RIVER IN THE ACME-ARTESIA REACH

In this report gain of flow to the Acme-Artesia reach of the Pecos River consists of flow in the river at the gaging station near Acme and all additions of flow to the river between the gaging stations near Acme and Artesia. Loss of flow consists of flow in the river at the gaging station near Artesia and all depletions of flow between the gaging stations near Acme and Artesia. Gain and loss of flow should be equal; small differences between total gain and total loss of flow shown on table 15 result from rounding values of increments, either of gain or loss.

SOURCE OF FLOW

The Pecos River within the Acme-Artesia reach gains water from tributaries, springs and seeps in the main channel, artificial drains, sewage effluent from communities, and precipitation.

The quantity of water contributed to the Pecos River from each source was not gaged continuously during the period 1956–59; however, the discharge to the river from each source, except precipitation, was either measured or computed from seepage investigations made periodically in the Acme-Artesia reach. The results of these seepage investigations are summarized in table 15.

TRIBUTARIES

The principal sources of water in the tributaries are runoff from areas upstream from the bottom land, drain discharge, springs and seeps, and spill from the Hagerman Canal and lakes and ponds.

None of the tributaries are perennial from their headwaters to the Pecos River, but are ephemeral and flow in direct response to precipitation. At times, runoff produces floods that overflow the banks of the tributaries and inundate some crop land and bottom land. The runoff in most of the tributaries is not gaged.

The Rio Hondo has perennial flow in the mountain area, but this flow is diverted for irrigation in the mountain valleys. Most of the tributaries west of the Pecos River have short reaches of perennial flow near the Pecos River, but tributaries east of the river are dry near the river. Perennial flow in the lower reaches of the tributaries is maintained by springs and seeps, where the channels of the tributaries intersect the water table, and by drains. Large artesian springs in the vicinity of Roswell contributed large perennial flows in the lower reaches of Berrendo Creek, North Spring River, and South Spring Creek, until ground-water withdrawals through wells lowered the artesian pressure and diverted the water from the springs.

For the purpose of this report, the flow in the lower reaches of the tributaries is divided into that contributed from sources upstream from the bottom land and that contributed from sources within the bottom land. This division of water in the tributaries according to sources inside and outside the bottom land is used in an inflow-outflow water study of the bottom land. Aside from floodflows, water contributed to tributaries from sources upstream from the bottom land are Roswell sewage effluent discharged to Bitter Creek, spill from Hagerman Canal to Rio Hondo and Ninemile Draw, drain discharge and seepage to the Rio Felix, and Artesia sewage effluent discharged to Eagle Creek. Water entering the tributaries from sources within the bottom land are drain discharge to Rio Hondo, Walnut and Cottonwood Creeks, springs and seeps in Bitter Creek, Rio Hondo, Ninemile Draw, Rio Felix, Walnut and Cottonwood Creeks; and spill from lakes and ponds in the bottom land, principally that in the Bitter Lake National Wildlife Refuge spilling to Bitter Creek.

Measurements of flow made at the mouth of each tributary during seepage investigation were corrected as follows in computing the amount of water contributed from botton-land sources: Bitter Creek—minus Roswell sewage; Rio Hondo—minus spill from Hagerman Canal; Ninemile Draw—minus spill from Hagerman Canal; Rio Felix—minus flow at gaging station near Hagerman; and Walnut Creek and Cottonwood Creek—no correction.

The perennial flows of the tributaries are not gaged continuously except that of Cottonwood Creek. The gaging station on Cottonwood Creek near Lake Arthur gages both low flow and floodflow. A gaging station is maintained on the Rio Felix above the head of the perennial flow.

SPRINGS AND SEEPS

The Pecos River gains flow from springs and seeps in the Acme-Artesia reach. A few springs have definite outlets, but most of this gain is by seepage of ground water through the banks and bed of the river. Measuring the contribution of water from each spring and seep was not feasible during a seepage investigation, but the rate of flow from all the springs and seeps within sub-reaches of the Acme-Artesia reach was estimated by indirect means. During each seepage investigation the Acme-Artesia reach of the Pecos River was divided into subreaches at the following sites (pl. 7): gaging station near Acme; just below Rio Hondo; near Bottomless Lakes; at bridge near Dexter; 0.8 mile above the Rio Felix; gaging station near Lake Arthur; and gaging station near Artesia. As listed in table 15, the flow from springs and seeps in each subreach is assumed to be equal to the amount that the measured discharge from the subreach exceeded the measured inflow to that subreach.

The values shown in table 15 do not indicate true discharge from seeps and springs but probably are minimum values for that discharge. Some water is lost from the subreach by evaporation and some may be lost by seepage. Accounting for either or both of these losses would increase the computed value for discharge by springs and seeps.

The quantity of water gained by the Pecos River from springs and seeps in the Acme-Artesia reach varies seasonally. The results of seepage investigations made in the period 1956–59 show that the largest gain from springs and seeps is during the winter months and the least gain is during the summer months. It was hoped that the maximum and minimum gain from those sources could be computed for each year 1956–59, but that was not possible because disturbances in river flow caused by pump diversions could not be completely analysed for their correct effect on downstream measurement sites.

The gain in flow from springs and seeps in the channel of the Pecos River is not uniform throughout the Acme-Artesia reach. A study of figure 13 shows that in January and February 1956 the gain in flow from springs and seeps in the channel of the Pecos River was largest in the subreaches from Rio Hondo to Bottomless Lakes and from Dexter to Rio Felix, and was smallest in the subreach from Rio Felix to Lake Arthur. Springs and seeps contributed about 60 percent of the low-flow gain from ground-water sources in the Acme-Artesia reach.

DRAINS

Drains (surface- and ground-water drains) discharge water to the Pecos River and its tributaries. Some of the drains obtain water only from outside the bottom land, while others obtain water only from within. Drains discharging water to the Pecos River from outside the bottom land are: Oasis-Miller, Zuber Hollow wasteway; Dexter-Greenfield lines A, D, and E; Hagerman lines A and D; and Lawrence Ranch. Drains discharging water to the river from sources within the bottom land are: East Grand Plains lines A, B, C, and D; Gravel Pit; Medley ditch; Berry ditch; Zuber Hollow ditch; and Lake Arthur line B. The locations of the mouths of these drains are shown on plate 7. Table 15 lists the drainage water by amount and source for the seepage investigations made in 1956–59.

SEWAGE EFFLUENT

The Pecos River receives some sewage effluent from the communities of Roswell, Dexter, Hagerman, and Artesia, of which all but Hagerman have plants for treating sewage. During the irrigation season, nearly all of the sewage effluent from Roswell, Dexter, and Artesia is used for irrigation on crop land, and during the winter months much of the effluent is used to irrigate fields of alfalfa and pasturelands. The town of Hagerman discharges raw sewage directly to the Pecos River. The quantity of sewage effluent discharged to the Pecos River from all communities in the area probably amounts to only a few hundred acre-feet per year.

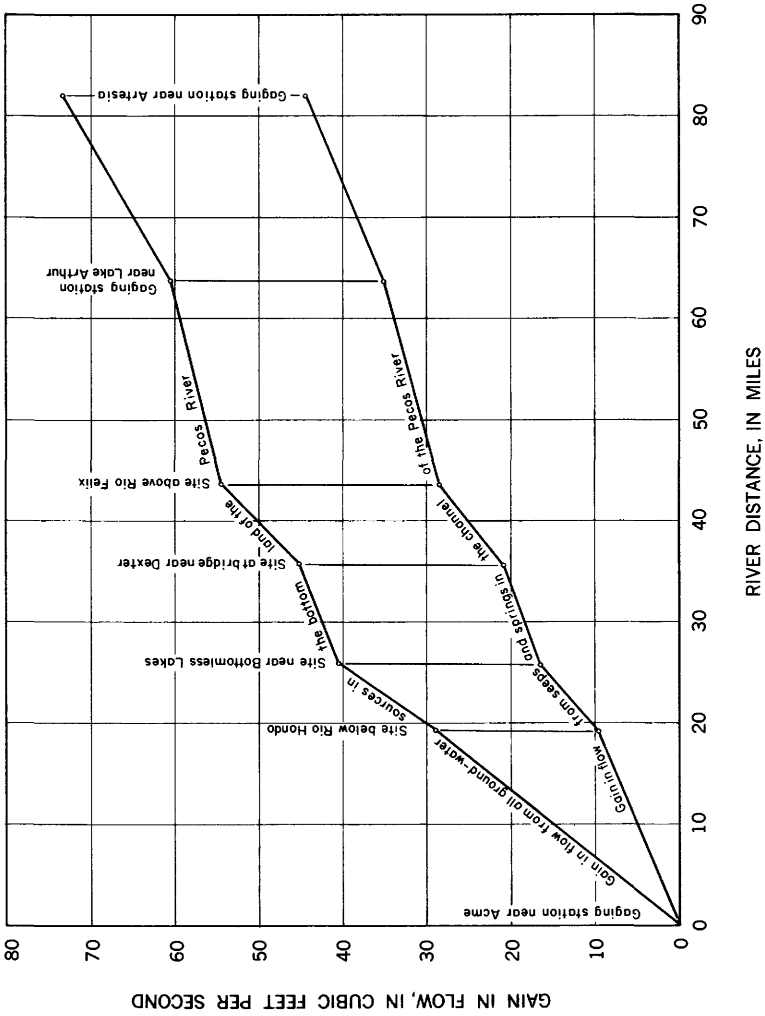

FIGURE 13.—Computed gain in ground water to the Pecos River in the Acme-Artesia reach, Roswell basin, New Mexico—average of seepage investigations January 4 and 5 and February 26 and 27, 1956.

PRECIPITATION

Precipitation on the Pecos River channel, on the perennial reaches of the tributary streams, and on lakes and ponds which discharge to the surface-water channels helps maintain the flow of the river. Some of the precipitation on the river and its tributaries reaches the Pecos River as sheet runoff from lands adjacent to the river and its tributaries; however, most of the precipitation on this land is consumed by evaporation and transpiration.

The Pecos River channel and the channels of the lower reaches of its tributaries have a total surface area of 1,140 acres, and the lakes and ponds discharging to the river have a total area of 1,110 acres. Precipitation records from the weather stations at Roswell, Hagerman, and the Bitter Lake National Wildlife Refuge in Chaves County and from the weather station at Artesia in Eddy County were used to compute the quantity of water contributed by precipitation to stream channels, lakes, and ponds in the Acme-Artesia reach during 1956–58. The average of the precipitation at the Roswell and the Bitter Lake National Wildlife Refuge weather stations was used to compute the precipitation on the lakes and ponds, because most of them are in the wildlife refuge and near Roswell. The precipitation on the lakes and ponds in 1956 was 3.73 inches, or 345 acre-feet; in 1957 it was 8.50 inches, or 785 acre-feet; and in 1958 it was 13.13 inches, or 1,215 acre-feet. The average of the precipitation at all four stations was used to compute the precipitation on the river and stream channels. The precipitation on these channels in 1956 was 5.15 inches, or 490 acre-feet; in 1957 it was 8.58 inches, or 815 acre-feet; and in 1958 it was 16.05 inches, or 1,525 acre-feet. The total precipitation on stream channels, lakes, and ponds was about 840 acre-feet in 1956, about 1,600 acre-feet in 1957, and about 2,740 acre-feet in 1958.

LOSS OF FLOW

The flow of the Pecos River and its tributaries is diminished principally by diversions for irrigation, by direct evaporation from the free-water surfaces and wet-sand bars in the channels, and by seepage. A small quantity of water is transpired by plants which draw water directly from the river.

SEEPAGE LOSSES

Seepage losses from the river in the Acme-Artesia reach probably are small, even at the peak of the irrigation season. In general, the water table slopes either toward the river or is at the level of the river in the reach. Seepage losses from the river may become appreciable when pumping in the cultivated area reverses the gradient of the water table in the vicinity of the river. Locally, the use of water by phreatophytes may have lowered the water table below river level during a part of the transpiration season and caused some seepage losses from the river.

Seepage losses, like gains in flow from springs and seeps, cannot be measured directly. The amount that measured inflow exceeds the measured discharge in a subreach of the river is considered, in this report, as loss of flow by seepage and evaporation. No attempt was made to compute seepage losses separately from evaporation (table 15) because data from seepage investigations were lacking in the necessary detail.

In general, seepage losses most likely will occur during the summer months because nonartesian water levels are at their lowest stage at that time. Also, seepage losses are larger in some subreaches than in others. It is believed that there were no seepage losses in the Acme to Rio Hondo subreach in the period 1956–59, and probably none in the Rio Hondo to Bottomless Lakes subreach in that period. Seepage losses probably occurred at places between Bottomless Lakes and the gaging station near Artesia only during a part of the summer months. Seepage losses probably were largest in the Rio Felix to Lake Arthur subreach. Seepage losses during low flow are small compared with other losses that decrease the low flow of the river.

DIVERSIONS

Water is diverted from the Pecos River and its tributaries for irrigation. The Hagerman Canal received approximately one-half of the surface water diverted in the basin, the canal's particular source being the Rio Hondo below its confluence with North Spring River and Berrendo Creek.

Some surface water is pumped from the Pecos River and its tributaries directly to field ditches. All operating surface-water pumps are equipped with devices that measure the amount of pumpage. Some of these devices are meters in the discharge line that record cumulative pumpage, readings of which are taken at monthly intervals. Other devices are float gages coupled to instruments that continuously record the time and the gage height in the discharge ditch. Computations, using data obtained by these measuring devices, showed that pumpage of surface water amounted to about 20,500 acre-feet in 1956, about 15,000 acre-feet in 1957, and about 15,000 acre-feet in 1958. One-half or more of these diversions were made either when the river was in flood or when water was being released from Alamogordo Reservoir. On the basis of pumpage records, it is estimated that pumpage of low flow amounted to about 10,000 acre-feet in 1956, about 6,700 acre-feet in 1957, and about 2,800 acre-feet in 1958.

EVAPORATION

Relatively large quantities of water are evaporated directly from surfaces of lakes, ponds, streams, and wet-sand bars in the Acme-Artesia reach. These surfaces comprised 1,110 acres of lakes and ponds, 570 acres of water in streams, and 570 acres of wet-sand bars.

Rates of evaporation have been computed from U.S. Weather Bureau records of evaporation from class-A land pans maintained at the Bitter Lake National Wildlife Refuge and Lake Avalon weather stations. Evaporation data from these stations were weighted to determine the rate of evaporation from a hypothetical class-A land pan at the geometric center of the lakes and from another hypothetical pan located at the midpoint at the Acme-Artesia reach. The evaporation from these two hypothetical pans would have been 102.6 and 106.4 inches in 1956, 97.0 and 100.7 inches in 1957, and 87.3 and 91.6 inches in 1958.

Gatewood and others (1950, p. 47–48) applied a coefficient of 0.70 to data from class-A pans to determine true evaporation from reservoir or lake surfaces and from wet-sand bars, and a coefficient of 0.75 to compute evaporation from a flowing stream. The coefficients developed by other investigators of evaporation are in approximate agreement with those used by Gatewood and others (1950). At the time this report was written, no single coefficient was accepted by all investigators; therefore, the coefficients applied by Gatewood and others (1950) in a bottom-land environment were adopted for use in this report. The evaporation from bodies of surface water and wet-sand bars was computed as about 14,000 acre-feet in 1956, about 13,000 acre-feet in 1957, and about 12,000 acre-feet in 1958. A discharge of 14,000 acre-feet a year would require a sustained flow of about 19.2 cfs.

CHEMICAL QUALITY OF WATER

The chemical quality of surface and ground waters was studied to determine the effect of evapotranspiration in the bottom land upon the mineral concentration of those waters. An attempt was made to compute the amount of water consumed by evapotranspiration by relating changes in mineral concentration in the water to water use by evapotranspiration. This was unsuccessful because the change in mineral concentration caused solely by evapotranspiration could not be distinguished from changes caused by other factors.

The chemical character of the water in a basin is governed by the character of the rocks, over or through which the water moves. Analyses of water samples show the kinds and concentrations of dissolved solids in the water.

The water analyses used in the preparation of this report are mostly those available from previous investigations in the Roswell basin. Sampling of ground and surface waters during the current investigation was limited largely to water from the test holes drilled in the bottom land and from the measurement sites of the seepage investigations on the Pecos River and its tributaries (table 15). Chemical analyses of surface water, other than those samples taken during the seepage investigations and spot sampling along the Pecos River, are of samples taken daily at gaging stations near Acme and Artesia. These samples were composited into samples representing periods of similar river stage no greater than 10 days in duration. For example, one composite sample might represent 10 consecutive days at low flow, and another sample might represent only 1 or 2 days at flood stage.

The chemical analyses in this report are expressed either in ppm (parts per million) or as epm (equivalents per million). One ppm equals one part, by weight, of a chemical constituent per million parts of water. For concentrations of dissolved solids that are normally encountered in irrigation water, 1 epm is equal to a milliequivalent per liter. The equivalent is the weight with reference to some standard (such as the combining weight either of oxygen, 8, or hydrogen, 1.008) of that quantity of an element, radical, or compound, that will react with another element or ion to complete a definite chemical reaction. An equivalent of an element or ion is exactly equal in combining power to one equivalent of another element or ion. When all major constituents of a water sample are analysed, the sum of the equivalents of cations should about equal the sum of the equivalents of anions.

Specific-conductance values, where used in this report, are expressed in micromhos at 25° C ($K \times 10^6$) (mhos, the reciprocal of ohms, multiplied by 10 to the 6th power). The specific conductance is a measure of the ability of water to conduct an electric current. The specific conductance is greater at greater concentrations of dissolved solids, but it does not indicate the chemical character of the dissolved solids.

GROUND WATER

The discussion of the chemical quality of ground water in the Acme-Artesia area relates primarily to water in or recharging the valley fill, because phreatophytes in the area obtain water from the fill. The chemical quality of the water in the valley fill is governed, in large part, by that of water reaching the valley fill, either as upward leakage or as artesian pumpage applied to the land. Precipitation, seepage losses from irrigation water derived from sources other than the artesian system, and evapotranspiration affect the quality of the water in the fill to a lesser degree.

Water reaching the valley fill from the artesian system is a calcium magnesium sulfate water having, in general, a dissolved solids content between 600 and 2,000 ppm. Northeast and east of Roswell, the waters from the artesian system contain dissolved solids in excess of 10,000 ppm; sodium and chloride are the dominant constituents (Hood and others, 1959). Except in this area of highly mineralized water, the water in most of the valley fill is suitable for agricultural, domestic, and industrial use.

Ground water in the bottom land generally is of poorer quality than ground water in the adjacent cultivated area. The chemical quality of ground water deteriorates in its travel between the point of recharge and the point of discharge, and the bottom land and the Pecos River are the ultimate areas of natural discharge. The use of water by phreatophytes also causes an increase in dissolved solids of the ground water in the bottom land. When water is evaporated or transpired, the dissolved solids in the water either go into plant tissue or are left in the soil; those returned to the soil by decay of plant tissue and those left in the soil are leached down to the water table. In effect, evapotranspiration in the bottom land depletes the water supply but does not remove the mineral content of the water; thus, the remaining ground water becomes more highly mineralized. Reducing or eliminating the use of water by phreatophytes would result in an improvement in the chemical quality of the ground water reaching the river. A study of the chemical analyses of ground water in the bottom land shows that except for a few local areas of highly mineralized water, the water is chemically suitable for irrigation and domestic use.

SURFACE WATER

The chemical quality of the water in the Pecos River varies according to the principal source of the riverflow. During the periods of low stage the water in the river in the Acme-Artesia reach is largely effluent ground water; therefore, the surface water is similiar in chemical character and concentration to the ground water. Evaporation from the river increases the amount of dissolved solids in the river water. During flood flows and water releases from Alamogordo Reservoir, the river water has a lower mineral content than during periods of low flow. During these high stages the effluent ground water is diluted, and saline encrustations on the riverbanks are flushed away.

Although all chemical constituents increase from Acme to Artesia, the increases in sodium and chloride are the largest. The greater increase in sodium and chloride can be shown by comparing the chemical analyses of composited river-water samples from the gaging stations near Acme and Artesia for the period October 1952 through September 1956 (figs. 14 and 15). These illustrations were prepared by plotting the percent sodium (the percentage of total cations represented by sodium in epm) against the ratio of chloride to sulfate, both expressed in parts per million. The two plots are similar in scatter of points plotted and in slope of the average line through the points; the data points plotted on the graph for the gaging station near Artesia tend to bunch where the percent sodium is about 52 and the ratio of chloride to sulfate is 1.0, whereas the data points on the graph for the gaging station near Acme tend to bunch where percent sodium is 40 and the ratio of chloride to sulfate is about 0.55. The points which tend to bunch were those for water samples taken at low flow. It is concluded that if the loss of water due to use by the bottomland vegetation is estimated by using river-discharge data and chemical analyses, the analyses should represent periods of sustained low flow when the quality of the river water is fairly uniform.

A study of the chemical analyses of water samples taken during seepage investigations show that the quality of the river water varied considerably from reach to reach and changed at the mouth of each

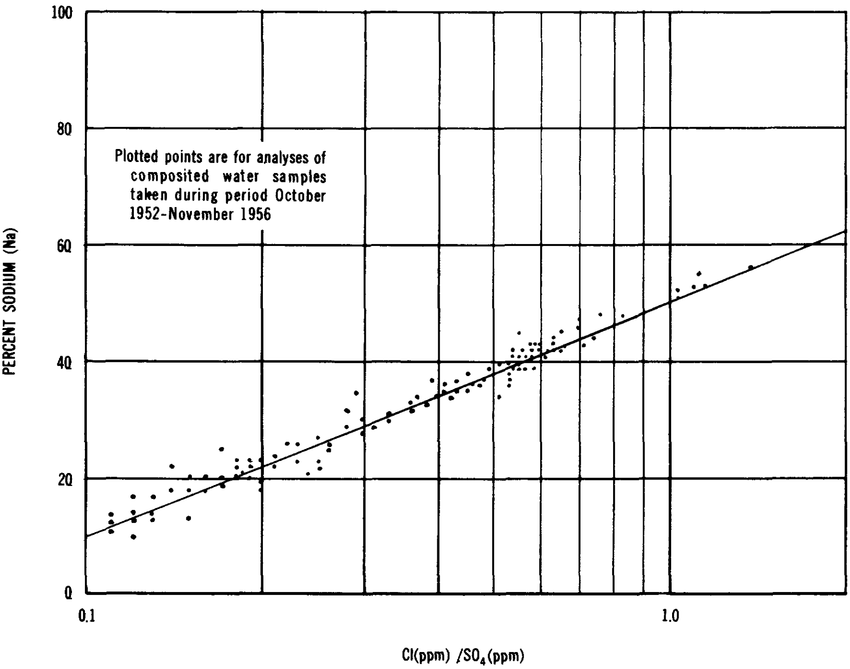

FIGURE 14.—Graph showing the relation of percent sodium to the chloride-sulfate ratio of water in the Pecos River at the gaging station near Acme, Roswell basin, New Mexico.

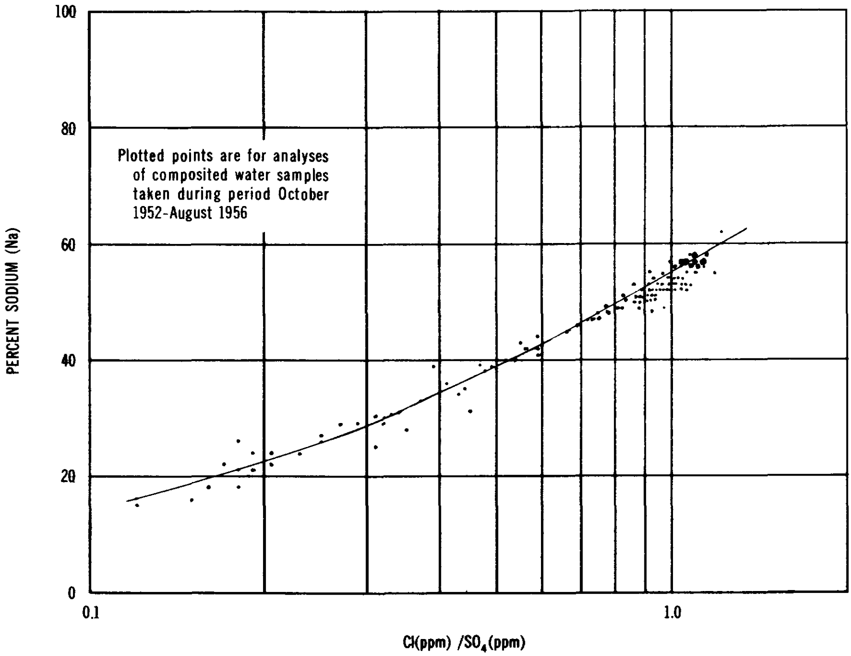

FIGURE 15.—Graph showing the relation of percent sodium to the chloride-sulfate ratio of water in the Pecos River at the gaging station near Artesia, Roswell basin, New Mexico.

tributary. In general, the chemical character of the river water was similar to that obtained from wells finished in the valley fill. Generally, the ratio of chloride to sulfate was less than 1.0 in both river and ground water, but the concentration of dissolved solids of the river water generally was higher than that of the ground water. In the vicinity of Bitter Lake and the Rio Hondo (an area of saline-water encroachment in the San Andres limestone) and near Lake Arthur, the chloride to sulfate ratio was generally higher than 1.0 in the river water and reflected the different character of the ground water in those areas.

Figure 16 illustrates the relation of the quality of the river water to that of the ground water in the Acme-Artesia area by a plot of the chloride to sulfate ratio, both in parts per million, and the specific conductance. The chemical quality of the river water is represented by water samples taken at the gaging station near Artesia. The chemical quality of the ground water is represented by water samples taken from wells finished in the Chalk Bluff formation east of the river and from wells finished in the Quaternary valley fill. Nearly all of the points representing water from the Chalk Bluff formation and from the shallow test holes near the river fall above the average line repre-

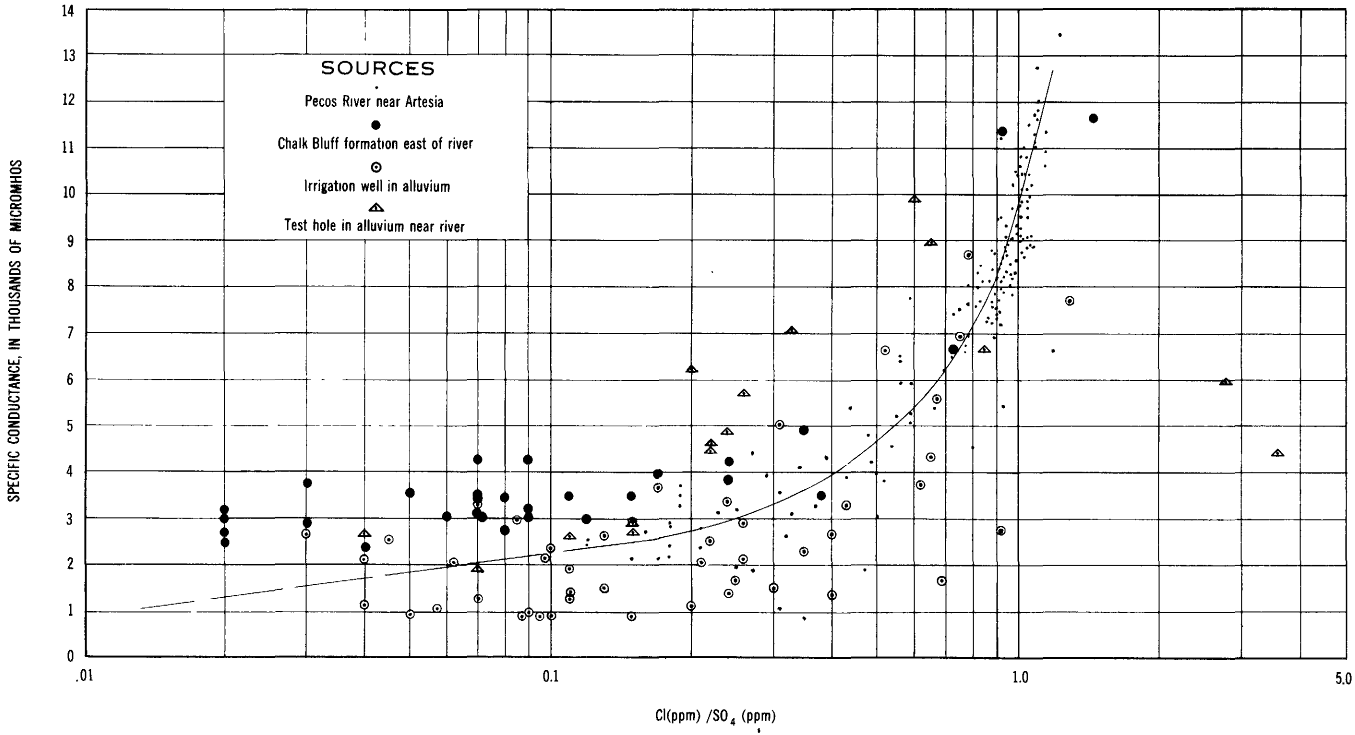

Figure 16.—Graph showing the relation of specific conductance to the chloride-sulfate ratio of water in the Pecos River at the gaging station near Artesia, water in the nonartesian aquifer, and water in the Chalk Bluff formation east of the Pecos River, Roswell basin, New Mexico.

senting river water. The test holes were drilled in valley fill consisting largely of debris from the Chalk Bluff formation. Most of the points representing water from other wells in the valley fill fall below the average line representing river water. It was concluded that water in the valley fill generally has a greater chloride content relative to a given specific conductance value than the water from the river, and that sufficient water discharges to the river from the Chalk Bluff formation to modify the chemical characteristics of the river water.

In figure 16 only a few plotted points representing ground water fell near the bunched points which represented low flow of the river at the gaging station near Artesia. This was due partly to the concentration of the river water by evaporation, but mostly to the lack of ground-water samples from near the riverbank, especially in the southern part of the Acme-Artesia reach.

USE OF WATER BY PHREATOPHYTES

OCCURRENCE OF PHREATOPHYTES

Phreatophytes are water-loving plants that habitually take their water supply either from the zone of saturation or from the capillary fringe above it. In the Roswell basin, few phreatophytes grow where the depth to the water table exceeds 20 feet. They infest land along both sides of the Pecos River and the lower reaches of its tributaries. In the Acme-Artesia area, the width of the phreatophyte-infested area ranges from a few feet at the river bank to a maximum of about 4 miles and averages $1\frac{1}{5}$ miles (pls. 8 and 9). Saltcedar, saltgrass, sacaton, and mesquite were the only phreatophytes mapped and studied; however, small tracts and isolated plants of other phreatophytes were observed.

METHODS USED IN MAPPING

Owing to lack of time and funds, most of the phreatophyte mapping for the 1956 survey was done from aerial photographs. Fortunately, aerial photographs and excellent topographic maps were available for the entire area of study. Several representative tracts were visited and were compared with the aerial photographs of those tracts. The aerial photographs of the representative tracts were used as base plots for comparing and delineating density, type, and extent of phreatophytic growth for the remaining tracts of phreatophytes in the area of study. The areal extent and growth density of each type of phreatophyte could be identified on aerial photographs by shading and tone. The same mapping method was used with the 1958 survey as was used with the earlier photographs; however, the 1958 mapping was more accurate owing to more field sampling surveys.

The 7½-minute topographic quadrangle maps (scale 1:24,000), published by the U.S. Geological Survey, were used as base maps on which to transcribe tract boundaries from the aerial photographs. A planimeter was used to measure areas of individual tracts on the topographic maps. Each of the phreatophyte species was assigned a symbol on the map, the density of shading of each symbol representing areal density.

AREAL DENSITY

Areal density as used in this report is a measure of the areal extent of the green transpiring material (leaves or fronds) in relation to the total area in which they grow. The concept of areal density as developed by Gatewood and others (1950) can be illustrated by picturing a single plant in full leaf with the sun directly overhead. The area of solid shade cast on the ground by the plant would be equivalent to the areal coverage of the transpiring material. The areal extent of that plant would be equivalent to the area within the shaded area. In a unit area of land, for example, 1 acre, where one species of phreatophyte is growing singly and in clusters, the areal density of that acre of land would be the ratio of area of solid shade to the total area.

Theoretically, in an area having a transpiring material growth of 100-percent areal density, the addition of a unit of transpiring material would choke out an existing unit of material. In the Acme-Artesia area, few stands of vegetation have an areal density of 100 percent. The natural areal density of phreatophytes in each tract was computed to an equivalent area of 100 percent to compare the amounts of vegetation in the different tracts of land, and to determine the net area occupied by the plants in each tract. For example, a 12-acre tract having a natural areal density of phreatophytes of 25 percent is virtually equivalent to a 3-acre tract having a 100-percent areal density.

The areal density of each parcel of phreatophytes was obtained by comparing its shading or tone on the aerial photographs with that of the representative parcels whose densities were determined by field measurements. A reconnaissance was made in several selected phreatophyte tracts after completion of the office mapping to compare the mapping with field conditions. Very few corrections were needed, and those resulted only in a small adjustment in the increase of density.

VERTICAL DENSITY

Vertical density as used in this report is a ratio of the vertical depth of the green transpiring material (leaves or fronds) on a plant to the optimum depth for that particular species. A 100-percent vertical density of growth is one in which the addition of one unit of transpiring material at the top theoretically would choke out an equivalent unit of transpiring material beneath it. The vertical density was estimated for all tracts of phreatophytes in the project area. Although little time was available in which to measure vertical density, estimates were made for the 1956 survey on the basis of several brief reconnaissance trips in the phreatophyte area. Vertical density data for the 1958 survey were more detailed than for the 1956 survey; accordingly, plates 8 and 9 are not directly comparable.

The frondage on isolated saltcedar plants and at the edges of saltcedar thickets reach a maximum depth of 18 feet, and in the denser parcels the maximum depth of frondage was 10 feet. The average depth of frondage on saltcedar was 13 feet in the Roswell basin; therefore, 13 feet was taken as the optimum depth of transpiring material for saltcedar and represents 100-percent vertical density. The average vertical density of saltcedar was estimated to be 75 percent of the optimum depth in 1956. In 1958, the average vertical density for all tracts of saltcedar in which vertical density was measured was 85 percent. Saltcedars in the area generally reach 100-percent vertical density in 5 to 10 years, but where the growing conditions are ideal they may reach 100-percent vertical density within 3 years.

The height of the grasses at 100-percent vertical density was about 3 feet. Vertical density of grasses in the study area was not estimated in detail.

VOLUME DENSITY

Foliage volume density of a particular phreatophyte species is the product of the areal and vertical density of the foliage, and is expressed as a percentage. In effect, it is the ratio of the volume of the green transpiring foliage of a particular phreatophyte species actually contained in an area to the maximum volume of green foliage that the area would contain if the areal and vertical densities each were 100 percent.

Volume density cannot be used directly to compare the volume of green foliage of one phreatophyte species with that of another species, because a specific volume density of one species of phreatophyte, for example, saltcedar, is not equivalent to the same volume density of a different species, for example, saltgrass. The difference in volume of green foliage at a given volume density is apparent from the fact that the optimum depth of green foliage of saltcedar at 100-percent vertical density is 13 feet whereas the optimum depth of saltgrass is about 3 feet.

The total amount of water transpired by a tract of phreatophytes is proportional to the amount of the green foliage. Each species of phreatophytes was computed as a net acreage at 100-percent volume density. For example, in a hypothetical 12-acre tract, the areal density was 25 percent and the vertical density was 75 percent; therefore, the volume density was 18.75 percent, equivalent to that on a 2¼-acre tract having a 100-percent volume density.

SPECIES

Saltcedar, saltgrass, sacaton, and mesquite are the principal phreatophytes in the project area. The distribution and areal density of these plants in 1958 are shown on plate 9. Other water-loving plants in the project area are cottonwood, willow, threadleaf sedge, and the hydrophytes such as cattail, tules, and watercress. They occupied relatively small areas and were not mapped.

SALTCEDAR

Saltcedar was first observed in the Roswell basin around Lake McMillan about 1912 and by 1958 had spread to about 28,000 acres of land in the Acme-Artesia reach of the Pecos River. Saltcedar, unless controlled, will overgrow much of the land occupied by phreatophyte grasses and probably some additional acreage of low-lying lands. Cultivation of the land or dense growths of other native plants retards or halts saltcedar encroachment; however, once saltcedar obtains a foothold it begins to crowd out other plants. By the time the saltcedar attains 75-percent areal density, it has crowded out nearly all the forage grasses, and the few that remain are inaccessible to stock. Volume densities will approach 100 percent in infested areas unless growth is checked.

During the 1958 phreatophyte survey, the areal density of 13 parcels of saltcedar was measured by the transect method. This method involved measuring the density of saltcedar, phreatophyte grasses, and mesquite along 174 random-sample lines 100 feet in length. The transect method is a slow but accurate method of measuring both areal and vertical density. Depending on the areal density, only 1,000 to 3,000 feet of transect lines in saltcedar could be measured per man-day. The rate of surveying is roughly in inverse proportion to the density.

To obtain a large sampling of saltcedar, it was necessary to devise a faster method of measuring areal density than the transect method without sacrificing accuracy. An office method devised for use in this study was similar in prinicpal to the transect method, except that the areal density was measured on aerial photogrphs with a magnifier and graphic scale. The smallest division on the scale was 0.1 mm and interpolations were made to 0.05 mm. A distance of 0.1 mm on the photographs, scale 1:10,000, represented about 3.3 feet on the ground. The length of the basic transect was increased to about 330 feet with the graphic scale, and this increased the quantity of saltcedar sampled in each parcel. Single plants, thickets of saltcedar, and open spaces less than about 1.5 feet in diameter could not be measured with the scale. The size of the small openings and small thickets was nearly equal in the parcels sampled, and the effects of not measuring more accurately than 1.5 feet were negligible. Two other disadvantages of the office photographic method were that vertical heights could not be measured and plant conditions could not be observed.

The areal density of 55 parcels was measured by the office photographic method, including three parcels measured by the transect method for comparison. About 228,000 feet of transect lines were measured by this method.

For mapping purposes, the parcels of saltcedar were delineated according to areal density. Dense saltcedar was estimated to have an areal density of 90 to 100 percent; moderately dense, 70 to 90 percent; moderate, 25 to 70 percent; sparse to moderate, 10 to 25 percent; and sparse, 2 to 10 percent. For ease in computing acreage to 100-percent areal density, an average percentage factor was computed for each of these categories: dense, 91 percent; moderately dense, 74 percent; moderate, 46 percent; sparse to moderate, 20 percent; and sparse, 5 percent. The vertical density of saltcedar was estimated as 75 percent in 1956, 80 percent in 1957, and 85 percent in 1958.

The areal extent of saltcedar infestations in the project area and the adjusted areas of 100-percent volume density are listed in table 7 for the period 1956–58. Data for 1957 were interpolated from the 1956 and 1958 phreatophyte surveys. There was about 23,000 acres of saltcedar in 1956, which was equivalent to about 6,300 acres having a 100-percent volume density. Table 7 shows that saltcedar encroached on 4,900 acres of grass lands from 1956 to 1958. The total saltcedar area was about 28,000 acres in 1958, which was equivalent to an area of 8,700 acres having a volume density of 100 percent.

Saltcedar in the project area grows where the depth to water ranges from a few inches to about 30 feet. Where the depth to water is considerably more than 20 feet, the plants probably live on waste water from fields and ditches. Seedlings require a relatively shallow water table and a soil that is moist for a protracted period of time, but once growth is established, the roots will follow for several feet a slow decline of the water table. The most luxuriant stands of saltcedar grew where the water table was less than 10 feet below the land surface and where the soil contained a high percentage of sand.

TABLE 7.—*Phreatophyte growth, in acres, in the Acme-Artesia reach, Chaves and Eddy Counties, N. Mex., 1956–58*

[Data for 1957 were interpolated from phreatophyte survey data obtained in 1956 and 1958.]

Phreatophyte	1956			1957			1958		
	Area of growth at natural density	Principal phreatophyte in tract adjusted to 100-percent volume density	Grasses in tract adjusted to 100-percent volume density	Area of growth at natural density	Principal phreatophyte in tract adjusted to 100-percent volume density	Grasses in tract adjusted to 100-percent volume density	Area of growth at natural density	Principal phreatophyte in tract adjusted to 100-percent volume density	Grasses in tract adjusted to 100-percent volume density
Saltcedar tract:									
Dense	2,600	1,770	0	2,900	2,110	0	3,200	2,480	0
Moderately dense	3,700	2,050	360	4,100	2,430	400	4,500	2,830	440
Moderate	4,500	1,550	1,370	5,000	1,840	1,520	5,500	2,150	1,670
Sparse to moderate	3,900	590	1,750	4,300	690	1,940	4,700	800	2,110
Sparse	8,500	320	4,540	9,300	370	4,970	10,200	430	5,450
Subtotal	23,200	6,280	8,020	25,600	7,440	8,830	28,100	8,690	9,670
Grass tract	14,700	11,020	11,020	12,300	9,200	9,200	9,800	7,350	7,350
Mesquite tract	3,400	170	0	3,400	170	0	3,400	170	0
Total	41,300	----------	19,040	41,300	----------	18,030	41,300	----------	17,020

GRASSES

Saltgrass and sacaton are the only major phreatophyte grasses indigenous to the Roswell basin. They have an economic value as forage for cattle. These plants are hardy and can withstand the high summer temperatures, saline soil, and highly mineralized water of the area. Luxuriant stands are associated with saltcedar despite the fall of saline exudate from the saltcedar fronds. Saltgrass and sacaton inhabited all parts of the river bottom land in 1956–58 and were associated with the other phreatophyte species; however, only isolated plants occurred where the density of saltcedar was greater than 90 percent. Although grasses grew where the water table was less than 10 feet below the land surface, the densest stands occurred where the depth to water was less than 5 feet.

Saltgrass and sacaton occupied about equal parts of the grassland. The volume density of the grass tracts was estimated to be between 75 and 100 percent. Where ample water supplies were available, it was assumed that both the areal and vertical densities approached 100 percent; however, a value of 75-percent volume density was used in all computations because the depth to water was greater than 5 feet throughout most of the area. In 1956, about 15,000 acres of grass had not been infested with saltcedar or mesquite except by isolated plants; however, saltcedar encroachment onto grassland annually diminished the acreage of grass. The 15,000 acres of grass in 1956 was equivalent to about 11,000 acres when adjusted to 100-percent volume density.

Grasses also grew in saltcedar areas where the saltcedar areal density was less than about 90 percent. Generally the grass density was very sparse in parcels of saltcedar having a density of greater than 90 percent and there was no grasses where the density of saltcedar approached 100 percent. For simplicity it was assumed that there were no grasses where the density of saltcedar was greater than 90 percent; in tracts of moderately dense saltcedar, grasses occupied about 50 percent of the land not occupied by saltcedar; and in saltcedar tracts of moderate density or less, grass occupied about 75 percent of the land not occupied by saltcedar.

Table 7 shows that phreatophyte grasses were growing exclusively on about 15,000 acres in 1956, about 12,000 acres in 1957, and about 10,000 acres in 1958. The total equivalent area of grasses adjusted to 100-percent volume density was about 19,000 acres in 1956, about 18,000 acres in 1957, and about 17,000 acres in 1958.

MESQUITE

Mesquite uses large quantities of water when the water table is at a shallow depth, but it can exist as a xerophyte. As phreatophytes, the plants are large and luxurious and tend to grow in dense thickets; as xerophytes the stands are sparse and the plants are smaller and seem to be in need of water.

Single mesquite plants were found in many locations throughout the entire Acme-Artesia reach of the Pecos River; however, there was only one major tract of mesquite, part of which might be classed as phreatophyte. This tract contained 3,400 acres east of the Pecos River near Dexter (pls. 8 and 9). The water table was about 10 to 25 feet below the land surface in this mesquite tract. The mesquite growth computed to 100-percent volume density would cover only 170 acres. There were no changes in area or density of mesquite in the period 1956–58.

QUANTITATIVE DETERMINATION

In any study of the rate of water used by phreatophytes, it is desirable to use several methods in determining the rate of use, because no one method can be singled out as the one that will give correct results under all conditions. Some methods are long, tedious, and very costly, and others require relatively little effort and use simple computations. The more costly methods generally are the most accurate, but it is seldom feasible or even necessary to strive for great accuracy in the determination of the amount of evapotranspiration from large areas, because there are many elusive variables involved. Four methods for determining the rate of evapotranspiration in phreatophyte areas are discussed in this report: extrapolation of rates of water use from other areas; inflow-outflow; pumping-well analogy; and transpiration well.

EXTRAPOLATION OF RATES OF WATER USE FROM OTHER AREAS

During 1943–44, Gatewood and others (1950) conducted a comprehensive investigation of water use by phreatophytes in Safford Valley, Arizona. The evapotranspiration rates obtained in the Safford Valley studies were extrapolated to the Roswell basin because the Roswell basin afforded phreatophytes an environment similar to that of the Safford Valley.

Studies by Raber (1937) and Horton (1923) have shown that the volume of water consumed by growing plants is proportional to the weight of the transpiring material. The main problem is the determination of the quantity of transpiring plant material for each of the phreatophyte species in the project area. Gatewood and others (1950, p. 27) devised a field method of evaluating the amount of transpiring material based on a percentage of volume density of plant material. If the rate of evapotranspiration is known for a unit area of phreatophyte species at a specific volume density, the rate of evapotranspiration for that phreatophyte species can be extrapolated to another area having the same species. This concept of volume density of transpiring material was used to extrapolate the rate of water use by phreatophyte species of the Safford Valley to similar species in the Roswell basin.

The principal source of error inherent in this method is the human error in determining growth densities, because the measure of volume density is an estimate of areal density of growth and optimum depth of growth of the transpiring foliage. Several people working separately probably would not assign the same volume density to a tract of plants unless representative tracts of known volume densities were available for frequent reference. It is not known how closely the growth densities assigned in the Safford Valley agreed with those assigned in the Roswell basin; however, it is assumed they probably are in reasonably close agreement.

Gatewood and others (1950) determined that the consumptive use of water in the Safford Valley was 7.2 feet and 3.3 feet for saltcedar and mesquite, respectively, for growths of 100-percent volume density for a 12-month period ending September 30, 1944. These figures include use of both ground water and precipitation. The consumptive use for saltgrass and sacaton was not determined in the Safford Valley studies.

After some differences of climate had been accounted for, the consumptive use of water by saltcedar and mesquite was estimated as 6.0 feet and 3.0 feet per year, respectively, for growths of 100-percent volume density in the Acme-Artesia area of the Roswell basin.

The depth of water in the principal grass tracts was between 5 and 8 feet, and no information is available on the rate of water use by grasses when the depth to water is that large. The consumptive use of water by grasses in the Roswell basin was estimated as 1.2 feet per year by extrapolation of water-use data developed by experiments on sacaton near Carlsbad, N. Mex., for the Pecos River Joint Investigation (National Resources Planning Board, 1942, table 100).

Phreatophytes in the project area obtained water primarily from ground water and precipitation. Phreatophytes growing in areas inundated by floods also receive some water from the floods. The amount received from flood waters probably is small compared to water received from the other two sources, and this small amount contributed by floods was disregarded in the computations of water use by phreatophytes.

Table 8 summarizes the computations of water use by phreatophytes in the Acme-Artesia area as determined by extrapolation of water-use rate by plant species in other areas. The total water used by each phreatophyte species was computed as the product of its acreage, at 100-percent volume density, and the unit rate of water use for that density. Total water use by all phreatophytes was computed as the sum of the water use by each of the phreatophyte species. The amount of precipitation used in the phreatophyte area was computed as the product of the effective precipitation for the year and the total acreage of the phreatophytes. The amount of ground water used in the phreatophyte area was computed as the total water use minus the total effective precipitation on the area.

TABLE 8.—*Water use in phreatophyte area in the Acme-Artesia area of the Roswell basin, Chaves and Eddy Counties, N. Mex., 1956–58, computed by extrapolating water-use rates from other areas*

Year	Saltcedar		Grass		Mesquite		Total water use in phreatophyte area (acre-feet)	Effective precipitation		Use of ground water in phreatophyte area (acre-feet)
	100 per cent volume density (acres)	Total water use (acre-feet)	100 percent volume density (acres)	Total water use (acre-feet)	100 percent volume density (acres)	Total water use (acre-feet)		Annual (feet)	On phreatophyte area (acre-feet)	
1956	6,300	38,000	19,000	23,000	170	500	61,500	0.43	18,000	43,500
1957	7,400	44,000	18,000	22,000	170	500	66,500	.71	29,000	37,500
1958	8,700	52,000	17,000	20,000	170	500	72,500	1.0	41,000	31,500

The amount of draft from the ground-water reservoir as computed for 1958 probably is more nearly correct than the amount that would be obtained if the actual total precipitation were used, because of the high intensity of rainfall during certain periods in 1958. January and March both had 24-hour rainfall in excess of 1 inch, preceded or followed by 2 or more rainy days. In September about 3 inches of rain fell in a 3-day period, 1 day having more than 2¼ inches of rain. At least 3 inches of precipitation during 1958 probably occurred at a time when it was ineffective in sustaining phreatophyte growth; therefore, the effective precipitation in 1958 was estimated to be about 1.0 foot.

INFLOW-OUTFLOW METHOD

The inflow-outflow method is an inventory of the surface and ground water that enter and leave the bottom land of the Acme-Artesia area and the change in water storage in that area. Inventories were made on the basis of calendar years in the period 1956–58 inclusive. Total inflow to the bottom land during the year must equal total outflow, plus or minus the difference between the amount of water storage in the area at the beginning of the year and that in storage at the end of the year.

Inflow to the bottom land of the Acme-Artesia area consists of surface water passing the gaging station near Acme, water from tributaries, irrigation-water wasteways and drains, sewage effluent, ground-water inflow to the nonartesian aquifer, and effective precipitation.

Outflow leaving the project area consists of surface water passing the gaging station near Artesia, evaporation from water and land surfaces, diversions from the river, ground-water movement out of the area, pumpage of ground water from the nonartesian aquifer, and transpiration by phreatophytes in the area.

Change in water storage occurs as changes in channel, bank, and ground-water storage.

It was believed that no appreciable error was introduced in the inflow-outflow computations by modifying the surface-water records of flow in the Acme-Artesia reach of the Pecos River to make a record showing continuous low-flow conditions throughout the period January 31, 1956 to December 31, 1958. The modification of the flow records for gaging stations on the Pecos River near Acme and Artesia was discussed on page 30. The total quantity of low flow past the gaging station near Acme during a year was subtracted from the total quantity of low flow past the gaging station near Artesia for that year. The difference in low flow amounted to 23,800 acre-feet, 20,000 acre-feet, and 34,000 acre-feet for 1956, 1957, and 1958, respectively. In effect, these quantities represent approximately the gain in low flow in the Acme-Artesia reach. This gain in flow passing the gaging station near Artesia is outflow, and is shown in figure 6 for 1956 by the area beneath the graph.

The quantity of ground water entering the nonartesian aquifer in the bottom land is from three sources: underflow past the gaging station near Acme; upward leakage from the artesian system; and nonartesian ground water beneath the cultivated area west of the river moving eastward to the bottom land.

The quantity of underflow entering the area past the gaging station near Acme and that leaving the area as underflow past the gaging station near Artesia probably are small and nearly equal. The principal slope of the water table is toward the river (pls. 5 and 6) in the vicinity of those gaging stations; consequently, the ground water moves toward the river rather than parallel with it. These quantities cancel each other in the calculation of inflow and outflow.

Water entering the nonartesian aquifer in the bottom land as upward leakage from the artesian system was computed to be about 10,000 acre-feet a year, based on data from Hantush (1955, p. 18–26, and 58). Most of the water in the nonartesian aquifer east of the river probably is from the artesian system.

The largest quantity of ground water flowing into the nonartesian aquifer in the bottom land is that which enters from another nonartesian aquifer beneath the cultivated area west of the river. On page 31 of this report, it was estimated that inflow from this source may have been about 67,000 acre-feet in 1956; however, some factors used in making that estimate probably made the estimate to low. Other computations were made, based on the assumptions that the eastward movement of ground water from the cultivated area to the bottom land is constant throughout the year and that the coefficient of permeability in the belt between the two areas is about 500 gpd per ft (p. 33). These computations indicate that the number of acre-feet of ground water which moved into the bottom land from that source was approximately 76,000 in 1956, 80,000 in 1957, and 80,000 in 1958. These quantities are used in the inflow-outflow water inventory.

Some water enters the bottom land through tributaries and drains. Table 15 summarizes the quantities contributed by these sources during seepage investigations made in 1956–59. Inflow from these sources amounted to about 6,200 acre-feet in 1956, 6,600 acre-feet in 1957, and 7,300 acre-feet in 1958. Of these quantities, drains carried 2,900 acre-feet, 2,200 acre-feet, and 2,000 acre-feet, and tributaries carried 3,300 acre-feet, 4,400 acre-feet, and 5,300 acre-feet, in the respective years. Most of that in the tributaries was spill from the Hagerman Canal. Some of the drain inflow was diverted for irrigation in the bottom land (1,800 acre-feet in 1956, and 1,700 acre-feet in 1957, and in 1958) with the result that about 80 percent of the amount diverted was used by crops and about 20 percent recharged the nonartesian aquifer as seepage. For simplicity in computation, the net drain inflow is considered as that part not diverted plus 20 percent of that which was used for irrigation. The net inflow from drains originating outside the bottom land was about 1,500 acre-feet in 1956, 800 acre-feet in 1957, and 600 acre-feet in 1958; therefore, the net inflow from tributaries and drains was about 4,800 acre-feet in 1956, 5,200 acre-feet in 1957, and 5,900 acre-feet in 1958.

Pumpage in the bottom land was from two sources, the river and the nonartesian wells. The river pumps are equipped with metering devices, most of which also record the time of operation; therefore, pumpage from low flows could be distinguished from pumpage from flood flows. Pumpage of low flow only was used in the inflow-outflow inventory of water. This amounted to about 10,000 acre-feet in 1956, 6,700 acre-feet in 1957, and 2,800 acre-feet in 1958. Pumpage from the river was delivered to fields outside of the bottom land and is considered as outflow. A few nonartesian irrigation wells in the bottom land were pumped, and water from these wells was applied to fields in the bottom land. Approximately 20 percent of the irrigation water pumped from wells returned to the nonartesian aquifer as seepage from fields. The net pumpage from wells (gross pumpage from wells minus seepage return) amounted to about 3,400 acre-feet in 1956, 3,400 acre-feet in 1957, and 2,400 acre-feet in 1958.

Precipitation on the channels of the Pecos River and tributaries, on the surface of lakes and ponds, and on the phreatophyte area constitutes inflow. A part of the precipitation, sufficient in intensity and duration to produce runoff from the phreatophyte area, was considered as ineffective precipitation on that area. All precipitation in 1956 and 1957 was considered as effective, but about 3 inches of precipitation in 1958 was considered as ineffective. Effective precipitation in the phreatophyte area amounted to about 18,000 acre-feet in 1956, 29,000 acre-feet in 1957, and 41,000 acre-feet in 1958. On river and river tributary channels, lakes, and ponds, precipitation amounted to about 800 acre-feet, 1,600 acre-feet, and 2,700 acre-feet respectively for these years.

The difference between water in channel and bank storage at the beginning and end of a year was considered to be negligible in the years 1956–58, and was omitted in computing inflow and outflow. A comparison of water levels in wells at the beginning and end of each year in and near the bottom land indicated that ground-water storage decreased about 4,100 acre-feet in 1956, increased about 4,100 acre-feet in 1957, and remained constant in 1958. A decrease in storage is considered to be equivalent to inflow, and an increase is equivalent to outflow.

Quantities of inflow and outflow used in computing evapotranspiration in the phreatophyte area of the Acme-Artesia area for the years 1956, 1957, and 1958 are given in table 9. The quantity of water discharged each year from the phreatophyte area by evapotranspiration was computed as the quantity required to bring outflow into balance with inflow. The quantity of ground water used each year in the period 1956-58 by evapotranspiration in the phreatophyte area is the total evapotranspiration from that area less the effective precipitation on the phreatophyte area.

TABLE 9.—*Inflow-outflow inventory of water for the bottom land of the Acme-Artesia reach of the Pecos River, Chaves and Eddy Counties, N. Mex., 1956–58*

	Acre-feet		
	1956	1957	1958
Ground water moving eastward from cultivated area west of river	76, 000	80, 000	80, 000
Upward leakage from artesian system	10, 000	10, 000	10, 000
Net drain and tributary inflow	4, 800	5, 200	5, 900
Effective precipitation	18, 800	30, 600	43, 700
Decrease in ground-water storage	4, 100	0	0
Total inflow	113, 700	125, 800	139, 600
Gain in reach passing gaging station near Artesia	23, 800	20, 000	34, 000
Pumpage of low flow from river	10, 000	6, 700	2, 800
Evaporation from free-water and sandbar surfaces	14, 000	13, 000	12, 000
Net pumpage from nonartesian aquifer	3, 400	3, 400	2, 400
Increase in ground-water storage	0	4, 100	0
Evapotranspiration in phreatophyte area	62, 500	78, 600	88, 400
Total outflow	113, 700	125, 800	139, 600
Ground water consumed in phreatophyte area	44, 500	49, 600	47, 400

PUMPING-WELL ANALOGY METHOD

The withdrawal of ground water by phreatophytes adjacent to the Pecos River measurably diminishes the flow of the river during the growing season. Each plant is, in effect, a small pump which diverts ground water that otherwise would have moved to the river. Theoretically, the effect on the flow of the Pecos River of the combined pumping of water by the phreatophytes could be duplicated with a few wells at selected locations. Plate 10 illustrates the analogy between the draft of ground water by phreatophytes and the discharge of water by a pumping well.

A formula for computing the effect of a pumping well on a nearby stream was developed by Theis (1941). The formula is an extension of Theis' nonequilibrium formula (Theis, 1935) and can be reduced to graphic form to permit the rapid computation of pumping effects on stream flow for a wide range of aquifer coefficients, for relatively wide ranges of distance of the well from the stream, and for varying lengths of pumping time. Several assumptions were necessary to the formulation of this method of computation, in addition to the original assumptions of the nonequilibrium formula. It was assumed that the stream was a straight line, that the ground water was in free communication with the stream (the direction of ground-water movement was reversible), and that the stream maintained a flow past the pumped area. One particular advantage of the pumping-well analogy method is that changes in ground-water storage are taken into account.

Most subreaches of the Pecos River in the Roswell basin meet the special requirements of the method. Although the river meanders, the meanders are restricted to a relatively narrow area, and therefore the river approximates a straight line. The direction of ground-water movement is reversible, and the river maintains flow past all gaging stations during the greater part of the year.

The subreach of the Pecos River between Bottomless Lakes and Dexter was chosen for computation because the subreach was the least complicated by inflow of drains and tributaries and outflow through diversions. Results of computation for this reach were extrapolated to the rest of the Acme-Artesia reach.

The valley fill near the river in the Bottomless Lakes to Dexter subreach is thin and is composed of fine-grained sediments. From the examination of drill cuttings and the results of pumping tests at test holes, the average coefficient of transmissibility was estimated to be about 10,000 gpd per ft, and the coefficient of storage was estimated to be 25 percent. The ratio of coefficient of storage to coefficient of transmissibility (S/T) was 2.5×10^{-5}. Using the graphic form of Theis' solution of the effect of pumping a nearby well on the flow in a stream, table 10 was prepared to show the percent of water diverted from the Pecos River for various lengths of pumping time and for various values of distance of the pumping well from the river, using a value for $S/T=2.5\times10^{-5}$.

TABLE 10.—*Percent of ground water intercepted by wells at selected distances from the Pecos River for selected periods of time.* $S/T=2.5\times10^{-5}$

Elapsed pumping time (months)	Distance of well from river (miles)													
	0.025	0.075	0.125	0.175	0.225	0.275	0.325	0.375	0.425	0.475	0.55	0.65	0.75	0.85
1	82	48	24	10	4	<1	0	----	----	----	----	----	----	----
2	86	61	41	25	13	7	2	<1	0	----	----	----	----	----
3	89	69	50	35	23	14	8	5	2	<1	0	----	----	----
4	91	72	56	41	30	20	13	8	5	2	<1	0	----	----
5	92	75	60	47	36	25	18	12	8	5	1	<1	0	----
6	92	77	63	50	40	30	22	17	11	8	3	1	<1	0

In order to compute the consumptive use of ground water by phreatophytes using the pumping-well analogy, the following data were needed: the draft on the river in the subreach, the length of the growing season, the area inhabited by phreatophytes, the effect on the riverflow caused by phreatophytic withdrawal of ground water at various distances from the river, and the average volume density of growth in the subreach.

The values used for draft on the river, or decrease in gain of riverflow through the subreach, were obtained by relating the adjusted gain in flow through the Bottomless Lakes to Dexter subreach to the adjusted gain of flow in the Acme to Artesia reach, as determined from seepage investigations. The result of 10 seepage investigations indicated that gain in that subreach was 7.9 percent of the gain in the Acme to Artesia reach. Using the factor derived from the seepage investigations, the maximum and minimum gains in the subreach were computed for the years 1956–58 (table 11). Although the maximum gain always occurred in late winter and early spring before the beginning of the growing season, the figure for maximum gain was considered to be applicable to the beginning of the season if evaporation from the river is taken into acount. The period of minimum gain is always late summer or early fall.

Evaporation diminishes the riverflow and must be added to the computed gain for each date of measurement. The river in the Bottomless Lakes to Dexter subreach consists of about 110 acres each of water surface and wet-sandbars. Evaporation for each date of gain was computed in cubic feet per second and added as gain on that day. The data used for computing draft from the river are shown in table 11.

TABLE 11.—*Computation of difference in gain of the Pecos River in Bottomless Lakes to Dexter subreach due to phreatophyte withdrawal of ground water*

Date of gain	Feb. 18, 1956	Jan. 4, 1957	Jan. 7, 1958
Gain in Acme-Artesia reach .... cfs	95	73	80
Gain in subreach [1] .... do	7.50	5.77	6.32
Evaporation in subreach .... do [2]	.83	.63	.51
Gain in subreach in nongrowing season .... do	8.33	6.40	6.83
Date of gain	Sept. 17, 1956	Sept. 17, 1957	Aug. 17, 1958
Gain in Acme-Artesia reach .... cfs	5.0	15	32
Gain in subreach [1] .... do	.40	1.19	2.53
Evaporation in subreach .... do [2]	2.59	2.07	2.63
Gain in subreach in growing season .... do	2.99	3.26	5.16
Difference in gain due to phreatophyte withdrawal of ground water .... cfs	5.34	3.14	1.67

[1] Gain in subreach = gain in Acme-Artesia reach ×0.079 (p. 72).
[2] Evaporation at Bitter Lakes Wildlife Refuge ×1.033.

The length of the growing season was estimated for the purposes of this computation. In the Roswell basin, saltcedar generally puts out fronds between April 1 and May 1 and drops its fronds late in October. Analyses of charts showing water-level fluctuations in transpiration wells (see "Transpiration-well method," p. 78) reveal that little ground water is used by phreatophytes before about May 1. The stems and twigs of the saltcedar were brittle and dry before fronding but became increasingly succulent during fronding.

The river hydrograph for the Artesia gage shows that the river flow decreases late in February. The lowest flow generally is in August or September, after which the river stage generally rises continuously and reaches peak flow in the winter. Ground-water levels in shallow test holes in the densest phreatophytic growth declined during the growing season and reached their annual lowest level between early September and mid-October. The period of evapotranspiration is about 6 months long and was assumed to begin in mid-April and to end in mid-October.

About 6,100 acres in the Bottomless Lakes to Dexter subreach were occupied by saltcedar and phreatophytic grasses. To develop the pumping-well analogy, the total area of phreatophytes was divided arbitrarily into strips of growth, each strip parallel to the river. The strips within half a mile of the river were 0.05 mile wide, and strips farther than half a mile from the river were 0.1 mile wide. The area of phreatophyte growth and its subdivision into strips are shown on plate 10.

The "ideal" wells simulating pumping by phreatophytes were considered as being spaced along a line perpendicular to the river and at the midpoint of the subreach. The well in each strip was at the center of the strip with respect to distance from the river. Thus, the strips of growth are 0.0 to 0.05, 0.05 to 0.10, . . . mile from the river, and the theoretical wells are 0.025, 0.075, . . . mile from the river. Table 10 shows that pumping a well in a strip beyond 0.80 mile from the river would have no effect on the river flow in a 6-month period, which is the length of the transpiration season.

The computation of the average areal density of the vegetation in the subreach was complicated by the presence of more than one type of phreatophyte, and it was necessary to convert the areal density of the grass tracts to an equivalent areal density of saltcedar that would use the same amount of water as the grass tracts. The results of computations by other methods indicate that the amount of water used by grass tracts of 100-percent volume density was about 20 percent of that required by saltcedar at 100-percent volume density. Accordingly, each tract of grass of a given density of growth was adjusted to an equivalent density of saltcedar, using this ratio. The average areal density of phreatophytes in the Bottomless Lake to Dexter subreach, as adjusted, amounted to 34 percent. This value was used for the 3 years for which water-use computations were made, because

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the 1958 phreatophyte survey showed that growth in the subreach had changed little in total area and areal density.

Vertical density increased in saltcedar tracts in the Roswell basin from 1956 through 1958. In the Bottomless Lakes to Dexter subreach, the vertical density was 75 percent in 1956, 80 percent in 1957, and 85 percent in 1958. The area of saltcedar, and the area of the other phreatophytes adjusted to saltcedar equivalent in the subreach, at 100-percent volume density, amounted to about 1,560 acres in 1956, 1,660 acres in 1957, and 1,770 acres in 1958. In the Acme-Artesia reach, the total area of saltcedar at 100-percent volume density was about 6,300 acres in 1956, 7,400 acres in 1957, and 8,700 acres in 1958.

Of the ground water consumed in the Bottomless Lakes to Dexter subreach, about 37 percent was used by grasses which occupied the equivalent of about 3,500 acres at 100-percent volume density during the 3-year period used for computation. In the total reach of the study area, grasses occupied the equivalent of 19,000 acres at 100-percent volume density in 1956, 18,000 acres in 1957, and 17,000 acres in 1958 (table 7).

The total amount of ground water consumed in the Bottomless Lakes to Dexter subreach was computed by relating draft on the river to the total area of growth in the reach, to the individual areas of the several strips of phreatophytic growth (pl. 10), and to the percent of ground water intercepted by hypothetical pumping wells in those strips, by the following formula:

$$Qd=\frac{AB_1A_1}{A}+\frac{QB_2A_2}{A}+\frac{QB_3A_3}{A}+\frac{QB_4A_4}{A}+\frac{QB_5A_5}{A}+\frac{QB_6A_6}{A}+\ .\ .\ .\ \frac{QB_nA_n}{A}$$

where

Qd=draft, in cubic feet per second, on the river in the reach during given period

Q=draft, in cubic feet per second, of ground water by phreatophytic growth in the reach

A=total area, in acres, of phreatophytic growth in reach

A_1=area, in acres, of strip of phreatophytic growth from 0.0 to 0.05 mile from river (pl. 10)

A_2=area, in acres, of strip from 0.05 to 0.10 mile from river

A_3, A_4, A_5, A_6, . . . and A_n=areas of strips, 0.05 or 0.10 mile in width at progressively greater distances from river. A_n represents area of the strip farthest from river, in which a measurable effect on river flow was caused by pumping in the strip in a 6-month period

B_1=percent, expressed as decimal fraction, of water diverted from the river by the well in strip A_1 (table 10)

B_2=percent, expressed as decimal fraction, of water diverted from the river by the well in strip A_2

B_3, B_4, B_5, B_6, . . . and B_n=percentages of water diverted from river by wells in strips A_3, A_4, A_5, A_6, . . . and A_n.

Solution for Q yields:

$$Q=\frac{Qd\ A}{B_1A_1+B_2A_2+B_3A_3+B_4A_4+B_5A_5+B_6A_6\ .\ .\ .\ B_nA_n}$$

Using specific data as an example for the period from Apr. 17 to Sept. 17, 1956:

$$Q=\frac{5.34\times 6{,}129}{\left[\begin{array}{r}.92\times 676+.75\times 662+.60\times 561+.47\times 505+.36\times 371+.25\times 378+.18\times 297\\ +.12\times 310+.08\times 268+.05\times 227+.01\times 384=15.98 \text{ cfs}\end{array}\right]}$$

The total ground-water draft by phreatophytes in the Bottomless Lakes to Dexter subreach was 15.98 cfs or 5,780 acre-feet during the 6-month transpiration season in 1956. For the 1,560 acres of saltcedar and saltcedar equivalent at 100-percent volume density in the subreach, the consumption of ground water was 3.71 acre-feet per acre in 1956. Extrapolating this figure to the 6,280 acres of saltcedar at 100-percent volume density in the Acme-Artesia reach, the apparent consumptive use of ground water by saltcedar in 1956 was 23,300 acre-feet. Of the 5,780 acre-feet of ground water used in the subreach, 37 percent, or 2,140 acre-feet was used by the equivalent of 3,450 acres of grass at 100-percent volume density, indicating a consumptive use of ground water of 0.62 acre-feet per acre. By extrapolation of this figure to the Acme-Artesia reach of the Pecos River, it was computed that 19,000 acres of grass at 100-percent volume density would have used 11,800 acre-feet of ground water in 1956. The sum of the individual computations for the three types of phreatophytes, including about 400 acre-feet of water used by mesquite, is about 36,000 acre-feet of ground water used by phreatophytes in the Acme-Artesia reach in 1956 (see section on extrapolation from other areas). The total amount of water used, including 18,000 acre-feet of precipitation, amounted to 54,000 acre-feet.

The data used and the results of computations for the 3 years 1956–58 are given in table 12. No correction of the consumptive use was made for variations in depth to water because the depth to water in the subreach is approximately the same as the average depth to water in the entire reach under consideration. The results given in the table indicate that the use of ground water declined during the 3-year period. The change in consumptive use varied inversely with change in the annual amount of precipitation. Compared to the results obtained by other methods of estimating the consumptive use of ground water by phreatophytes, the figures obtained for the 3 years 1956–58 are low, but the trend of change is consistent with the precipitation. The results for the 3 years are comparable in the methods of correction used throughout the computations.

Several sources of error are inherent in the pumping-well analogy method of computation, all of which tend to yield a minimum value. A source of error that may appreciably affect the computation is that of precipitation reaching the water table. Although it is assumed that vegetation intercepted and consumed all water from precipitation, it is possible, especially in 1958, that heavy precipitation and consequent runoff from adjacent uplands, accumulating in the bottom lands, recharged the shallow water and increased summer discharge to the river, thereby decreasing the apparent effect of phreatophytic withdrawal of ground water on the river. Another source of error that may affect the figure for ground-water use is that of increased river flow which puts water into bank storage. The return of bank storage to the stream would increase the apparent summer gain of the stream and thereby reduce the apparent decrease in gain owing to the effects of the phreatophytes.

Sources of error of a more basic nature are the periods for which computations are made and the generalizations that were necessary to reduce the computations to a manageable number. The effect of a pumping well on the flow of a stream, assuming a uniform rate of discharge from the well, increases as time increases (table 10), and if more than one well is pumped, the change of flow in the stream at any given time represents an integration of the effects from the several wells. If the wells are at different distances from the stream, there will be a component of change in streamflow due to the arrival at the stream, at different times, of effects from progressively more distant wells. Should the rate of discharge change at the several wells, the effects of the changes also will be integrated, so far as the flow of the stream is concerned. As a result of this integration of effects, the streamflow after a long period of pumping will indicate the average effect or the average rate of pumping. Theoretically, then, the average rate of pumping could be obtained by using the change in streamflow during one period, as was done in this study. Ideally, to check results, it would be desirable to make several computations during the season, perhaps at 1-month intervals, and particularly early in the transpiration season when the rate of water use by the phreatophytes is accelerating. However, it is probable that the rate of use was fairly constant during the season after the plants had attained their full foliage.

The division of the phreatophyte area into strips for computation and the subsequent computations were feasible only if it were assumed that the growth density was homogenous. Otherwise, it would have been necessary to compute average growth densities and amounts of saltcedar equivalent for each separate strip. This procedure would have increased the number of computations several-fold. Actually, the greatest densities were near the river. Growth on tracts away from the river generally was not dense and included much grass. This would indicate that the equation for determining the rate of phreatophyte water use should include a factor, appropriate to each strip, that would relate the acreage at 100-percent volume density in the strip to the pumping rate in that strip. Because there are so many qualifying factors and, therefore, so many additional calculations involved, it was decided to use the generalization in order to do the work within the time available.

TABLE 12.—*Data used, and the results of computation of the consumptive use of ground water by phreatophytes in the Acme-Artesia reach, 1956–58, by the pumping-well analogy method*

[Computations based on investigations in Bottomless Lakes to Dexter subreach]

	1956	*1957*	*1958*
Period use for computing average rate of ground-water consumption in Bottomless Lakes to Dexter subreach	Apr. 17 to Sept. 17	Apr. 17 to Sept. 17	Apr. 17 to Aug. 17
Draft (*Qd*) on river ---------------- cfs --	5.34	3.14	1.67
Draft on ground water (*Q*) in subreach computed as saltcedar discharge --- cfs --	15.98	9.40	5.44
Quantity of ground water consumed by phreatophytes in subreach during growing season ------------- acre-feet --	5,780	3,400	1,970
Equivalent area of saltcedar in subreach at 100-percent volume density -- acres --	1,560	1,660	1,770
Unit consumptive use of ground water by saltcedar ---------- acre-feet per acre --	3.71	2.05	1.11
Equivalent area of saltcedar in Acme-Artesia reach at 100-percent volume density ------------------------ acres --	6,280	7,440	8,690
Consumptive use of ground water by saltcedar in Acme-Artesia reach acre-feet per year --	23,300	15,200	9,600
Quantity of ground water used by grass in subreach during growing season acre-feet --	2,140	1,260	710
Unit consumptive use of ground water by grass -------------- acre-feet per acre --	.62	.36	.21
Equivalent area of grass in Acme-Artesia reach at 100-percent volume density acres --	19,000	18,000	17,000
Consumptive use of ground water by grass in Acme-Artesia reach acre-feet per year --	11,800	6,900	3,600
Consumptive use of ground water by mesquite in Acme-Artesia reach acre-feet per year [1] --	440	390	340
Total consumptive use of ground water by phreatophytes in Acme-Artesia reach acre-feet per year --	35,500	22,500	13,500
Precipitation ---------------- acre-feet --	18,000	29,000	41,000
Total evapotranspiration -- do ---	53,500	51,500	54,500

[1] From section on "Extrapolation from other areas."

TRANSPIRATION-WELL METHOD

The transpiration-well method for determining evapotranspiration was first used by White (1932) in Escalante Valley, Utah. He observed diurnal fluctuations on recorder charts from observation wells located in phreatophyte areas and concluded that the fluctuations were a measure of the ground-water withdrawals by evapotranspiration from those phreatophyte areas. During his investigation, White (1932, p. 59–61) derived a formula to compute the daily draft of ground water by phreatophytes. Gatewood and others (1950, p. 139–155) found that this formula generally was valid; however, some modifications were required when applied to areas containing saltcedar.

The theory of the transpiration-well method was described by White (1932, p. 60–61) as follows:

> During the day the capillary fringe is depleted by the plants, and the movement of ground water by capillary action to meet the depletion is more rapid than recharge by hydrostatic or artesian pressure. Therefore the water table declines and the head increases. During the night transpiration and evaporation losses are small, the water table moves upward, and the pressure head declines.
>
> From about 6 to 10 in the evening and again from about 6 to 10 in the morning recharge approximately balances discharge, and for a few hours the water table is nearly at a standstill. This state of equilibrium would be reached earlier both in the evening and in the morning if it were not for a lag in some of the operations. At or soon after sunset, the rate of transpiration and evaporation declines to a small fraction of the rate that prevails during the day, but for a time the plants continue to draw some water to fill their circulatory systems, which have become somewhat depleted. (Nearly all plants become slightly wilted during the day, particularly on hot days, and tend to have a drooping appearance at night, quite in contrast with their fresh, turgid appearance in the morning.) Moreover, during the day the recharge of the capillary fringe from the zone of saturation lags somewhat behind the discharge by plant action. By midnight, or slightly before, the veins of the plants have become filled with water. Meanwhile capillary equilibrium has been nearly established in the capillary fringe, and during the hours from midnight to morning there is little movement of water to the fringe from the zone of saturation.
>
> Between midnight and 4 a.m. the water table is approximately at a mean elevation for the 24-hour period, and therefore the head is also approximately at a mean provided there is no net gain or loss in water-table elevation during the 24-hour period. If the water table has a net fall during the 24 hours, the head in the early morning hours mentioned is slightly above the noon to noon mean; and if it has a net rise, the head is slightly below the mean but the difference is generally not great. The velocity of water moving through a rock or soil varies approximately as the hydraulic gradient. Therefore if the slight losses by transpiration and evaporation between midnight and 4 a.m. are neglected, as well as the slight difference between the hydraulic head at this time and the true mean for the day, the hourly rate of recharge from midnight to 4 a.m. may be accepted as the average rate for the 24-hour period. The total quantity of ground water withdrawn by transpiration and evaporation during

the 24-hour period can then be determined by the formula $q=y\ (24r\pm s)$, in which q is the depth of water withdrawn, in inches, y is the specific yield of the soil in which the daily fluctuation of the water table takes place, r is the hourly rate of rise of the water table from midnight to 4 a.m., in inches, and s is the net fall or rise of the water table during the 24-hour period, in inches. In field experiments the quantities on the rigth-hand side of the formula except the specific yield can be readily determined from the automatic records of water-table fluctuation.

During 1958, continuous recording water-level gages were maintained on four shallow wells in tracts of phreatophytes. Three wells were in moderate to dense saltcedar and one was in dense phreatophyte grasses (principally threadleaf sedge, saltgrass, and sacaton). Continuous records of diurnal fluctuations were made throughout the 1958 growing season, except for short periods when the recorders were not operating because of mechanical failure. Transpiration was interpolated for the periods of missing records.

The specific yield of the aquifer was not determined at the four well sites; however, the average specific yield probably is about 20 percent at the three wells in the tracts of saltcedar and about 15 percent at the well in the tract of grass.

During the Safford Valley studies (Gatewood and others, 1950) it was learned that saltcedar continued to transpire water throughout the night and that to obtain the correct transpiration value the apparent transpiration value must be multiplied by a factor of 1.25. The coefficient of 1.25 required to correct for night transpiration of saltcedar in Safford Valley was assumed to be applicable in the Roswell basin.

The transpiration wells were within tracts of phreatophytes of uniform density. Transpiration well 10.25.15.323 (pl. 9) was in a parcel of dense saltcedar having a maximum vertical height of 12 feet. Within 50 feet (estimated radius of influence) of the well, the areal density was 75 percent and the average vertical height was 11 feet; therefore, the volume density was 63 percent. The soil consists of fine sand, silt, and clay. The depth to the water table below the land surface during the 1958 growing season ranged from a high of 5.7 feet in the spring to a low 7.2 feet in the fall, and averaged 6.4 feet. Evapotranspiration from this tract was computed to be 5.0 feet per acre per year during 1958.

Transpiration well 11.25.25.133 (pl. 9), was in a parcel of dense phreatophyte grasses, principally threadleaf sedge, saltgrass, and sacaton. The volume density was 90 percent within a radius of 50 feet of the well. The soil consists principally of silty clay with a few stringers of fine silty sand less than 1-inch thick. The depth to the water table below the land surface ranged from 1.6 to 5.5

feet and averaged 4.1 feet during the 1958 growing season. The annual rate of evapotranspiration was computed to be 2.8 feet per acre for the year.

Transpiration well 11.25.36.142 (pl. 9), was in a parcel of moderately dense saltcedar. The areal density of saltcedar was about 80 percent, and average vertical height was 13 feet within a radius of 50 feet of the well; therefore, the volume density was 80 percent. The soil consists of fine sand, silt, and clay. The depth to the water table ranged from 9.7 feet in the spring to 11.9 feet in the fall and averaged 10.8 feet during the 1958 growing season. The evapotranspiration was computed to be 3.3 feet per acre per year during 1958.

Transpiration well 17.27.7.331 (pl. 9) was in a parcel of dense saltcedar having an average vertical height of 12 feet. The areal density was 90 percent within a radius of 50 feet of the well; therefore, the volume density was 83 percent. Here, also, the soil consists of fine sand, silt, and clay. The depth to the water table ranged from 0.8 to 6.0 feet and averaged 3.3 feet during 1958. The water level in this well responded almost immediately to changes in stage of the Pecos River. For this reason the diurnal fluctuations in this well were useless in determining annual evapotranspiration. Comparison of the few days of useful record with records from the other transpiration wells indicated a high rate of evapotranspiration.

The average depth to the water table was 7 feet throughout the bottom land of the Acme-Artesia reach of the Pecos River during 1958. Using data from two transpiration wells in tracts of saltcedar and adjusting for differences in depth to water, the annual rate of evapotranspiartion was computed to be 4.8 feet per acre for a tract of saltcedar of 100-percent volume density. Therefore, 8,700 acres of saltcedar of 100-percent volume density consumed about 42,000 acre-feet of ground water during 1958.

The average depth to the water table was 4.1 feet at one transpiration well in a tract of phreatophyte grasses, and the consumptive use of water there was computed to be 2.8 feet per acre. The average depth to water in all of the tracts of phreatophyte grasses was 7 feet, and the consumptive use after adjusting for the greater depth to water probably was about 1.4 feet per acre for tracts of grass of 100-percent volume density. Therefore, 17,000 acres of phreatophyte grasses of 100-percent volume density consumed about 24,000 acre-feet of ground water during 1958.

No transpiration wells were maintained in the tract of mesquite. As seen elsewhere in this report, the total quantity of ground water consumed by the mesquite in the project area was small, and for purposes of this computation it was considered negligible. The total consumption of ground water by saltcedar and phreatophyte grasses during 1958 was about 66,000 acre-feet.

The 1958 transpiration well data was extrapolated to the years 1956 and 1957 by comparing evaporation rates from class-A land pans for the same years. Then by using phreatophyte acreage data from table 7 it was computed that saltcedar consumed about 35,000 and 40,000 acre-feet of ground water, and phreatophyte grasses consumed 35,00 and 32,000 acre-feet during 1956 and 1957, respectively. The total consumptive use of ground water was about 70,000 and 72,000 acre-feet, respectively, for 1956 and 1957.

COMPARISON OF RESULTS

Table 13 summarizes the results from the four methods used in computing evapotranspiration in the bottom land along the Acme-Artesia reach of the Pecos River in the years 1956-58. The computed consumptive use of ground water varied between wide limits. In 1956, the range of consumptive use of ground water was from a minimum of 36,000 acre-feet for the pumping-well analogy method, to a maximum of 70,000 acre-feet for the transpiration-well method. In 1957 the consumptive use of ground water ranged from a minimum of 23,000 acre-feet to a maximum of 72,000 acre-feet, and for 1958 ranged from 13,500 acre-feet to 66,000 acre-feet. The pumping-well analogy method was expected to give minimum values—that is, figures that are smaller than the actual value—whereas, the other three methods could result in maximum values. It is estimated that the consumptive use of water from all sources by native vegetation in the bottom land along the Pecos River between Acme and Artesia was between 70,000 and 80,000 acre-feet annually during the period 1956–58.

TABLE 13.—*Use of water in the phreatophyte area in the Acme-Artesia reach of the Pecos River, Chaves and Eddy Counties, N. Mex., 1956–58*

Method of computation	Use of water (acre-feet)								
	1956			1957			1958		
	Ground water	Precipitation	Total	Ground water	Precipitation	Total	Ground water	Precipitation	Total
Extrapolation of water-use rates from other areas	44,000	18,000	62,000	38,000	29,000	67,000	32,000	41,000	73,000
Inflow-outflow	44,000	18,000	62,000	50,000	29,000	79,000	47,000	41.000	88,000
Pumping-well analogy	36,000	18,000	54,000	23,000	29,000	52,000	14,000	41,000	55,000
Transpiration well	70,000	18,000	88,000	72,000	29,000	101,000	66,000	41,000	107,000
Average			66,000			75,000			81,000

CONCLUSIONS

TREND OF WATER USE WITH UNCONTROLLED PHREATOPHYTE GROWTH

In the period 1956–58, phreatophytes were growing on about 41,000 acres of land adjacent to the Pecos River and its tributaries between Acme and Artesia. Saltcedar and grasses (chiefly sacaton and saltgrass) comprised the bulk of this vegetation. During this period the total area of phreatophytes remained almost constant, and it is probable under existing climatic conditions that the total area suitable for large scale phreatophyte growth in the Acme-Artesia reach has been infested by this vegetation and that no substantial increase in phreatophyte acreage will occur. Casual consideration of the idea that the maximum phreatophyte acreage has been attained might lead to the conclusion that phreatophyte growth and rate of water usage will be constant in the future. This is not true. The total area possible for phreatophyte growth probably has been infested, but the density of infestation is not 100 percent, and the quantity of water used annually by the vegetation will increase if the density of the vegetation becomes greater.

In 1958, saltcedar infested about 28,000 of the 41,000 acres of phreatophyte land. The average areal density of saltcedar in the 28,000-acre area was about 36 percent, and the vertical density was about 85 percent; grass occupied most of the remaining 64 percent of the 28,000-acre tract. Where growing conditions are favorable, saltcedar will gradually spread and replace existing vegetation. Conditions are favorable for the growth of saltcedar in most of the 41,000-acre phreatophyte area. Again, casual thinking may mislead one into concluding that it makes no difference which phreatophyte occupies an area. Some phreatophytes can replace others without causing any increase in water consumption, but where saltcedar replaces grass an increase in water use will result. A unit area of saltcedar at 100-percent volume density uses about 5 times as much water as does a unit area of grass at 100-percent volume density. Thus, the rate of water use is related to plant type and to volume of plant material.

The phreatophyte area in the Acme-Artesia reach presents a large potential for the increase in the use of water by phreatophytes if they are permitted to grow unchecked. For example, consider the 28,000-acre area that saltcedar has infested with a volume density of saltcedar growths of about 30 percent. The use of water in 1958 by saltcedar and grass in that tract was about 62,000 acre-feet. Computations were based on rates of consumptive use of 6.0 feet and 1.2 feet per acre per year for saltcedar and grasses, respectively, at 100-percent volume density. If the area had been filled with saltcedar to 100-

percent volume density, the water use would have been about 168,000 acre-feet a year provided the water levels in the phreatophyte area were at about the 1958 level. To make the water-waste specter more awesome, assume that the entire 41,000 acres of phreatophytes, which used about 69,000 acre-feet of water a year in the 1956–58 period, was occupied by saltcedar growth of 100-percent volume density. The water demand would be about 245,000 acre-feet a year; however, this amount of water might not be available to support the growth. In contrast, if the 41,000-acre phreatophyte area were covered only with grass, the water use would be about 45,000 acre-feet a year. It is important to recognize that a large increase in water use probably will occur if the further spread of saltcedar is not controlled. Some measures should be taken to slow or stop the trend in its rate of water use.

A plan of action to reduce substantially the waste of water by phreatophytes must be based on control both of saltcedar growth and of the nonartesian water levels, the latter in order to prevent an increase in waste by evaporation and replacement cover due to a subsequent rise in the water table. Saltcedar is the most hearty consumer of water of all the phreatophytes in the Acme-Artesia reach; it expands in acreage at the expense of the other phreatophytes; and it is a nonbeneficial plant. The phreatophyte grasses provide grazing for cattle at times and, therefore, have some value. The eradication of saltcedar and the encouragement of grass growth or cropping on the denuded saltcedar tracts will reduce water waste and prevent erosion of the land.

METHODS OF ERADICATING SALTCEDAR

The eradication of saltcedar is difficult. Burning, spraying with chemicals, mechanical clearing, and lowering of ground water levels below the reach of saltcedar roots have had varying degrees of success.

Research projects in progress in the western States have been described by Robinson (1958). The general opinion was that burning alone has not been notably successful in the control of saltcedar. Chemical sprays of 2, 4–D and 2, 4, 5–T have shown encouraging signs of effective control. The spraying of saltcedar during the period of full-leaf has been more effective than spraying during the season when the plant is dormant. Spraying is hazardous to nearby crops, and great care must be taken to prevent crop damage. Mechanical clearing also has shown great promise in controlling growth. Cutting the plant at land surface is much less effective than cutting deep to get the root crown. The best results in eradicating saltcedar have been obtained from mechanical clearing to cut the root crowns followed by spraying the young regrowth.

Lowering of the nonartesian ground-water levels would be effective, but this cannot be done in all saltcedar areas because of adverse effects on nearby surface streams and wells. To control saltcedar growth by lowering the nonartesian water levels would require that the water table be lowered in a matter of a few days to a level several feet below the lowest seasonal level. Lowering the water table slowly might permit the plants to extend their roots downward rapidly enough to keep pace with the water-table decline. The amount of lowering required to kill saltcedar would depend on the type of material in the upper part of the alluvium and the thickness of the capillary zone. If the material is well-sorted sand or gravel, lowering the water table 2 or 3 feet might be adequate, because the capillary zone is only a few inches thick in such material. If the material is poorly sorted sand, silt, and clay, the capillary zone may be several feet thick, and a water table decline of 2 or 3 feet would not deprive the plants of water.

A hydrograph of the water-level fluctuations in well 10.25.33.341 (fig. 11) shows seasonal changes in shallow water levels of 4 to 5 feet; thus, it would seem that the phreatophytes near this well have established roots through the range of this change. Lowering the water level 3 feet near this well when the water level is high would cause little or no water shortage to phreatophytes in that area, but suddenly lowering the water level 3 feet when water levels are at their seasonal low might be sufficient to deprive the plants of water. Thus the amount of water table decline required to kill the phreatophytes would depend on the soil characteristics and on the time of year the artificial lowering was made.

Even though a rapid lowering of water levels might not be feasible, depressing the water table in the phreatophyte area by whatever manner possible would be beneficial. A lowering of the water table in some areas would dry up marshy areas and alleviate moist soil conditions, which are conducive to the propagation of phreatophyte seedlings.

Lowering the nonartesian water levels in the Acme-Artesia reach might be done by one or more of the following methods: (a) withdrawal of water from artesian wells in the phreatophyte area to reduce recharge to the alluvium as upward leakage from the artesian system; (b) withdrawal of water from the base of the valley fill by wells in the phreatophyte area to intercept the upward leakage of artesian water; (c) withdrawal of water from nonartesian wells in the phreatophyte area; and (d) withdrawal of water from the alluvium by drains in the phreatophyte area or drains upgradient to intercept nonartesian water moving to the phreatophyte area. The water table could not be lowered rapidly by drains, but drains used in conjunction with mechanical or chemical eradication of the saltcedar would discourage regrowth by eliminating moist soil conditions at the land surface.

Estimating the cost of clearing saltcedar is beyond the scope of this report. However, experience by others has shown that costs vary with the density of the growth; therefore, the cost of eradicating saltcedar in the Acme-Artesia reach in the near future would be considerably less costly than after a few more years of uncontrolled growth.

POTENTIAL REDUCTION IN USE OF WATER BY PHREATOPHYTES

To better identify local problems regarding saltcedar eradication and reduction in water consumption by phreatophytes in the Acme-Artesia reach, the reach will be discussed as a series of subreaches. Methods of reducing nonbeneficial consumption of water in these reaches will be introduced in the discussion.

ACME TO BITTER CREEK

The Acme to Bitter Creek subreach extends from U.S. Highway 70 near Acme to about the middle of sec. 28, T. 10 S., R. 25 E., a distance of about 18 river miles. In 1958, phreatophytes infested about 8,000 acres of this reach. The saltcedar growth in a single tract having a 100-percent areal density would occupy about 2,300 acres; grass would cover about 4,200 acres at 100-percent areal density. Use of water by these phreatophytes was about 18,000 acre-feet a year in 1956–58. If saltcedar overgrew the area to 100-percent volume density, the use of water would be about 48,000 acre-feet a year. It is doubtful, however, that such a growth density would be attained throughout the subreach. Parts of secs. 32 and 33, T. 9 S., R. 25 E., and secs. 4 and 5, T. 10 S., R. 25 E., have only a veneer of soil overlying bed rock. Although isolated saltcedars or even small groups of plants might find growing conditions favorable locally, probably no dense growth could develop. Because the total phreatophyte area could not be overgrown by saltcedar at 100-percent volume density, the probable maximum water use would not exceed 40,000 acre-feet a year. The entire area would be suitable for grass growth. Clearing the saltcedar and allowing grass to grow would reduce the annual use of water in the reach to about 10,000 acre-feet, a reduction of 8,000 acre-feet from the use in 1958.

The geology and hydrology of the subreach will permit moderate lowering of nonartesian water levels in parts of the subreach by one or more of the methods mentioned on page 84. Excessive lowering of the nonartesian ground-water levels near the lakes and ponds of the Bitter Lake National Wildlife Refuge would dry up those bodies of surface water to the detriment of the wildlife; consequently, creating large-scale water-level declines probably would not be desirable in the refuge area.

Practically all of the water in the alluvium in the Acme to Bitter Creek subreach is from upward leakage from the artesian system, and intercepting this artesian water before it recharges the alluvium would lower the nonartesian water levels. Withdrawing water from artesian wells or from wells tapping the base of the alluvium would intercept some recharge. The decline in nonartesian water levels caused by intercepting this form of recharge probably would be too slow to kill saltcedar immediately. However, this method, used in conjunction with mechanical or chemical eradication, would help in controlling regrowth or spread of saltcedar. One advantage in using artesian wells or wells reaching the base of the alluvium is that these wells would have a natural flow and would require little pumping.

The withdrawal of water from artesian wells in the Acme to Bitter Creek subreach would have a beneficial effect on the quality of the artesian water in the irrigated area near Roswell. Water in the artesian aquifer in this subreach is saline, and withdrawal of saline water from the artesian acquifer by wells in quantities sufficient to lower nonartesian water levels appreciably would reduce the amount of saline ground water moving toward the Roswell area.

Ground-water levels are between 4 and 7 feet in much of the phreatophyte area west of the Pecos River in this subreach. East of the river, water levels are deeper than 10 feet. It is probable that drains west of the river could lower shallow water levels suffciently to prevent the occurrence of moist soil conditions that promote the spread of saltcedar. Drains might be especially effective in the area between the lakes in the wildlife refuge and the Pecos River without interfering with the lake levels.

Clearing the saltcedar and planting as much of the denuded area as possible with crops yielding feed and shelter to wildlife would change use of water from nonbeneficial to beneficial. Some crops might grow by subirrigation and use less water than the saltcedar.

Mechanical clearing of the saltcedar, periodic spraying of regrowth, and construction of several drains, probably would be most effective in reducing water waste with the least possible chance of interfering with operation of the wildlife refuge.

BITTER CREEK TO 3 MILES BELOW RIO HONDO

This subreach extends from Bitter Creek southward to the southern boundary of sec. 13, T. 11 S., R. 25 E., a distance of about 9 river miles. Conditions are extremely favorable for a large-scale increase in the growth of saltcedar in this subreach, particularly west of the river where saltcedar could expand to about 100-percent volume density throughout the length of the subreach. In 1956–58 phreatophytes in the subreach infested about 8,000 acres and consumed about 12,000 acre-feet of water a year, a consumption rate that might rise to about 40,000 acre-feet a year if saltcedar attains a 100-percent volume density over the area west of the river. The bulk of the phreatophyte growth east of the river is grass that grows on a pediment cut on the Chalk Bluff formation; the amount of ground water available to plants in that area probably would be insufficient to support a dense growth of saltcedar; therefore, most of the grass area east of the river probably is not seriously threatened by a large-scale invasion of saltcedar.

Eradicating the saltcedar and maintaining a grass cover over the subreach would reduce the 1958 rate of water use from 12,000 acre-feet a year to about 10,000 acre-feet. Although this seems like a small reduction in water use, the potential savings of water in future years would be large considering the rate of water use that could develop if the saltcedar were allowed to grow unchecked.

The depth to water in the subreach from Bitter Creek to 3 miles below the Rio Hondo ranges between 4 and 7 feet west of the Pecos River and averages about 5 feet; east of the river, the depth to water ranges between 6 and 12 feet and averages about 10 feet. Much of the phreatophyte area west of the river would waste less water if the water level was lowered several feet, but only a relatively small area east of the river would benefit by lowering the nonartesian water level there.

Reducing the use of water by evapotranspiration and controlling the spread of saltcedar in this subreach can be accomplished to some extent by lowering the nonartesian water levels. The thickness of the alluvium in this area generally is less than 100 feet, and much of the alluvium is less than 50 feet thick, particularly east of the Pecos River. Recharge to the alluvium primarily is from upward leakage of water from the artesian system, but some recharge to the alluvium in the bottom land is provided by seepage from irrigated fields in the Roswell area. Withdrawal of water from wells tapping the San Andres limestone between Bitter Creek and the Rio Hondo could intercept some recharge from the artesian system, but to effect much of a decrease in recharge would require a relatively large quantity of discharge because of the high transmissibility of the San Andres in that area. Wells tapping the San Andres limestone near the river would flow naturally and probably would not require pumping equipment. Such wells would yield saline water as in the subreach upstream, thereby alleviating the encroachment of saline water toward Roswell. Disposal of the saline water probably would be a problem. Some could be placed in the river, but some probably would have to be discharged by large evaporation tanks.

Wells tapping the base of the alluvium in the general area between Bitter Creek and the Rio Hondo would be more effective in lowering nonartesian water levels than deeper wells, if the rate of discharge remained the same. Wells drilled to the base of the alluvium between Bitter Creek and the Rio Hondo and located where the land surface is below an altitude of about 3,465 feet would flow about half of the year. Although the land surface in some of this area is a few feet above an altitude of 3,465 feet, wells could be made to flow by placing them in ditches or drains dug to the proper depth. The nonartesian water level in most of sec. 33, T. 10 S., R. 25 E. probably could be lowered appreciably by a system of drains and companion relief wells.

The pumping of nonartesian wells would be effective in lowering water levels but would at the same time increase upward movement of water from the artesian aquifer.

Drains probably would be effective in lowering water levels west of the river. A few drains exist in the area; rehabilitation of these drains and construction of additional drains would be required. A few short drains would dry up the local marshy area east of the river.

Deepening and straightening of the Rio Hondo in the bottom land would facilitate surface-and ground-water drainage. A system of drains could be constructed as tributaries to the Rio Hondo.

Reducing waste of water by phreatophytes between Bitter Creek and 3 miles below the Rio Hondo could be accomplished by periodic clearing of the saltcedar, chemical spraying of the regrowth, and controlling of the nonartesian water levels by use of drains, relief wells, and pumping of shallow wells. The area west of the Pecos River will require more attention in the control of shallow water levels than will the area east of the river.

THREE MILES BELOW RIO HONDO TO 4 MILES ABOVE RIO FELIX

This subreach extends from sec. 13, T. 11 S., R. 25 E., to sec. 23, T. 13 S., R. 26 E., and is about 21 river miles in length. In 1956–58, phreatophytes covered about 9,600 acres, of which about 6,700 acres were infested with saltcedar. The saltcedar, if reduced to an area equivalent to 100-percent areal density, would cover only 2,000 acres.

The phreatophytes in this subreach consumed about 16,000 acre-feet of water a year, of which saltcedar used about 12,000 acre-feet a year. About 1,200 acres of grass grew on a pediment east of the river, and, as in the subreach described previously, saltcedar probably will not infest the pediment area with more than a sparse growth. Grasslands west of the river are susceptible to invasion by saltcedar and probably can support a moderately dense growth of saltcedar. Water use by phreatophytes could increase to about 35,000 acre-feet a year in this subreach, an increase of about 19,000 acre-feet a year over the annual use in 1956–58. A grass cover over the phreatophyte area would use only about 12,000 acre-feet of water a year.

West of the Pecos River, springs and seeps fed in part by seepage from the Hagerman Canal and seepage from irrigated fields form marshy areas which were grass covered in 1956–58. These marshy areas provide favorable conditions for the invasion of saltcedar. Properly constructed drains would intercept the water from the springs and seeps, thereby drying up the marshy areas. Drainage wells in these marshy areas might be inadvisable because they probably would induce additional seepage from the nearby canal. Elsewhere in this subreach, the depth to water is between 6 and 10 feet and averages about 8 feet. Drains would be deep and expensive to construct in much of the subreach. East of the Pecos River, drains might be constructed in selected areas in secs. 24, 25, and 36, T. 11 S., R. 25 E., to lower the nonartesian water levels, thereby discouraging the spread of saltcedar in those areas.

The principal means of controlling saltcedar growth in this reach probably would be by periodic clearing and spraying of the regrowth.

FOUR MILES ABOVE RIO FELIX TO 1 MILE BELOW COTTONWOOD CREEK

This subreach extends from sec. 23, T. 13 S., R. 26 E., to sec. 35, T. 16 S., R. 26 E., a distance of about 34 miles. In 1956–58 the subreach contained about 9,000 acres of phreatophytes which consumed about 20,000 acre-feet of water a year. The annual consumption of water could rise to about 38,000 acre-feet. Saltcedar has infested about one-half the phreatophyte acreage in the subreach and has an average areal density of about 50 percent, a density of saltcedar greater than in any other subreach between Acme and Artesia. Conditions are favorable for the saltcedar tracts to attain 100-percent volume density in a relatively short period of years. Except for the large tract of grass between Walnut and Cottonwood Creeks west of the river, and a few scattered tracts of phreatophytes east of the river, the phreatophytes are concentrated in a narrow band along both sides of the Pecos River. The river is entrenched deeper in the valley fill in this subreach than

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in other subreaches between Acme and Artesia, and natural drainage of the fill by the deep river channel maintains a control on the spread of saltcedar away from the river channel. Saltcedar probably will be slow to invade the large grass tract between Walnut and Cottonwood Creeks under existing climatic conditions because the existing drains in that area keep the ground-water levels at sufficient depth to discourage its spread. Additional drains in that area would help in controlling the spread of saltcedar but might not be necessary, provided the existing drains and the channel of Cottonwood Creek are kept clean. Keeping the channel of Cottonwood Creek open by periodic dredgings between U.S. Highway 285 and the mouth of the creek would facilitate surface- and ground-water drainage.

Chemical spraying and then burning might be highly effective methods in controlling the saltcedar growth in this subreach. Some of the saltcedar helps to keep the river from cutting a wider channel; therefore, mechanical clearing in much of this subreach might not be desirable. Killing the trees by chemical spray and burning and leaving the trees in place would help control the river within its present banks. Grass probably would not grow if the saltcedars were cleared, because most of the saltcedar tracts are in low-lying areas which are inundated by medium floods in the river. Killing the saltcedars and leaving them in place would reduce the use of water in the phreatophyte area in the subreach to about 10,000 acre-feet a year.

Pumping for irrigation is lowering ground-water levels immediately west of the phreatophyte area. It is anticipated that any rise in water levels in the phreatophyte area because of saltcedar eradication will be controlled by the eventual expansion to the phreatophyte area of the drawdown caused by pumping for irrigation.

ONE MILE BELOW COTTONWOOD CREEK TO ARTESIA

This subreach is between sec. 25, T. 16 S., R. 26 E., and the Artesia gage, a distance of about 7 river miles. In 1956–58 phreatophytes in this reach occupied about 2,700 acres and consumed about 7,000 acre-feet of water a year. Conditions in the area are favorable, particularly west of the river, for the continued encroachment and density increase of saltcedar. If the growth trend is permitted to continue without control, the water use in this subreach could increase to about 15,000 acre-feet a year. A grass cover would use about 3,000 acre-feet a year.

A system of drains or shallow drainage wells in secs. 2 and 12, T. 17 S., R. 26 E., would lower the water table sufficiently to discourage the increase in density and area spread of salcedar in that area. If the saltcedars were cleared and drains were constructed, the drains would keep the ground-water levels from rising and thus would assist in keeping the saltcedars from regrowing quickly. The drains would reduce the maintenance work required in keeping the area cleared of saltcedar. Drainage wells might be less desirable than drains because of pumping costs and also the danger of lowering water levels below river level.

Eradicating the saltcedar, lowering the water table by drains, and allowing a grass cover to develop could reduce the water use in the subreach to about 3,000 acre-feet a year, a reduction of about 4,000 acre-feet.

SUMMARY FOR ACME-ARTESIA REACH

A study of table 14 indicates that a water-salvage program consisting of clearing all saltcedar and encouraging a grass cover probably would reduce the 1958 rate of water use in the bottom land by about 28,000 acre-feet a year. If no water-salvage program is attempted, the use of water by evapotranspiration in the bottom land probably will increase during a period of years to about 168,000 acre-feet a year, or about 95,000 acre-feet a year more than the present rate of use, if climatic conditions continue about the same as in 1956–58. If a series of wet years occurs, the rate of saltcedar encroachment and the increase in the density of all phreatophytes would accelerate, and, furthermore, the total area of phreatophytes might increase several thousand acres because the increase in soil moisture would be favorable for the spread of phreatophytes to areas that previously were too dry.

TABLE 14.—*Annual use of water in the phreatophyte area in Acme-Artesia reach of the Pecos River with controlled and uncontrolled phreatophyte growth under climatic conditions similar to that of 1956–58*

[Assumed water use of 6.0 feet and 1.2 feet per acre a year for saltcedar and grass respectively at 100-percent volume density]

Reach	Use of water (acre-feet)		
	1958	If controlled (saltcedar eradicated and grass left)	Maximum if not controlled
Acme to Bitter Creek	18,000	10,000	40,000
Bitter Creek to 3 miles below Rio Hondo	12,000	10,000	40,000
3 miles below Rio Hondo to 4 miles above Rio Felix	16,000	12,000	35,000
4 miles above Rio Felix to 1 mile below Cottonwood Creek	20,000	10,000	38,000
1 mile below Cottonwood Creek to Artesia gage	7,000	3,000	15,000
Total Acme to Artesia gage	73,000	45,000	168,000

TABLE 15.—*Gain and loss of flow, in cubic feet per second, in the Acme-Artesia reach of the Pecos River as determined by seepage investigations, Chaves and Eddy Counties, N. Mex., 1956–59*

[Subreaches are divided by the following sites on the Pecos River: at gaging station near Acme, just below Rio Hondo, near Bottomless Lakes, at bridge near Dexter, 0.8 mile above Rio Felix, at gaging station near Lake Arthur, and at gaging station near Artesia. Discharge measurements of some drains and pump diversions were provided by the State Engineer's office]

Area of measurement	1956						1957						1958				1959	
	Jan. 4	Jan. 5	Feb. 26	Feb. 27	June 3	Oct. 17	Jan. 2	Jan. 3	Mar. 4	Mar. 5	June 19	June 20	Jan. 23	Jan. 24	Nov. 5	Nov. 6	Jan. 8	Mar. 6
Gain of flow to the Acme-Artesia reach of the Pecos River from sources outside the bottom land of that reach																		
Pecos River at gaging station near Acme	11.7	11.8	11.6	8.75	0.30	0.0	4.98	3.97	0.47	1.26	0.0	0.0	13.8	9.54	79.5	83.9	51.3	53.6
Tributaries in subreach:																		
Acme to Rio Hondo	([a])	([a])	([a])	([a])	([a])	[b]2.07	[a] [c]17.4	[a] [c]16.7	([a])	([a])	[d]1.24	[d]1.67	([a])	([a])	[a] [b]11.7	[a] [b]12.5	([a])	([a])
Rio Hondo to Bottomless Lakes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bottomless Lakes to Dexter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[b]3.56	[b]3.45	0	0
Dexter to Rio Felix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rio Felix to Lake Arthur	.39	.19	3.57	3.64	.06	.07	2.88	2.38	.49	.49	.17	.14	2.11	2.42	3.75	3.58	2.59	1.37
Lake Arthur to Artesia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Drains in subreach																		
Acme to Rio Hondo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rio Hondo to Bottomless Lakes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bottomless Lakes to Dexter	.25	.25	1.92	1.92	.35	.54	.15	.15	.45	.41	.26	.26	1.55	1.54	2.13	2.05	2.00	2.28
Dexter to Rio Felix	.97	.99	1.24	1.34	.73	.50	.59	.66	1.02	1.23	.47	.47	.45	.49	.74	.68	.83	1.05
Rio Felix to Lake Arthur	.09	.17	.17	.12	.10	.10	.09	.09	.62	.09	0	0	.09	.09	.09	.09	.09	.09
Lake Arthur to Artesia	.37	.28	.87	.75	.29	.39	.16	.34	.67	.80	.76	.83	.08	.29	.06	.07	1.24	.33
Subtotal	13.8	13.7	19.4	16.5	1.83	3.67	26.2	24.3	3.72	4.28	2.90	3.37	18.1	14.4	101.5	106.3	58.0	58.7

Gain of flow to the Pecos River from ground-water sources within the bottom land of the Acme-Artesia reach

Tributaries in subreach:																		
Acme to Rio Hondo	[e]19.7	[e]19.9	[e]18.9	[e]19.6	[e]7.40	5.00	[e]13.5	[e]13.9	[e]11.4	[e]11.6	[e]4.38	[e]6.05	[e]15.9	[e]14.5	[e]13.1	[e]13.9	[e]15.6	[e]11.4
Rio Hondo to Bottomless Lakes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bottomless Lakes to Dexter	.82	.95	.88	.64	.21	.09	.86	.82	.52	.44	.10	.09	.54	.54	.5	.5	.70	.76
Dexter to Rio Felix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rio Felix to Lake Arthur	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lake Arthur to Artesia	2.49	2.77	2.92	3.15	.94	.38	.84	1.24	1.01	1.18	.25	.19	.33	.42	1.42	1.33	1.70	1.49
Drains in subreach:																		
Acme to Rio Hondo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rio Hondo to Bottomless Lakes	[f]3.91	[f]3.93	3.84	3.69	1.82	1.79	2.59	2.52	3.12	3.08	.99	1.19	4.00	3.80	9.43	9.04	8.73	8.15
Bottomless Lakes to Dexter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dexter to Rio Felix	2.24	2.06	.77	.69	1.51	.39	1.08	1.09	.42	.51	1.35	1.29	1.01	.81	.66	.66	.68	.79
Rio Felix to Lake Arthur	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lake Arthur to Artesia	.10	.10	.14	.12	.20	.03	.01	0	.01	.02	0	0	0	0	0	0	0	0
Springs and seeps in Pecos River Channel in subreach: [g]																		
Acme to Rio Hondo	9.7	8.9	8.8	10.4	3.0	3.8	6.1	8.0	4.6	4.5	2.2	2.8	7.5	9.8	15.9	14.0	([h])	3.2
Rio Hondo to Bottomless Lakes	9.1	9.0	6.1	5.5	6.8	2.6	5.4	8.3	5.0	5.8	3.5	.6	7.5	7.3	([h])	([h])	1.8	6.3
Bottomless Lakes to Dexter	4.0	5.6	3.3	4.0	3.1	0	2.6	.7	[i]6.0	4.5	1.0	1.8	0	3.0	([h])	3.0	5.0	6.8
Dexter to Rio Felix	[i]6.6	5.8	9.2	10.0	2.0	3.2	6.1	[i]8.2	[i]6.0	1.1	1.6	1.2	7.3	6.7	([h])	.7	([h])	6.5
Rio Felix to Lake Arthur	[i]2.2	4.4	11.0	6.8	0	1.1	[k].7	[i] [k]2.5	[k]7.8	7.6	([l])	([l])	5.4	[k]6.3	([h])	16.3	13.0	([l])
Lake Arthur to Artesia	12.8	11.7	3.5	11.2	3.2	1.1	[k]2.9	2.3	[k]2.4	10.0	([l])	([l])	3.5	[k]2.9	([h])	6.6	([l])	([l])
Subtotal	73.7	75.1	69.4	75.8	30.2	19.5	42.7	49.6	48.3	50.8	-------	-------	53.0	56.2	----------	----------	([l])	([l])
Total gain of flow	87.5	88.8	88.8	92.3	32.0	23.2	68.9	73.9	52.0	55.3	-------	-------	71.1	70.7	----------	----------	-------	-------

See footnotes at end of table.

TABLE 15.—*Gain and loss of flow, in cubic feet per second, in the Acme-Artesia reach of the Pecos River as determined by seepage investigations, Chaves and Eddy Counties, N. Mex., 1956–59*—Continued

[Subreaches are divided by the following sites on the Pecos River: at gaging station near Acme, just below Rio Hondo, near Bottomless Lakes, at bridge near Dexter, 0.8 mile above Rio Felix, at gaging station near Lake Arthur, and at gaging station near Artesia. Discharge measurements of some drains and pump diversions were provided by the State Engineer's office]

Area of measurement	1956						1957						1958				1959	
	Jan. 4	Jan. 5	Feb. 26	Feb. 27	June 3	Oct. 17	Jan. 2	Jan. 3	Mar. 4	Mar. 5	June 19	June 20	Jan. 23	Jan. 24	Nov. 5	Nov. 6	Jan. 8	Mar. 6
	Loss of flow from the Acme-Artesia reach of the Pecos River																	
Effective pump diversion in subreach: [m]																		
Acme to Rio Hondo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rio Hondo to Bottomless Lakes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bottomless Lakes to Dexter	0	0	0	0	0	2.4	0	0	1.80	1.80	0	0	0	0	0	0	0	0
Dexter to Rio Felix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rio Felix to Lake Arthur	0	0	0	0	3.2	10.9	0	0	7.50	9.30	([l])	([l])	0	0	0	0	([l])	([l])
Lake Arthur to Artesia	0	1.5	0	0	0	0	0	0	0	0	([l])	([l])	0	0	0	0	([l])	([l])
Seepage and evaporation in subreach: [n]																		
Acme to Rio Hondo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	([h])	0
Rio Hondo to Bottomless Lakes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	([h])	([h])	0	0
Bottomless Lakes to Dexter	0	0	0	0	0	.8	0	0	([i])	0	0	0	2.7	0	([h])	0	0	0
Dexter to Rio Felix	([j])	0	0	0	0	0	0	([j])	([i])	0	0	0	0	0	([h])	0	([h])	0
Rio Felix to Lake Arthur	([j])	0	0	0	4.6	0	([k])	([j k])	([k])	0	([l])	([l])	0	([k])	([h])	0	0	([l])
Lake Arthur to Artesia	0	0	0	0	0	0	([k])	0	([k])	0	([l])	([l])	0	([k])	([h])	0	([l])	([l])
Pecos River at gaging station near Artesia	87.5	87.3	88.6	92.2	24.2	8.86	68.9	73.9	42.7	44.1	8.15	4.44	68.4	70.5	166	160	91.3	96.0
Total loss of flow	87.5	88.8	88.6	92.2	32.0	23.0	68.9	73.9	52.0	55.2	------	------	71.1	70.5	------	------	------	------

[a] Roswell sewage effluent not gaged separately from other flow of Bitter Creek.
[b] Roswell sewage effluent.
[c] Contains spill from Hagerman Canal.
[d] Flow from an artesian well.
[e] Contains some Roswell sewage effluent.
[f] Estimated 2.7 cfs unmeasured flow from East Grand Plains drains.
[g] Not measured directly, but computed as the quantity of measured discharge in excess of measured inflow.
[h] Fluctuating river stage—no computation.
[i] Flow in Pecos River at bridge near Dexter was estimated.
[j] Flow in Pecos River 0.8 mile above Rio Felix was estimated.
[k] Based on an estimated adjustment of the measured flow at gaging station near Lake Arthur.
[l] Uncertain of diversion effects on river flow.
[m] Diversion that affected the river flow at the downstream end of the subreach.
[n] Not measured directly, but computed as the quantity of measured inflow in excess of measured discharge from subreach.

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