Geology and Hydrology Between Lake McMillan and Carlsbad Springs Eddy County, New Mexico

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1828

Prepared in cooperation with the Pecos River Commission

Geology and Hydrology Between Lake McMillan and Carlsbad Springs Eddy County, New Mexico

By E R COX

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1828

Prepared in cooperation with the Pecos River Commission

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON 1967

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

Library of Congress Catalog-Card No GS 66-319

For sale by the Superintendent of Documents, U S Government Printing Office
Washington, D C 20402

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLE

GEOLOGY AND HYDROLOGY BETWEEN LAKE McMILLAN AND CARLSBAD SPRINGS, EDDY COUNTY, NEW MEXICO

By E. R. Cox

ABSTRACT

The hydrology of the Pecos River valley between Lake McMillan and Carlsbad Springs, Eddy County, N Mex , is influenced by facies changes in rocks of Permian age Water stored for irrigation leaks from Lake McMillan into evaporite rocks, principally gypsum, of the Seven Rivers Formation and from Lake Avalon into carbonate rocks of the Tansill Formation This leakage returns to the Pecos River at Major Johnson Springs and Carlsbad Springs The river has perennial flow between Major Johnson Springs and Lake Avalon, but it loses water into evaporite rocks of the Yates Formation in this reach

Ground-water movement is generally toward the Pecos River in aquifers in the Pecos River valley except in the Rustler Formation east of the river where it moves southeastward toward playas east of Lake Avalon

The chloride content of ground and surface waters indicates that surface water moves from some reaches of the Pecos River and from surface-storage reservoirs to aquifers and also indicates the degree of mixing of ground and surface waters

About 45,000 acre-feet of ground water is stored in highly permeable rocks in a 3-mile wide part of the Seven Rivers Formation between Lake McMillan and Major Johnson Springs This water in storage comes from leakage from Lake McMillan and from alluvium north of the springs The flow of Major Johnson Springs is derived from this aquifer That part of the flow derived from the alluvium north of the springs averaged 13 cfs (cubic feet per second) from 1953 through 1959 , about 8 cfs of this flow had not been previously measured at gaging stations on the Pecos River and its tributaries

The most favorable plans for increasing terminal storage of the Carlsbad Irrigation District are to construct a dam at the Brantley site (at the downstream end of Major Johnson Springs), or to use underground storage in the permeable Seven Rivers Formation between Lake McMillan and Major Johnson Springs in conjunction with surface storage To avoid excessive leakage from a reservoir at the Brantley site, the dam should be downstream from all springs in the Major Johnson Springs area but upstream from a point where the river begins losing water to the Yates Formation

INTRODUCTION

Since the contruction of McMillan Dam in 1893, water has seeped from Lake McMillan into gypsiferous rocks that crop out along the east shore of the lake. This leakage returns to the Pecos River at

Major Johnson Springs, about 3 5 miles downstream from McMillan Dam. Lake Avalon, a reservoir about 15 miles downstream from McMillan Dam, also loses water from storage, particularly at high levels, through dolomite along the south shore of the lake. This leakage returns to the Pecos River as part of the flow of Carlsbad Springs, about 4 miles downstream from Avalon Dam.

Water is diverted from Lake Avalon to farms in the Carlsbad Irrigation District from about 3 to 20 miles downstream from Avalon Dam. Problems that have faced the water users in the area for many years are the loss of reservoir water by leakage and by evaporation, the use of water by nonbeneficial vegetation, and the loss of storage capacity by sediment deposited in the reservoirs.

Studies made by the Pecos River Commission have assumed that reservoir, river, and canal leakage in the reach between Lake McMillan and Carlsbad eventually returns to the Pecos River system. In the preparation of routing studies and in determining flood inflow and other determinations that the Pecos River Commission may make, it is necessary to account for the flow of water in the Pecos River system.

PURPOSE AND SCOPE OF THE INVESTIGATION

The main purpose of this study was to learn if all water leaking from Lake McMillan returns to the Pecos River at Major Johnson Springs, to determine the amount of water discharging at Major Johnson Springs that has not previously been measured at a gaging station of the river, and to delineate the principal aquifers and their water-bearing characteristics To accomplish this, a study was made of the geology and hydrology in the area between Lake McMillan and Carlsbad Springs to determine (1) the relationships between ground-water levels and surface-water flow and (2) the effects of changes in stages of Lake McMillan and Lake Avalon on ground-water levels, spring discharge, and the flow of the Pecos River. In addition, data compiled during this investigation might be applicable to the evaluation of the present storage facilities in this part of the Pecos River valley. Part of this report is devoted to discussions of the present storage facilities, the possibilities for additional reservoir sites, and the utilization of underground storage

The U S. Geologcal Survey entered into a cooperative agreement with the Pecos River Commission in 1952 to investigate the geologic and hydrologic conditions in the Pecos River valley between Lake McMillan and Carlsbad Springs. Some phases of the investigation were begun in October 1952, and the study has continued intermittently since that time Most of the fieldwork was done in 1955 Test wells were drilled in the area between Lake McMillan and Major

Johnson Springs in October and November 1956, and in March and April 1957 with equipment owned by the New Mexico State Engineer Office.

LOCATION AND EXTENT OF THE AREA

The area investigated lies in the Pecos River valley from the north end of Lake McMillan to Clarlsbad in central Eddy County, N Mex (fig. 1) It includes about 300 square miles.

TOPOGRAPHY AND DRAINAGE

Two lines of foothills extend from the Guadalupe Mountains through the area investigated. The one extending north and northeast from the main part of the mountains includes the Azotea Mesa, the Seven Rivers Hills, and the McMillan Escarpment; the other extending northeast from Carlsbad Caverns includes the Cueva Escarpment, the Ocotillo Hills, the Avalon Hills, and the Alacran Hills The Seven Rivers embayment is a gently sloping plain betwen the main part of the Guadalupe Mountains and the Azotea Mesa and Seven Rivers Hills. Fade-Away Ridge is a low divide trending northeast from near Lake Avalon. Figure 1 shows the main topographic and drainage features in part of the Pecos River valley in southeastern New Mexico.

North of the Seven Rivers Hills, the Pecos River is in a broad alluvial valley about 10 miles wide Between the Seven Rivers Hills and Carlsbad, the floor of the valley is generally less than a mile wide. The valley widens to as much as 20 miles south of Carlsbad. Several terraces extend from the flood plain of the Pecos River to the slopes of the Guadalupe Mountains on the west and to the Mescalero Ridge on the east The area between the flood plain and the higher terraces is of low relief and has a modified karst topography.

The Pecos River flows generally south-southeast through Eddy County The drainage tributary to the Pecos River in this area extends more than 80 miles from the crest of the Guadalupe Mountains on the west to the Mescalero Ridge on the east (fig 1)

All the tributaries to the Pecos River in the area of this investigation have intermittent flow. Sand dunes and shallow depressions trap most of the runoff east of the Pecos River. Dagger Draw drains a small area east of the river between Lake McMillan and Lake Avalon. North, middle, and south Seven Rivers and Rocky Arroyo drain the area west of the river. Runoff from storms enters the Pecos River between Lake McMillan and Lake Avalon from these tributaries

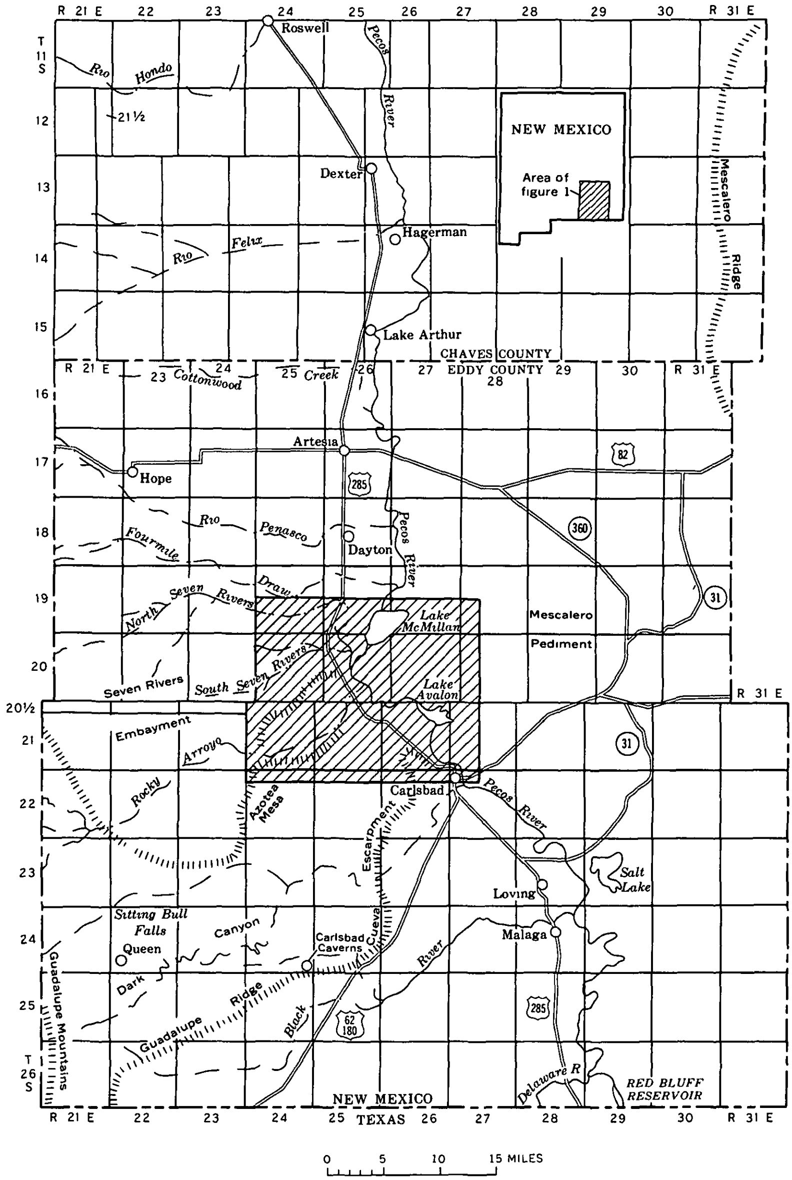

FIGURE 1.—Map of part of southeastern New Mexico showing area of investigation, topographic features, and drainage

PREVIOUS INVESTIGATIONS

The geologic and hydrologic conditions in the Pecos River valley from Lake McMillan to Carlsbad have been studied by many geologists and engineers since McMillan and Avalon Dams were constructed in the 1890's by private interests Flood damage to the dams, loss of storage by the deposition of suspended sediment in the reservoirs, loss of water from storage by leakage, and the apparent need for additional storage prompted most of the investigations

The U.S. Bureau of Reclamation (formerly the U.S. Reclamation Service) assumed control of the Carlsbad Irrigation Project, which included McMillan and Avalon Dams, in 1906 Many investigations of the area followed this acquisition. Most of the investigations were reconnaissance studies, and the findings were not published They are listed in a report by the U.S. Bureau of Reclamation (1957) Some of the reports that have been published are listed at the end of this report.

One of the early studies was made in 1905 by Willis T. Lee, of the U.S. Geologic Survey. This investigation was requested by B M. Hall, Supervising Engineer of the Reclamation Service to determine whether a reservoir would be sufficiently watertight to justify construction of a dam at the No 3 site between Lake McMillan and Lake Avalon (See pl. 1) Lee concluded that the No. 3 site was not suitable for a dam because of the unfavorable geologic setting Also, Lee suggested that not all the leakage from Lake McMillan returned to the Pecos River at Major Johnson Springs G. B. Richardson prepared notes on the proposed No 3 reservoir site after a 2-day inspection of the area in 1911 He suggested that this was an unusually good site, in view of the poor conditions for damsites in the Pecos River valley N H Darton visited the No. 3 site in 1922 and reported on the geology of the area Darton suggested that the construction of a reservoir at this site would be relatively safe and that geologic conditions are similar to conditions at Lake Avalon. Lee revisited the area in 1923 and again reported unfavorably on the construction of a dam at the No. 3 site. Richardson and Darton concurred with the conclusions of Lee's second report

Meinzer, Renick, and Bryan (1926) later investigated the No 3 site. They described the geology of the area and suggested that leakage would be too great to warrant construction of a dam at the site.

Kirk Bryan reported on the geology of the Lake Avalon area in 1927 to determine the feasibility of increasing storage by raising Avalon Dam He concluded that serious leakage would result if the level of Lake Avalon were raised above an altitude of 3,192 feet. F. L. Ransome examined the geology of the Lake Avalon area in 1928 and concluded that the level of Lake Avalon could be raised to an altitude of 3,200 feet without serious leakage. Bryan reexamined the Lake Avalon area in 1929 and concluded that serious leakage and possible collapse would result if the level of Lake Avalon were raised above an altitude of 3,192 feet.

Fiedler and Nye (1933) wrote a comprehensive report on the geology and hydrology of the artesian area north of the Seven Rivers Hills. In that report, Fiedler (p. 252) suggested that the base flow of Major Johnson Springs is derived from leakage from the artesian aquifer north of the springs. (The base flow of Major Johnson Springs is that part of the spring flow that is not derived from leakage from Lake McMillan.) Morgan (1938) described the geology and shallow ground-water resources of the artesian area. Theis (1938) studied the origin of water in Major Johnson Springs and concluded that apparently all water lost by leakage from the Pecos River above Seven Rivers returns to the river at Major Johnson Springs. Also, he suggested that the base flow of Major Johnson Springs is directly derived from the alluvium and only indirectly derived from leakage from the artesian aquifer north of the springs.

Theis, Morgan, Hale, and Loeltz (1942, p. 51–62) described the hydrology of the area between Lake McMillan and Carlsbad. Bjorklund and Motts (1959) studied the geology and hydrology of the Carlsbad area.

The U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers have studied possible ways of increasing storage for the Carlsbad Irrigation District and of providing flood-control facilities on the Pecos River. Logs of core holes drilled in the vicinity of the No. 3 reservoir site were used in this report for geologic interpretation and preparation of illustrations.

WELL-NUMBERING SYSTEM

The system of numbering wells in this report is that generally used by the Geological Survey and the State Engineer throughout New Mexico. This system is based on the common subdivisions in sectionized land. The well number, in addition to designating the well, locates its position to the nearest 10-acre tract in the land net. The number is divided into four segments by periods. In this report the first segment denotes the township south of the New Mexico base line; the second, the range east of the New Mexico principal meridian; and the third, the section.

The fourth segment of the number, which consists of three digits, locates the well in a particular 10-acre tract. For this purpose, the section is divided into four quarters—numbered 1, 2, 3, and 4—in the following order: northwest, northeast, southwest, and southeast. The first digit of the fourth segment gives the quarter section, 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 Finally, the 40-acre tract is divided into four 10-acre tracts, and the third digit denotes the 10-acre tract. Thus, well 20.26.17 334 in Eddy County is in the SE¼SW¼SW¼ sec. 17, T. 20 S., R. 26 E. The letter "a" is added to the last segment to designate the second well in the same 10-acre tract

Figure 2 shows the system of numbering sections in a township and of numbering the tracts in a section

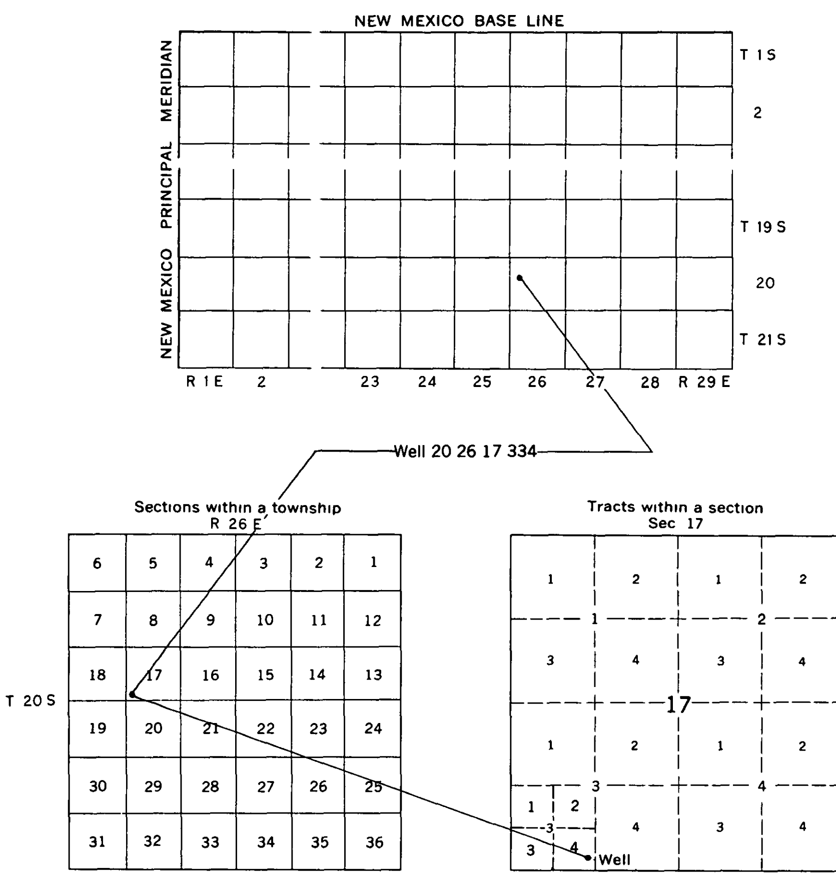

FIGURE 2—System of numbering wells

ACKNOWLEDGMENTS

Acknowledgment is given farmers and ranchers in the area for their cooperation by supplying information and allowing access to their property. Also, acknowledgment is given the Bureau of Reclamation and the Carlsbad Irrigation District for allowing test drilling on lands controlled by their organizations

GEOLOGY

The rocks pertinent to this investigation are sedimentary rocks of Permian and Quaternary age. The rocks of Permian age were deposited in three environments basin or forereef, reef, and shelf or back reef. The forereef rocks are dark-colored limestone, quartzose and calcareous sandstone, red silt and clay, and evaporites The reefs are gray to white massive fossiliferous limestone The back-reef rocks are light-colored thin-bedded limestone and dolomite, calcareous sandstone and siltstone, red silt and clay, and evaporites

Reef building began in the Permian sea during middle Guadalupe time and resulted in two types of reefs: small patch reefs generally no more than a few hundred feet across and barrier reefs extending for hundreds of miles. An advancing sea deposited marine sediments in both the basin and on the shelf before the Goat Seep reef began to build up along the margin of the basin (King, 1948, p. 50). The reef growth was apparently controlled by the rate of regional subsidence The Goat Seep reef grew principally upward, evidence indicating that the rate of reef growth was about equal to subsidence (Newell and others, 1953, p. 105–106).

At the time of the Goat Seep reef growth, quartz sandstone and limestone of the Delaware Mountain Group were deposited in the Delaware basin, and limestone and calcareous sandstone were deposited on the shelf in the shallow water of the lagoon near the reef The material deposited in the lagoon near the reef was, for the most part, probably derived from weathering of the reef Farther from the reef, evaporite rocks and red silt and clay were deposited in the shallow water of the lagoon

Reef building was greatest during late Guadalupe time. Thick beds of sandstone alternating with thin beds of limestone of the upper part of the Delaware Mountain Group were deposited in the basin at the time the Capitan reef was forming over the Goat Seep reef. Growth of the Capitan reef was rapid compared with subsidence, and the entire reef grew basinward several miles as it grew upward about 1,300 feet (Newell and others, 1953, p 204)

Carbonate rocks were deposited in the shallow lagoon in a band 5 to 10 miles wide parallel and adjacent to the reef, and evaporite rocks and red silt and clay were deposited in the remainder of the lagoon. This change from carbonate rocks to evaporite rocks is abrupt along a line parallel to the reef front During the basinward growth of the reef, the facies change in the younger rocks was progressively nearer to the latest reef escarpment, and some of the back-reef rocks overlie part of the Capitan reef.

Overlying the Guadalupe Series is a thick mass of rocks, mainly evaporites, which constitute the Ochoa Series. Rocks of the Ochoa Series, deposited in the Delaware basin, are as much as 4,000 feet thick (King, 1948, p. 95) They spilled over the basin in middle Ochoa time and overlie both reef and back-reef rocks The area was tilted, then erosion removed much of the Ochoa Series west of the present Pecos River before the Rustler Formation was deposited in late Ochoa time

Rocks that crop out in the Pecos River valley between Lake McMillan and Carlsbad Springs are in ascending order the Queen Formation, back-reef equivalent to the upper part of the Goat Seep reef; the Seven Rivers, Yates, and Tansill Formations, back-reef equivalents to the Capitan reef; the Rustler Formation; and alluvium. The surface distribution of rocks in the area of this report is shown in plate 2

Thin alluvium and residual material cover much of the Pecos River valley and, for the most part, are above the water table in the area between Lake McMillan and Carlsbad Springs. Plate 3 is a subcrop map and idealized section *A–A′* of the Permian formations except where the alluvium is thick

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING CHARACTERISTICS

SAN ANDRES LIMESTONE

The oldest formation having significance to the problems treated in this investigation is the San Andres Limestone of Permian age It is underlain by a considerable thickness of older Paleozoic sedimentary rocks and overlain by the Grayburg Formation

The San Andres Limestone is reported to be 1,565 and 1,597 feet thick in two oil-test wells in T. 19 S, R 25 E., about 6 miles west of Lake McMillan From about Lake McMillan to Roswell, the San Andres consists primarily of limestone with minor amounts of dolomitic limestone, dolomite, sandstone, and shale. From Roswell northward, the San Andres contains much gypsum, anhydrite, halite, and red silt and clay.

The carbonate rocks of the San Andres Limestone range from light tan to black, but are generally dark gray. They are very fine to coarse-grained, and the thickness of bedding ranges from a fraction of an inch to about 5 feet. The very fine grained rocks, generally dolomitic limestone or dolomite, are dense and contain few open spaces. These rocks are generally light gray to light tan, although some are dark gray to black. The coarse-grained rocks, generally limestone or slightly dolomitic limestone, are thickly bedded They are characteristically dark gray, although some are light gray and others black and petroliferous Most of the limestone contains solution cavities and other openings; some is cavernous Many of the limestone beds are fossiliferous, but the dolomitic beds are not (Fieldler and Nye, 1933, p 63–64)

The San Andres Limestone and younger carbonate rocks contain the principal aquifer in the Pecos River Valley from Roswell to Lake McMillan Some of the precipitation and runoff in the uplands west of the valley floor, where the carbonate rocks crop out, percolate downward and move laterally through the limestone toward the Pecos River through joints, fractures, and bedding planes Water containing dilute carbonic acid has enlarged the openings by solution, forming a series of interconnected openings and channels and, in places, caverns Ground water is under artesian pressure in the San Andres Limestone and younger carbonate rocks in part of the Pecos River valley. The natural discharge of this artesian system was large springs in the Roswell area, and smaller springs along the Pecos River and the lower reaches of north, middle, and south Seven Rivers These springs discharged water directly or indirectly into the Pecos River resulting in a gain in the flow of the river downstream from Roswell However, since extensive development of the artesian water for irrigation through wells, the artesian head has declined markedly and has brought about a large decrease in the flow of the springs. Some of the springs have stopped flowing, notably in the forks of Seven Rivers and in the Roswell areas.

Fiedler and Nye (1933, p. 148) divided the artesian area into five segments in which the artesian water is most extensively developed: the Roswell, Dexter, Cottonwood, Artesia, and Seven Rivers segments These segments are separated by areas where the limestone is less permeable and not extensively developed for irrigation water This report is primarily concerned with the Seven Rivers segment

The Seven Rivers segment of the artesian area is mainly recharged in the outcrop area of the carbonate rocks west of the Seven Rivers embayment The area of greatest recharge probably is from 25 to 45 miles west of Major Johnson Springs between Four Mile Draw and south Seven Rivers (Theis and others, 1942, fig. 5) Some recharge, however, may come from the northern part of the artesian area, because the piezometric surface in that area slopes eastward and southeastward toward the Pecos River.

ARTESIA GROUP

Clastic and evaporite rocks of the Artesia Group form the top confining bed for the artesian aquifer in the San Andres Limestone near Roswell and in younger carbonate rocks from about Lake Arthur to Major Johnson Springs In this report the formational names Grayburg, Queen, Seven Rivers, Yates, and Tansill of the Artesia Group will be used

GRAYBURG FORMATION

The Grayburg Formation consists primarily of dolomite with minor amounts of dolomitic limestone and thin beds of fine-grained sandstone in the carbonate facies and gypsum, sandstone, and red silt and clay in the evaporite facies Most of the sandstone beds in the carbonate facies persist virtually unchanged through the evaporite facies, whereas the dolomite, for the most part, grades into evaporite rocks, silt, and clay in the evaporite facies

The carbonate-evaporite facies change in the Grayburg Formation is about 50 miles north of the latest Capitan reef front This facies change in the artesian area takes place in the vicinity of Lake Arthur Solution openings have formed from near Lake Arthur to Dayton in the predominantly carbonate rocks of the Grayburg Artesian wells have been finished in the Grayburg and the lower part of the Queen Formation.

QUEEN FORMATION

The basal 100 feet of the Queen Formation is predominantly sandstone, and the upper 100 feet, the Shattuck Member of Newell and others (1953), contains 50 feet of sandstone at the top, which is called the Artesia red sand in the subsurface. The remaining part of the Queen contains alterating beds of sandstone, limestone, and dolomite

The upper part of the Queen Formation is gypsiferous in the subsurface near Major Johnson Springs Gypsum was logged in the upper 178 feet of the Queen in an oil-test well in sec 11, T 20 S , R. 26 E., and cores of the Artesia red sand contained stringers of selenite and alabaster in a hole drilled by the Bureau of Reclamation in sec. 28, T 20 S , R 26 E.

The predominance of sandstone in the Queen Formation probably represents greater agitation during deposition in the lagoon than during the deposition of the underlying Grayburg and the overlying Seven Rivers Formations The frosted quartz grains, especially in the Artesia red sand, and their similarity to the grains of sand in the upper part of the Delaware Mountain Group indicate a more frequent exchange of water between the lagoon and the basin However, most of the sand and silt-size grains are calcareous, and are probably detritus from the Capitan reef. The siliceous and calcareous grains are cemented with calcium carbonate

Rocks of the Queen Formation crop out at the base of hills on both sides of Rocky Arroyo and in the Seven Rivers embayment in the area of this study (See pl 2)

Solution of the rocks has taken place in the Queen Formation near the Pecos River from near Artesia to the Seven Rivers Hills Most of the wells in the Seven Rivers segment of the artesian area derive water from the Queen Formation The solution has taken place mostly along joints in limestone and dolomite

Sandstone of the Queen Formation is less permeable than the limestone and dolomite This is evident by springs and seeps issuing along the top of sandstone beds in the Guadalupe Mountains

In addition to the artesian wells in the southern part of the artesian area, the Queen Formation yields water to stock wells in the Seven Rivers embayment and in the Guadalupe Mountains

SEVEN RIVERS FORMATION

The Seven Rivers Formation and the overlying Yates and Tansill Formations constitute the shelf or back-reef equivalents of the Capitan Limestone The Seven Rivers Formation consists of about 300 feet of dolomite with a few sandy beds in the carbonate facies and anhydrite, gypsum, and red silt and clay in the evaporite facies between the uppermost sandstone of the Queen Formation and the basal sandstone of the Yates Formation. The upper 30 to 50 feet of dolomite that extends from the carbonate facies through most of the evaporite facies and caps the Seven Rivers Hills and the McMillan Escarpment was named the Azotea Tongue by Lang (1937)

The beds of carbonate rocks of the Seven Rivers Formation generally range from 6 inches to 4 feet in thickness In the Rocky Arroyo area, the joint pattern gives outcrops of the Seven Rivers a blocky appearance However, dolomite of the Azotea Tongue along the top of the McMillan Escarpment is thinly bedded (from 1 to 3 in. in thickness) and it can be quarried into blocks from 1 to 2 feet across

The dolomite is generally light gray to grayish brown, but some thin beds are pink The darker rocks are generally coarser grained than the lighter rocks. The dolomite is detrital and probably consists of particles eroded from the Capitan reef which have been cemented and dolomitized.

The Seven Rivers Formation in the Rocky Arroyo area contains secondary concretions of dark-brown iron oxide East and southeast of Lake McMillan, dolomite of the Seven Rivers contains asphaltlike inclusions in solution openings and is petroliferous in places

The evaporite facies of the Seven Rivers Formation is primarily red and reddish-brown clay and silt with gypsum and a few thin stringers of dolomite. The gypsum was originally deposited as anhydrite, and most of it has been altered to gypsum by circulating ground water. Anhydrite was penetrated near the base of the Seven Rivers in a core hole drilled in sec. 28, T. 20 S., R. 26 E., by the Bureau of Reclamation The gypsum is white and red with a few bright green stringers The dolomite that persists through the evaporite facies is thinly bedded (generally less than 6 in. and commonly less than 1 in thick). It is very fine grained and light gray, white, or pink.

The Seven Rivers Formation crops out along a belt from the Azotea Mesa through the Seven Rivers Hills and Seven Rivers embayment to the northeast shore of Lake McMillan. (See pl. 2.) The carbonate-evaporite facies change occurs about 12 miles from the latest reef front (See pl. 3.)

A system of interconnected solution channels in the evaporite facies of the Seven Rivers Formation from Lake McMillan to Major Johnson Springs occurs under an area about 5 miles long and 3 miles wide Although solution openings have formed a short distance into the dolomite, they are confined almost entirely northwest of the carbonate-evaporite facies change These solution openings may extend to the top of the underlying Queen Formation where less permeable sandstone prevents further downward circulation of water. Also, the less soluble dolomite in the carbonate facies has retarded formation of solution features to any great degree in the Seven Rivers Formation east and southeast of the facies change. The solution channels have formed mostly in a zone extending about a mile on each side of a line from the southeast tip of Lake McMillan to Major Johnson Springs.

The system of solution channels in the Seven Rivers Formation between Lake McMillan and Major Johnson Springs probably began to form as gypsum in the Seven Rivers was removed by solution. Removal of the gypsum permitted many of the rocks to collapse, and alluvium filled the resulting basin north of the springs. The removal of gypsum and other rocks was not complete, however, in the area between Lake McMillan and Major Johnson Springs because stringers of dolomite extended a short distance into the evaporite facies and restricted the circulation of ground water. Solution channels in the Seven Rivers are connected hydraulically with the alluvium north of Major Johnson Springs, and ground water from the alluvium probably circulated through solution channels in the Seven Rivers to Major Johnson Springs before the construction of McMillan Dam. This circulation of ground water enlarged the solution openings, and

231-544 O—66——2

leakage from Lake McMillan circulating through this system may have further enlarged them.

Sinkholes are exposed along the eastern shore of Lake McMillan. Test holes drilled within a quarter of a mile of the shore of the lake did not penetrate solution openings in gypsum. Therefore, the solution openings are probably confined to a narrow band along the base of the McMillan Escarpment. These solution openings probably extend under Lake McMillan, but no test holes have been drilled on the lake floor. The area of greatest sinkhole formation is within a mile of the southeast corner of Lake McMillan.

Solution channels may extend half a mile east and half a mile southeast of the southeast tip of Lake McMillan. Test holes drilled a mile east and a mile southeast of this sinkhole area did not penetrate solution channels in gypsum, but a test hole about three-quarters of a mile south of the southeast tip of Lake McMillan penetrated solution channels in gypsum and dolomite.

The storage capacity of Lake McMillan has decreased steadily since its construction in 1893 owing to the deposition of suspended sediment especially during floods. The deposition of suspended sediment in the reservoir was rapid for about the first 20 years, and by the early 1940's less than half of the original storage capacity remained. Since the 1940's, the storage capacity of Lake McMillan has changed little. Much of the suspended sediment carried by the Pecos River during floods is deposited in the bottom lands upstream from Lake McMillan where the flood plain is heavily covered with saltcedar. The suspended sediment carried by normal flows and some carried by flood flows, however, reaches the lake. The reason the storage capacity of the lake has not decreased substantially since the 1940's could be that silt and clay have been carried into solution channels in the underground reservoir. If such is true, the size of the underground reservoir could have been reduced since the construction of McMillan Dam.

Whether the size of the underground reservoir in the Seven Rivers Formation has been increased by leakage circulating through the system or decreased by silt and clay being deposited in the system since the construction of McMillan Dam is not known. Both processes have probably been active.

The evaporite facies of the Seven Rivers Formation yields water to stock wells north of Seven Rivers Hills and near Major Johnson Springs. Two irrigation wells in sec. 17, T. 20 S., R. 26 E., near Major Johnson Springs, reportedly yield 1,400 gpm (gallons per minute) of water each without noticeable drawdown from a permeable aquifer in the Seven Rivers. Stock wells near Rocky Arroyo may yield water from solution channels in carbonate rocks of the Seven Rivers.

YATES FORMATION

The Yates Formation consists of about 300 feet of alterating beds of sandstone and dolomite in the carbonate facies and about the same thickness of gypsum, red clay and silt, and sandstone in the evaporite facies Sandstone beds at the top and bottom of the Yates distinguish it from the underlying Seven Rivers and the overlying Tansill Formations These sandstones have been used as marker beds in the subsurface.

The Yates Formation in the carbonate facies is characterized by alternating beds of fine-grained sandstone and dolomite. The sandstone beds are generally composed of calcareous fragments that are cemented by calcium carbonate, but they do contain a few well-rounded quartz grains The sandstone is buff to orange in the carbonate facies As in the Queen Formation, the abundance of calcareous clastic material in the Yates may indicate periods of greater agitation in the lagoon because the calcarenite is probably derived from weathering of the reef Similarly, the quartz grains were probably derived from the Delaware basin during times of water connections between the lagoon and the open sea. The dolomite in the Yates is generally more thinly bedded than the dolomite in the underlying Seven Rivers Formation Otherwise, the characteristics of the dolomites in the two formations are similar.

In the evaporite facies, the Yates Formation is primarily gypsum, red clay and silt, and sandstone, with a few thin stringers of dolomite The sandstone is generally gray to brown; its color is the only criterion for distinguishing the Yates from other formations in the evaporite facies.

The Yates Formation crops out in the area of this investigation along a belt parallel to the reef escarpment extending from between Rocky Arroyo and Spencer Draw on the southwest to just east of Lake McMillan on the northeast (See pl 2) The Yates ranges in thickness from more than 300 feet near the reef to 0 along the southeast slope of Seven Rivers Hills and McMillan Escarpment The Yates is 310 feet thick at a measured section on the south side of Dark Canyon in the SE¼ sec 27, T 23 S., R. 25 E. (Bjorklund and Motts, 1959, table 6). The carbonate-evaporite facies change occurs about 7 miles from the latest Capitan reef front (See pl 3.)

The Yates Formation yields water to stock wells near the Pecos River between Lake McMillan and Lake Avalon Most of these stock wells are in the evaporite facies of the Yates near Rocky Arroyo west of the river and near Dagger Draw east of the river. Ground water is stored principally in solution openings in gypsum in this area and is recharged by runoff into sinkholes and by seepage from the Pecos River downstream from Major Johnson Springs The discharge area for water in the Yates is Carlsbad Springs

TANSILL FORMATION

The Tansill Formation consists primarily of thin-bedded light-gray to grayish-brown dolomite in the carbonate facies and of gypsum and red clay and silt in the evaporite facies. The Ocotillo Member of DeFord and Riggs (1941) is a 5- to 10-foot thick siltstone in the upper part of the Tansill The Ocotillo Member consists of gray to brown calcareous silt in the carbonate facies and of reddish-brown silt and clay in the evaporite facies

The Tansill Formation is about 100 feet thick in a roadcut on U S. Highway 285 just north of Carlsbad. However, DeFord and Riggs (1941) suggested that the Tansill is more than 300 feet thick near the reef The Tansill is 225 feet thick in a test well drilled by the city of Carlsbad in 1963 in the SW¼SW¼ sec 25, T. 21 S , R. 26 E., near Carlsbad Springs

The Tansill Formation crops out a short distance back reef from the reef escarpment and caps hills along the Cueva Escarpment, the Ocotillo Hills, and the Avalon Hills. (See pl. 2.) The carbonate facies grades into the evaporite facies about 4 miles from the latest reef front (See pl. 3) Evaporite rocks of the Tansill crop out northwest of the Ocotillo Hills west of the Pecos River, and north of Lake Avalon and along Dagger Draw east of the river.

Solution openings have formed in dolomite of the Tansill Formation from the south shore of Lake Avalon to near Carlsbad Springs. These solution openings are interconnected, and water moves from Lake Avalon through these solution channels to form part of the discharge of Carlsbad Springs.

The Tansill Formation is probably above the zone of saturation except near the Capitan reef and in the area between Lake Avalon and Carlsbad Springs Perched water occurs in the Tansill in Dagger Draw

CAPITAN LIMESTONE

The Capitan Limestone consists of 1,500 to 2,000 feet of massive reef limestone and reef talus (Newell and others, 1953, p. 105). The reef is composed of light-gray to white massive crystalline limestone with abundant white calcite crystals The reef talus has a similar appearance, but it is thickly bedded. In places, younger parts of the reef grew on older reef talus. The reef grew basinward as well as upward, so that the reef appears wedge shaped in cross section.

The Capitan Limestone crops out along a narrow band from Guadalupe Peak in Texas, about 46 miles southwest of Carlsbad, to near

Carlsbad and forms the Cueva Escarpment. East of Carlsbad the Capitan is covered by younger rocks of the Ochoa Series.

Exposures of Capitan Limestone can be seen best on canyon walls southwest of Carlsbad in exposures that are seldom more than 2 to 3 miles wide Most of the material exposed is reef talus

Solution openings have formed to various degrees in the Capitan Limestone and its back-reef equivalents near the reef These solution openings are interconnected to form an integrated conduit system southwest of Carlsbad. The caverns at Carlsbad Caverns National Park were formed by solution and collapse in the Capitan and its back-reef equivalents Solution openings are extensively formed in the Capitan and its back-reef equivalents in the northern and western parts of Carlsbad and adjacent areas in La Huerta and Happy Valley. This aquifer in the Capitan and the Yates and Tansill Formations near Carlsbad is called the "limestone aquifer" in this report Many wells tap the limestone aquifer in this area, and the water is pumped for irrigation, public supply, industrial, and domestic uses

The limestone aquifer is recharged by precipitation in the Guadalupe Mountains and by seepage from Lake Avalon and the Pecos River between Major Johnson Springs and Lake Avalon The most noticeable recharge occurs after heavy precipitation in the Guadalupe Mountains when runoff flows in the numerous arroyos that are cut into the Capitan Limestone or its back-reef equivalents Runoff seeps into the rocks directly or through a thin mantle of alluvium in the bottoms of the arroyos

OCHOA SERIES

Overlying the Capitan Limestone and its equivalents are rocks of the Ochoa Series of Permian age The Ochoa Series is divided into the Castile, Salado, and Rustler Formations and the Dewey Lake Redbeds In eastern Eddy County, N Mex., the Ochoa Series is overlain by red beds of Triassic age

The Rustler Formation is the only geologic unit in the Ochoa Series that has any bearing on the hydrology of the Pecos River valley between Lake McMillan and Carlsbad Springs The Castile Formation is principally anhydrite and does not crop out in the area of this investigation The relatively impermeable anhydrite of the Castile prevents water in the Capitan Limestone from moving southeastward into the Delaware basin The Salado Formation is primarily halite and is in the subsurface east of Carlsbad overlying the Capitan and the back-reef rocks No water is known to occur in the Salado in this area The Dewey Lake Redbeds do not occur in the area of this investigation

RUSTLER FORMATION

The Rustler Formation consists of anhydrite, gypsum, red clay and silt, and two dolomite beds The upper dolomite was named the Magenta Dolomite Member; and the lower dolomite, the Culebra Dolomite Member (Adams, 1944). In the eastern Eddy County where the entire formation is in the subsurface, the Rustler is more than 400 feet thick. However, in the Alacran Hills near Lake Avalon only the lower 150 to 200 feet of the Rustler remains

The lower part of the Rustler Formation, including the Culebra Dolomite Member, extends from Carlsbad to near Fade-Away Ridge east of the Pecos River in the area of this investigation (See pl 2.) Solution of gypsum by ground water and collapse have resulted in ridges and valleys and discontinuous outcrops of Rustler Usually, the Culebra Dolomite Member is exposed on ridges and hills, whereas other beds of the Rustler are covered by a thin mantle of alluvium in valleys and depressions

The Culebra Dolomite Member is the principal water-bearing zone in the Rustler, and it locally contains large quantities of water in solution channels Because the water is poor in quality, however, it is not extensively used other than for watering livestock Few stock wells have been drilled into the Rustler in the area of this investigation because water can be obtained at shallow depths from perched-water zones near depressions

ALLUVIUM

Alluvium of Quaternary age covers much of the Pecos River valley between Lake McMillan and Carlsbad Springs Alluvium in the valley between Seven Rivers Hills and Carlsbad is relatively thin; but north of Seven Rivers Hills and south of Carlsbad, broad plains are underlain by alluvium as much as 250 feet thick

Nye (Fiedler and Nye, 1933, p 10–12) defined three terrace levels in the valley north of Seven Rivers Hills These terraces—Lakewood, Orchard Park, and Blackdom—are 20 to 30 feet, 20 to 35 feet, and 60 to 80 feet, respectively, above the Pecos River in the Roswell area In addition, Nye described higher surfaces called gravel-capped mesas, 150 to 200 feet above the river, and limestone uplands (Fiedler and Nye, 1933, p 13–15). Meinzer, Renick, and Bryan (1926, p 6) described terrace levels 15 to 30 feet, 75 feet, and 150 feet above the river between Lake McMillan and Lake Avalon

The oldest alluvium in the valley seems to be conglomerate exposed adjacent to the Pecos River and some of its tributaries The conglomerate has been divided into the quartzose and the limestone conglomerates by Meinzer, Renick, and Bryan (1926, p 8–10) The conglomerates are as much as 75 feet thick in the area between Lake

McMillan and Lake Avalon, but Hendrickson and Jones (1952, p 24) reported conglomerate more than 300 feet thick elsewhere in the Pecos River valley in Eddy County.

The quartzose conglomerate consists of pebbles of chert, quartzite, limestone, and igneous rocks with a siliceous sand matrix cemented with calcium carbonate The pebbles are subangular to well rounded and are as much as 3 inches in diameter, the siliceous pebbles being usually less than 1 inch in diameter. Generally, the siliceous pebbles are more abundant than the calcareous pebbles, and the siliceous pebbles are more rounded The quartzose conglomerate is well indurated, and the rock in some places fractures across the pebbles. Lenses of calcareous-cemented sandstone occur in the conglomerate. The lenses are as much as 3 feet thick and probably consist of beds of pure matrix and cement.

The overlying limestone conglomerate contains more limestone pebbles than the quartzose conglomerate, and it contains abundant subangular to subrounded limestone cobbles Generally, the limestone conglomerate contains siliceous pebbles, abundant limestone pebbles and cobbles, and calcareous matrix and is cemented by calcium carbonate Although well indurated, it is not as resistant to erosion as the underlying quartzose conglomerate.

The contact between the two conglomerates is gradational Limestone pebbles are abundant in the upper part of the quartzose conglomerate, and siliceous pebbles are abundant in the lower part of the limestone conglomerate This suggests that the conglomerates are conformable The difference in lithology of the pebbles indicates different sources. The source of the siliceous pebbles is probably near the headwaters of the Pecos River in northern New Mexico, whereas the source of the limestone pebbles is probably the limestone uplands west of the Pecos River.

Conglomerate crops out along the Pecos River from Lake McMillan to Lake Avalon and in the Carlsbad Springs area. (See pl. 2.) The limestone conglomerate forms steep bluffs on both sides of the river from Major Johnson Springs to near Lake Avalon The quartzose conglomerate is exposed near river level in places and forms isolated hills near the river Conglomerate has been penetrated by wells within about 2 miles of the river near the No. 3 damsite.

The conglomerate is above the zone of saturation in much of the area between Lake McMillan and Carlsbad However, perched water occurs in conglomerate about 2 miles northwest of the No 3 damsite. Water occurs in solution channels in conglomerate at the base of the alluvium in the Pecos River valley north of Major Johnson

Springs, south of Carlsbad, in the Black River valley southwest of Carlsbad, and possibly near Carlsbad Springs

Large depressions have formed in gypsum of the Rustler Formation east of Fade-Away Ridge and north of Alacran Hills by solution and collapse; they have been refilled by reworked gypsum, red clay and silt, and sand Some of these depressions contain playa lakes. Attempts have been made by local residents to drill irrigation wells in sand More than 200 feet of reworked gypsum, red clay and silt, and sand was reportedly penetrated in drilling a test well for irrigation water in sec. 21, T 20 S., R 28 E. This well reportedly yielded 100 gpm, but so much fine sand was pumped from the well that the land surface collapsed around the casing and the well was abandoned

Caliche caps many of the hills and ridges near the river and east of the river between Lake McMillan and Carlsbad The caliche is commonly less than 5 feet thick and forms a veneer on the underlying rock. Generally, the caliche contains fragments of older rock cemented with calcium carbonate. The caliche is well indurated at places, but elsewhere it is unconsolidated and easily eroded. Caliche in the river channel near Major Johnson Springs shows evidence of solution, and delicate boxwork structures are exposed

Isolated outcrops of travertine in the valleys along middle and south Seven Rivers and Rocky Arroyo are evidence of former springs. These outcrops of travertine are less than 10 feet thick, but travertine 20 to 30 feet thick occurs at Sitting Bull Falls in the Guadalupe Mountains. Early settlers in the area established a community along the lower reach of south Seven Rivers; they used the springs for irrigation and travertine for building stone These springs stopped flowing a short time after heavy pumping from wells began in the artesian area north of Major Johnson Springs Travertine was penetrated from 15 to 25 feet below land surface in well 20.26 21.111 near Major Johnson Springs This travertine is overlain by 5 feet of caliche and 5 feet of sand indicating the existence of springs near Major Johnson Springs before the formation of the caliche

Dune sand covers much of the Pecos River valley east of the river The dune sand is as much as 60 feet thick in Eddy County (Hendrickson and Jones, 1952, p 26) and was deposited by wind on the Mescalero pediment surface The sand is very fine grained, well sorted, and calcareous, and contains pebbles of caliche and pebbles from the quartzose conglomerate. The dune sand is generally above the zone of saturation. However, dune sand probably was the source of part of the sand mixed with reworked gypsum and clay in depressions and sinkholes below the water table. Part of the precipitation that falls on the dune sand probably reaches the zone of saturation in the underlying rocks, whereas part is used and transpired by plants growing on the dunes and part accumulates in depressions and evaporates.

HYDROLOGY

MOVEMENT OF GROUND WATER WITH RESPECT TO THE PECOS RIVER SYSTEM

Movement of ground water in the area is complex and is influenced greatly by differences in permeability due to the different facies of the rocks In this report, the area is divided into six zones having similar hydrologic and geologic characteristics The zones and water-level contours or direction of movement of water in the rocks of each zone are shown in plate 4

ZONE 1: ALLUVIUM AND THE SEVEN RIVERS FORMATION NORTH AND NORTHWEST OF MAJOR JOHNSON SPRINGS

The alluvium and the Seven Rivers Formation north and northwest of Seven Rivers Hills, Major Johnson Springs, Lake McMillan, and McMillan Escarpment constitute a single aquifer in which the water moves toward Major Johnson Springs (pl 4). This aquifer is recharged by leakage from the underlying artesian aquifer, precipitation in the area, percolation of irrigation water, and water lost from the Pecos River in Kaiser Channel upstream from Lake McMillan. Also, the aquifer is recharged intermittently by floodflows in tributaries to the Pecos River

Most of the water in the alluvium in zone 1 moves southward to Major Johnson Springs Small amounts of water move notheastward and eastward in the alluvium and the lower part of the Seven Rivers Formation in the Seven Rivers embayment to Major Johnson Springs, and some moves from the Pecos River upstream from Lake McMillan southwestward through the alluvium to the springs. Water from these sources makes up the base flow of the springs. Except for the seepage from the river in Kaiser Channel upstream from Lake McMillan, the water that discharges as base flow of Major Johnson Springs has not been in the river previously, and it may be considered as water new to the Pecos River

ZONE 2· THE EVAPORITE FACIES OF THE SEVEN RIVERS FORMATION BETWEEN LAKE McMILLAN AND MAJOR JOHNSON SPRINGS

Water leaks from Lake McMillan into the evaporite facies of the Seven Rivers Formation and moves under artesian pressure southwestward to Major Johnson Springs through interconnected solution channels (pl. 4). The solution openings are saturated to an altitude slightly above that of Major Johnson Springs. The fact that the hydraulic gradient of the piezometric surface in this aquifer is almost flat indicates that the water moves with relative ease through highly permeable rocks.

The coefficient of transmissibility of the aquifer can be estimated (The coefficient of transmissibility is the amount of water in gallons per day moving through a section of the aquifer 1 mile wide under a hydraulic gradient of 1 foot per mile.) In December 1957, the discharge from the aquifer was about 40 cfs, or about 26 million gallons per day Assuming this amount of water was moving across a line 2 5 miles long perpendicular to a line between wells 20.26.11.413 and 20.26 15.313 (pl. 4) at a measured hydraulic gradient of 0.2 foot per mile, the coefficient of transmissibility of the aquifer is about 50 million gallons per day per foot.

A dike was constructed along the southeastern shore of Lake McMillan in 1908 and 1909 to prevent water from reaching most of the sinkholes in the Seven Rivers Formation Also, suspended sediment deposited in Lake McMillan by the Pecos River has retarded leakage by covering sinkholes under the lake. In 1953 and 1954 the dike was extended along most of the eastern shore of Lake McMillan, and the lake was prevented from reaching many exposed sinkholes even during periods of high lake level. These factors have combined to reduce leakage from Lake McMillan since the construction of the dam.

Occasionally, breaks have occurred in the dikes, and lake water has inundated sinkholes. Also, whirlpools have formed in the lake, an indication that the sediment cover over the sinkholes in the lake floor has been disturbed. These conditions resulted in high rates of leakage, for short periods of time, until the dikes were repaired and the sediment cover on the lake floor was restored. The leakage is erratic at times, but for the most part, the leakage rate changes with the stage of Lake McMillan. (See fig. 3.)

All leakage from Lake McMillan apparently reappears in the Pecos River at Major Johnson Springs. The relatively impermeable carbonate rocks of the Seven Rivers Formation are a barrier to movement of water in that formation southward and southeastward from Major Johnson Springs. Although permeability data are generally lacking on the carbonate rocks, dolomite of the Seven Rivers is relatively impermeable at the site of an oil-test well in the SE¼ sec 26, T. 20 S., R. 26 E., and in test holes drilled for permeability data by the Bureau of Reclamation in the SE¼ sec 12, the NW¼ sec 23, and the SE¼ sec. 28, T. 20 S , R 26 E If all leakage from Lake McMillan does not reappear in the Pecos River at Major Johnson Springs, the amount not accounted for is too small to be measured

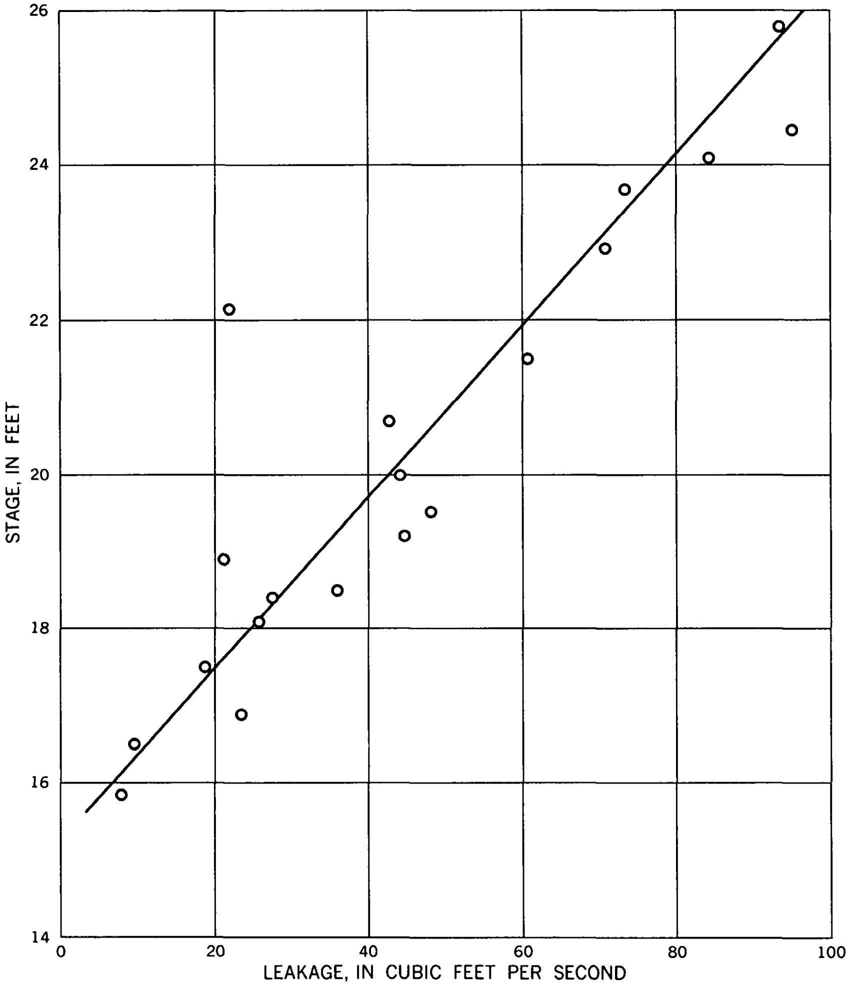

FIGURE 3 —Relationship between stage and leakage of Lake McMillan, based on 1954–59 data

Additional evidence that water does not move with ease from the evaporite facies through the carbonate facies of the Seven Rivers Formation is the fact that water levels in wells in the Yates Formation between Lake McMillan and Lake Avalon are almost 100 feet lower in altitude than water levels in wells in the Seven Rivers between Lake McMillan and Major Johnson Springs (See pl 4) If the Seven Rivers were uniformly permeable and hydraulically connected with the Yates near these wells, the water levels would be nearly the same

The volume of water in storage in the permeable aquifer in the Seven Rivers Formation between the southeast tip of Lake McMillan and

Major Johnson Springs can be estimated. If the aquifer is 4 miles long, 3 miles wide, and 150 feet thick, the volume of the aquifer is about 1 million acre-feet. The porosity of the aquifer (the ratio of the volume of openings to the total volume of the aquifer) cannot be determined with available data. Meinzer (1923, p. 10) lists porosity determinations for carbonate rocks (limestone, marble, and dolomite) and for gypsum. These porosity values range from 0.53 to 13.36 percent for 11 tests of carbonate rocks and from 1.32 to 3.96 percent for apparently 2 tests of gypsum. The average porosity for these 13 tests is 4.51 percent. Using these porosity values, the volume of water in storage in the aquifer is between 5,300 and 136,000 acre-feet and is probably about 45,000 acre-feet. Computations by Theis, Sayre, Morgan, Hale, and Loeltz (1942, p. 58) indicate that the storage capacity is about 50,000 acre-feet, the minimum storage capacity being about 20,000 acre-feet.

ZONE 3: WATER IN THE SEVEN RIVERS AND YATES FORMATIONS WEST OF THE PECOS RIVER

Ground water in the area west of the Pecos River moves eastward and northeastward down the dip of the strata toward the river (pl. 4). The water moves through solution channels in calcareous and gypsiferous rocks. The sandstones are relatively impermeable, and many perched-water zones occur above beds of standstones in the Yates, Queen, and Grayburg Formations.

Part of the ground water in zone 3 north of Rocky Arroyo might discharge into the Pecos River at Major Johnson Springs. Most of it, however, moves toward the Pecos River downstream from Major Johnson Springs, moves under the Pecos River, mixes with seepage from the river, and eventually discharges at Carlsbad Springs. Ground water in the deeper shelf aquifers in the Seven Rivers embayment probably moves into the artesian system north of Major Johnson Springs.

Ground water in zone 3 south of Rocky Arroyo discharges into the Pecos River at Carlsbad Springs. Most of the water in the shelf aquifers moves into the limestone aquifer west of the river and thence to Carlsbad Springs (based on interpretation of water-level contours in fig. 26 of Bjorklund and Motts, 1959). Some of the water, however, may move under the Pecos River between Major Johnson Springs and Lake Avalon and mix with leakage from the river and Lake Avalon, as indicated by the water-level contours in plate 4. This water also discharges at Carlsbad Springs.

ZONE 4: WATER IN THE YATES AND TANSILL FORMATIONS EAST OF THE PECOS RIVER

Ground water moves through solution channels in the Yates and Tansill Formations east of the Pecos River between Major Johnson Springs and Lake Avalon (pl. 4), and it eventually drains into Carlsbad Springs East of the river, water in the Tansill is perched above the main zone of saturation in the Yates Also, the river is perched above the water table and loses water to the underlying Yates and Tansill between Major Johnson Springs and Lake Avalon. Water seeping from the river joins the ground water moving northeastward under the river from zone 3, moves in an arc from the vicinity of the mouth of Rocky Arroyo, passes under Lake Avalon, and moves southward through the Tansill and Yates to Carlsbad Springs.

ZONE 5: WATER IN THE LIMESTONE AQUIFER AND ALLUVIUM NEAR CARLSBAD

Water moves through the limestone aquifer (the Captain and Goat Seep Limestones and their back-reef equivalents) to the Pecos River at Carlsbad Springs The most permeable part of this aquifer is about 10 miles wide near Carlsbad and about 2 miles wide along a belt parallel to the Guadalupe Mountain front (Bjorklund and Motts, 1959, p 140) Water in the limestone aquifer is under artesian pressure and moves with relative ease to the vicinity of Carlsbad Springs (pl. 4) where it has sufficient head to move through alluvium and discharge into the Pecos River.

Ground water in the alluvium in the northern part of Carlsbad and the area adjacent to the city north of the Pecos River discharges into the river at Carlsbad Springs This water is from canal leakage, irrigation return, leakage from the underlying limestone aquifer, and precipitation

ZONE 6: WATER IN THE RUSTLER FORMATION AND ALLUVIUM NORTH AND EAST OF LAKE AVALON

Ground water in the Rustler Formation and alluvium north and northeast of Lake Avalon moves southeastward (pl 4) into playas east of Lake Avalon where it is discharged by evapotranspiration, or it continues underground and is discharged into the Pecos River downstream from Carlsbad Springs

FLUCTUATION OF WATER LEVELS

Water levels in wells finished in the alluvium north and northwest of Major Johnson Springs fluctuate seasonally in response to pumping for irrigation Water levels are highest in January and lowest from July to September. (See fig 4) The highest water level in a year occurs just before pumping begins, and the lowest water level occurs near the end of the irrigation season The water levels fluctuate from year to year, owing to differences in pumpage and recharge. Increased precipitation usually results in less pumpage, more recharge, and rising water levels, whereas decreased precipitation results in more pumpage, less recharge, and declining water levels The water levels have a net downward trend for the period of record; the water level in well 20.26 7 122 declined from 46 3 to 87 3 feet below land surface from January 1941 to January 1961

Water levels in wells in the Seven Rivers Formation between Lake McMillan and Lake Avalon fluctuate with the stage of Lake McMillan (See fig. 5.) Also, the fluctuation of water levels in individual wells in this highly permeable aquifer are almost identical (See fig 6) The stage of Lake McMillan fluctuates as a result of irrigation demands, flood and base flows of the river, and releases from Alamogordo Reservoir about 140 miles north of Lake McMillan The stage of the lake varies widely during a year (See fig 5.) The level is highest

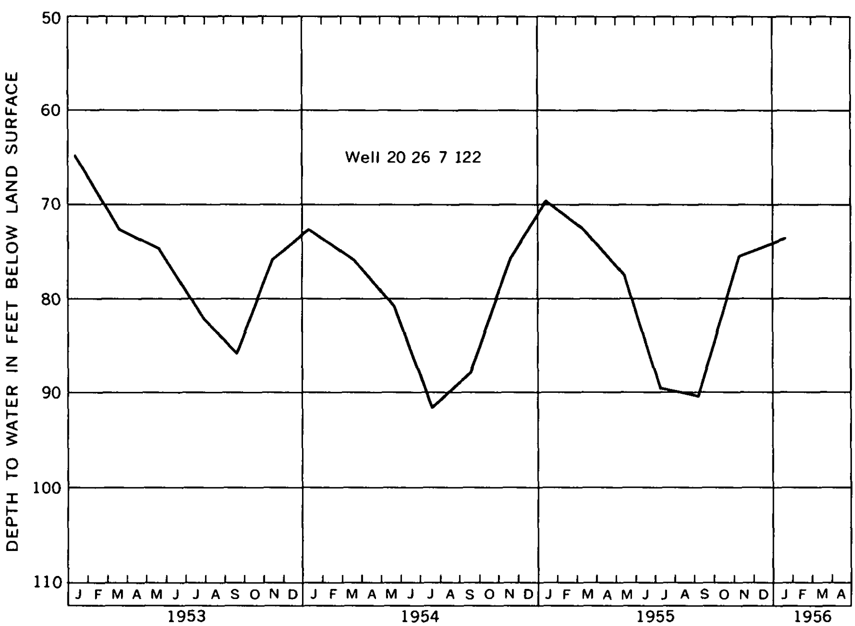

FIGURE 4—Water level in alluvium northwest of Major Johnson Springs

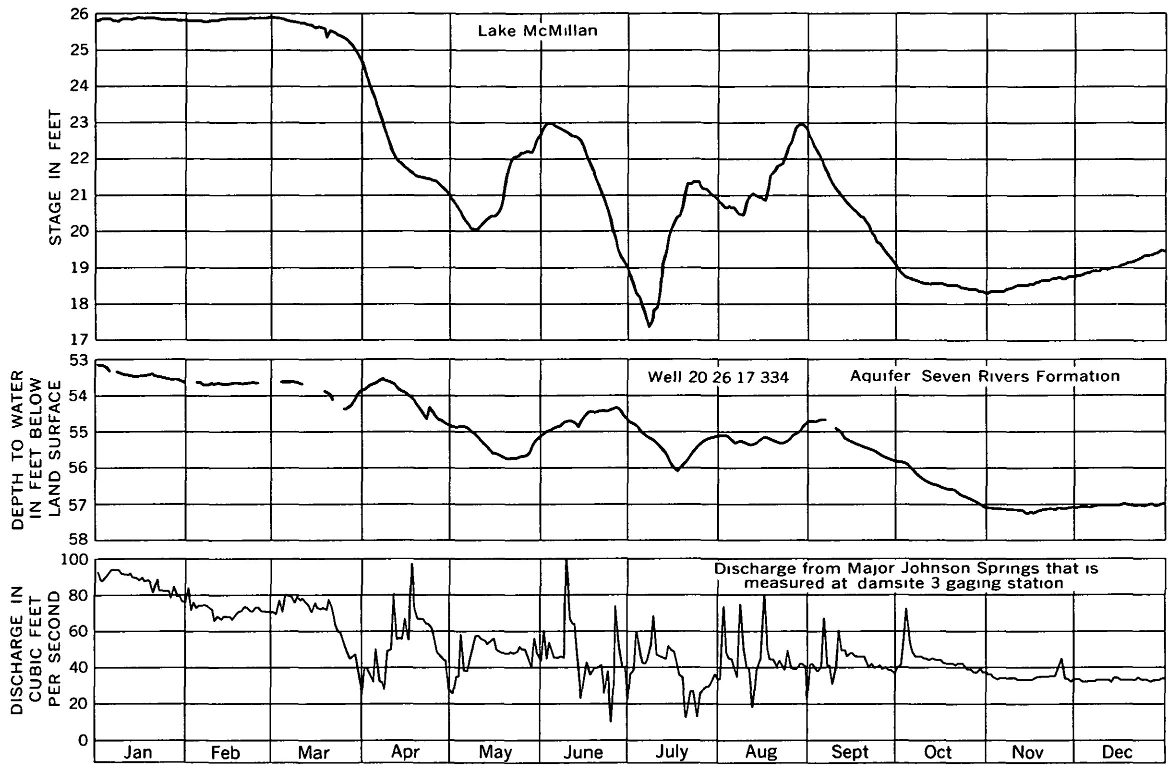

FIGURE 5—Stage of Lake McMillan, water level in Seven Rivers Formation, and measured discharge of Major Johnson Springs, 1959

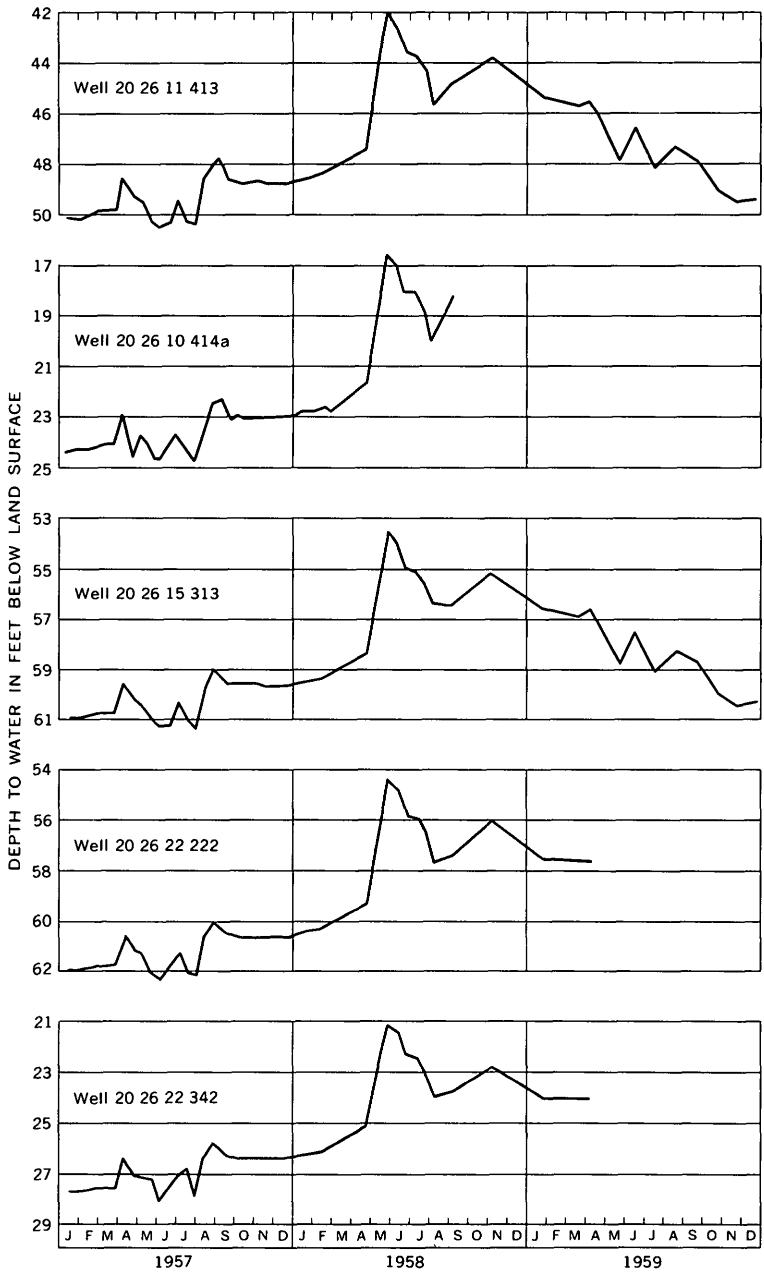

FIGURE 6.—Water levels in selected wells in the Seven Rivers Formation between Lake McMillan and Major Johnson Springs

in the winter of some years, and highest in the summer of other years. Because the water in the alluvium north and northwest of Major Johnson Springs is hydraulically connected with that in the Seven Rivers, pumping from wells in the alluvium causes minor fluctuation of water levels in wells in the Seven Rivers Formation. The fluctuations in the Seven Rivers Formation are larger in wells near Major Johnson Springs.

Water levels in wells in the Yates Formation between Lake McMillan and Lake Avalon do not fluctuate with the stage of Lake McMillan, but they apparently fluctuate with the stage of Lake Avalon (figs. 7 and 8). The water levels are generally lower in summer than in winter, just as the stage of Lake Avalon is lower in summer owing to irrigation releases. Lake Avalon, when full, backs water upstream to the mouth of Dagger Draw, and leakage from the lake and the river between Major Johnson Springs and Lake Avalon recharges the aquifer in the Yates. Well 20 27.29.441 is nearer Lake Avalon than the other two wells shown in figure 7, and the water level in it is affected sooner than water levels in the other wells. Also, in wells 20.26 25.121 and 20.26.36.411, minor fluctuations of water levels, which are not apparent in well 20.27 29.441, are attributed to changes in discharge of the Pecos River between Major Johnson Springs and damsite 3 gaging station (fig. 9) and possibly to recharge of the aquifer through sinkholes near the wells

Fluctuations of water levels in wells near Carlsbad are caused mainly by changes in amount of precipitation and pumpage of water from the aquifers. Water levels in wells in the limestone aquifer rise during times of greater precipitation and less-than-average pumpage, and decline during times of lesser precipitation and greater-than-average pumpage Water levels in wells in the alluvium overlying the limestone aquifer in La Huerta, north of the Pecos River from Carlsbad, fluctuate in phase with water levels in the limestone aquifer because the two aquifers are connected Water levels in wells in the alluvium, however, fluctuate less than water levels in the limestone aquifer.

231-544 O—66——3

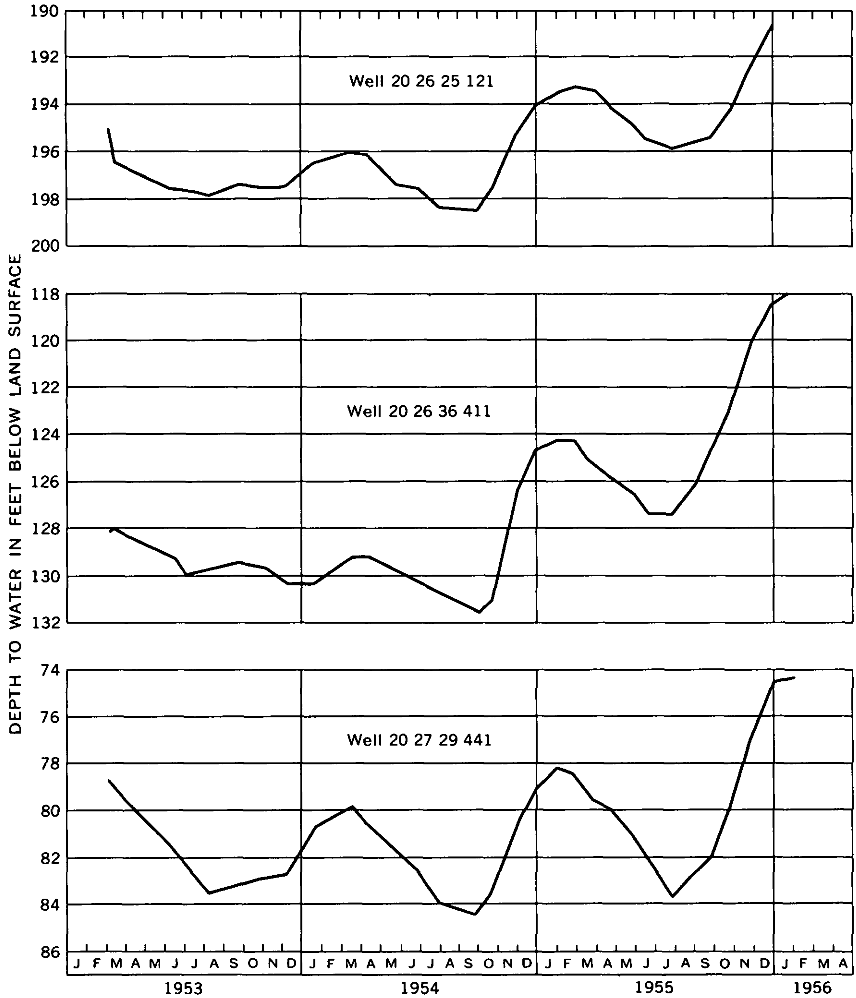

FIGURE 7.—Water levels in selected wells in the Yates Formation between Lake McMillan and Lake Avalon

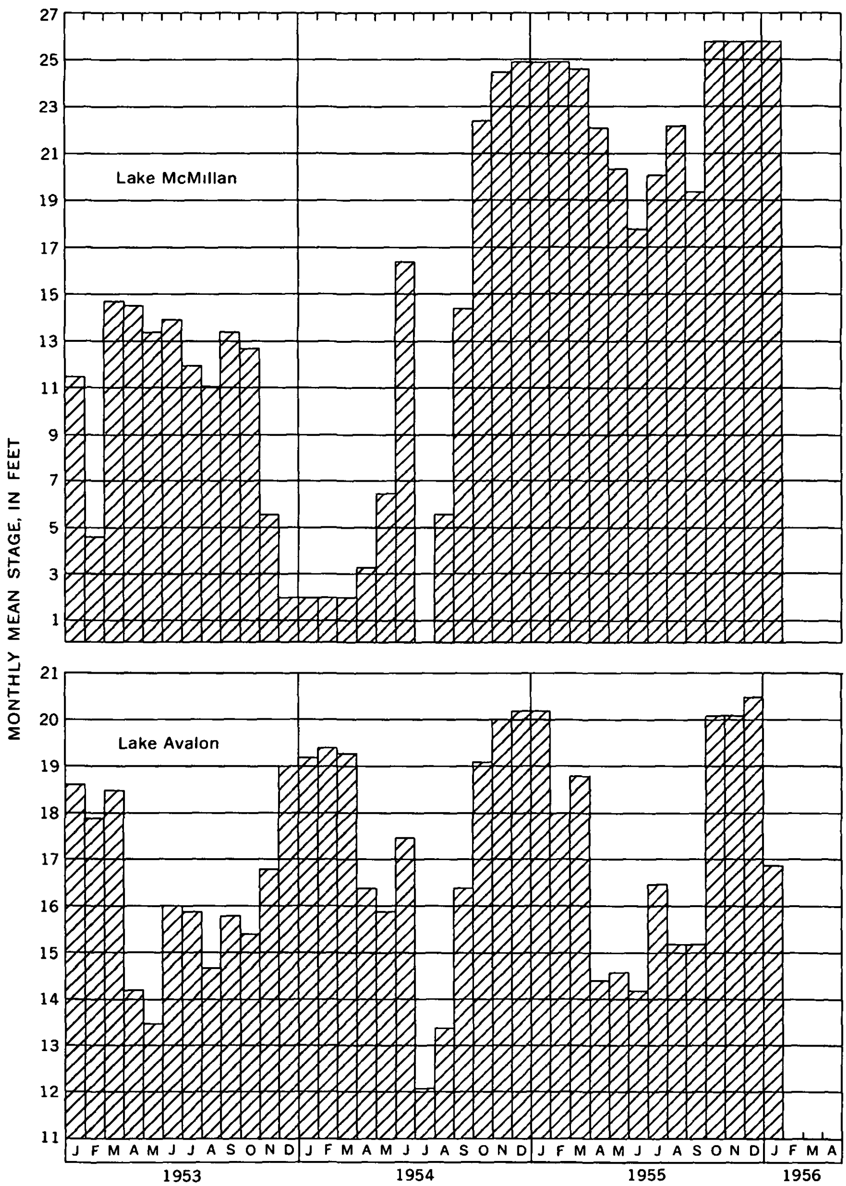

FIGURE 8.—Monthly mean stages of Lake McMillan and Lake Avalon

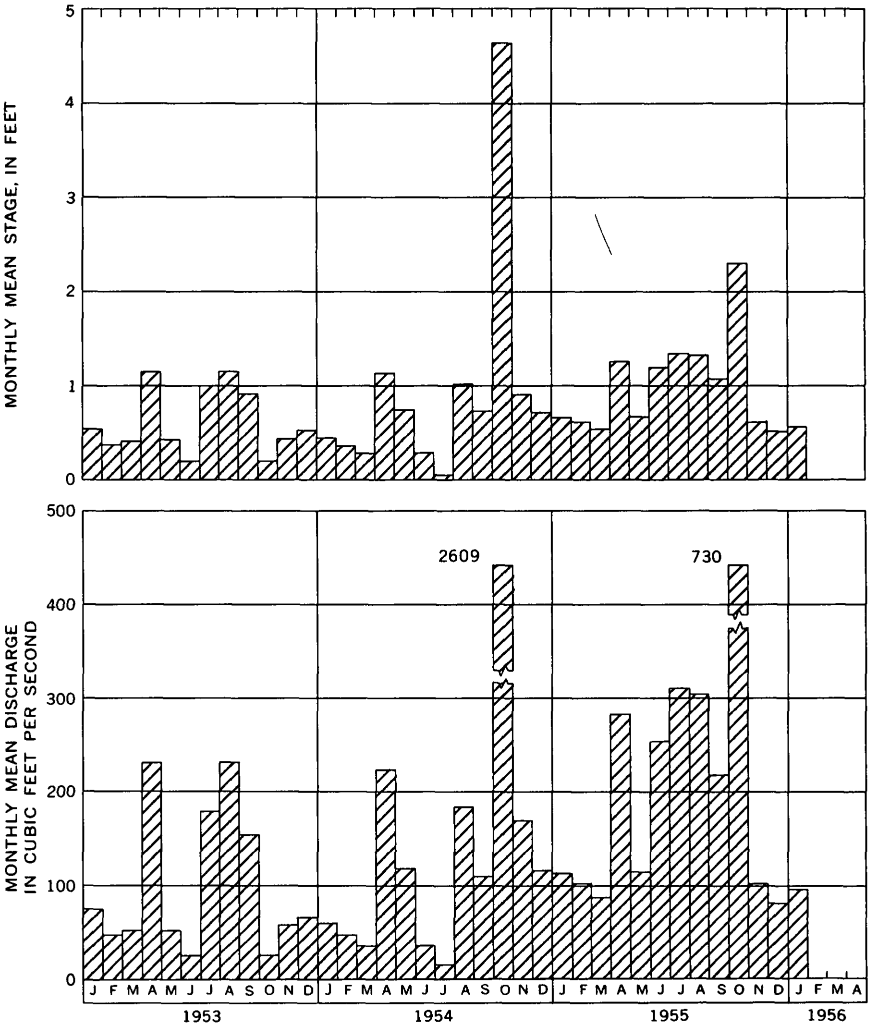

FIGURE 9 —Monthly mean discharge and stage of Pecos River at damsite 3 gaging station

QUALITY OF WATER IN RELATION TO OCCURRENCE OF GROUND WATER

The ground water in the area between Lake McMillan and Carlsbad Springs had a bicarbonate content of more than 100 ppm (parts per million) from all wells sampled and more than 200 ppm in most wells The high bicarbonate content of the water is attributed to the prevalence of limestone and dolomite in the area. The water from most wells sampled had a sulfate content of more than 1,000 ppm due to the abundance of gypsum in the area. The chloride content of ground water between Lake McMillan and Carlsbad Springs generally ranged from 10 to 1,000 ppm. The specific conductance, which roughly indicates the concentration of dissolved solids, of water from wells between Lake McMillan and Carlsbad Springs generally ranged from 1,000 to 6,000 micromhos at 25° C.

The differences in quality of ground and surface water between Lake McMillan and Carlsbad Springs define to some extent the source of recharge and movement of ground water The chloride content and specific conductance of water in wells and the Pecos River system are shown in plate 5. The chloride content of water in the river system varies throughout a year depending on the amount of flood runoff, irrigation return, and evaporation. But generally, the surface water has a much higher chloride content than ground water in the area of this report Therefore, aquifers that have a higher chloride content near the Pecos River are recharged by leakage from the Pecos River system.

The high chloride content of water from wells in the Seven Rivers Formation between Lake McMillan and Major Johnson Springs indicates that the water in the Seven Rivers is mostly leakage from the Pecos River and Lake McMillan The chloride content of water from wells in the alluvium north and northwest of Major Johnson Springs is lower than that of Lake McMillan and also lower than that of water from wells between the lake and the springs (See pl 5) Wells finished in the Seven Rivers Formation within 2 miles northwest of Major Johnson Springs yield water with a chloride content lower than water from Lake McMillan and higher than water from the alluvium. This indicates that water from wells in the Seven Rivers Formation within 2 miles northwest of Major Johnson Springs is a mixture of water leaking from Lake McMillan and water from the alluvium north and northwest of the springs.

Water with a chloride content of more than 200 ppm in wells in the Yates Formation between Lake McMillan and Lake Avalon north and northeast of the Pecos River indicates recharge to this aquifer from the Pecos River Water in well 20 26.25.121 in the Yates has 67 ppm chloride, indicating the well is nearer an area of recharge from precipitation than other wells in the Yates.

Wells finished in the Yates Formation south and southwest of the Pecos River between Lake McMillan and Lake Avalon yield water having chloride contents of less than 50 ppm. The low chloride contents indicate that water seeping from the river into the Yates between Lake McMillan and Lake Avalon does not move southward

Wells in the limestone aquifer between Lake Avalon and Carlsbad Springs and within 2 miles southwest of the springs yield water with higher chloride content than wells in the limestone aquifer farther west and southwest of Carlsbad Springs The higher chloride content of water in wells between Lake Avalon and Carlsbad Springs and wells within 2 miles southwest of the springs is attributed to leakage from Lake Avalon

Wells 5 miles or more west of the Pecos River yield water generally having less than 30 ppm chloride and less than 2,000 micromhos specific conductance Wells yielding water moderately high in chlorides, not resulting from leakage from the Pecos River, are in the flats southeast of Fade-Away Ridge and the irrigated areas along the lower reaches of north and south Seven Rivers and in the vicinity of Carlsbad. The wells southeast of Fade-Away Ridge tap the Rustler Formation, which is known to contain halite in places, or reworked material derived from the Rustler The wells in the irrigated areas containing water with high chloride concentrations tap alluvium which has been recharged with irrigation water upgradient from the wells Water in aquifers recharged by percolation of irrigation water usually gains in dissolved-solids content

INFLOW-OUTFLOW RELATIONSHIPS FROM KAISER CHANNEL GAGING STATION TO LAKE AVALON

The surface inflow and outflow of Lake McMillan and Lake Avalon are measured at gaging stations on the Pecos River. Kaiser Channel gaging station records the inflow to Lake McMillan, and below McMillan Dam gaging station records the outflow from the lake. Damsite 3 gaging station records the inflow to Lake Avalon; below Avalon Dam gaging station and Carlsbad main canal gaging station record the outflow from Lake Avalon The locations of these gaging stations are shown on plate 1

Kaiser Channel gaging station is in Kaiser Channel, a conveyance channel upstream from Lake McMillan The channel was constructed by the Bureau of Reclamation in 1948–49 This gaging station measures flows in the channel to its capacity of about 1,500 cfs (cubic feet per second). Larger flows break out of the channel and flood the bottom lands upstream from Lake McMillan Part of the floodwater reaches Lake McMillan and part is lost by seepage and evapotranspiration in the bottom lands upstream from the lake

Water is lost by seepage from the conveyance channel between Kaiser Channel gaging station and Lake McMillan because the channel is perched above the water table in the alluvium A loss of 2.8 cfs was measured in a 2.7-mile reach of the channel downstream from the gaging station when the flow was about 55 cfs

The Pecos River does not flow between Lake McMillan and Major Johnson Springs except when water is released or spilled from the lake.

The river flows perennially between Major Johnson Springs and Lake Avalon. The river is perched above the water table and loses water in the reach from about the downstream end of the Major Johnson Springs area to Lake Avalon Damsite 3 gaging station is in the losing reach of the river between Major Johnson Springs and Lake Avalon; therefore, because of losses above and below it, the station does not accurately measure the flow of Major Johnson Springs or the inflow into Lake Avalon.

The complex hydrology of the Pecos River system between Kaiser Channel gaging station and Lake Avalon has been analyzed by using data on streamflow from the gaging stations and from miscellaneous sites, stage and content of Lake McMillan, evaporation, precipitation, and water levels in observation wells.

Leakage from Lake McMillan was determined by subtracting the outflow from the inflow at different stages of the lake The inflow is the streamflow recorded at Kaiser Channel gaging station plus precipitation on the lake surface. Outflow is the streamflow recorded at below McMillan Dam gaging station plus evaporation from the lake. Precipitation and evaporation are measured at a weather station near Avalon Dam. Adjustments for change in content of Lake McMillan were avoided by selecting periods when the lake stage remained steady for several days. The relationship between the stage of Lake McMillan and leakage from the lake is shown in figure 3.

Most of the flow of Major Johnson Springs represents the discharge of the highly permeable aquifer in the Seven Rivers Formation between Lake McMillan and Major Johnson Springs. Changes in the amount of water in storage in that aquifer affect the flow of the springs and are reflected in fluctuations of water levels in wells near the springs.

To correlate the flow of Major Johnson Springs with the recorded flow of the Pecos River at damsite 3 gaging station, several sets of miscellaneous streamflow measurements were made in the reach of the river between the springs and the gaging station. The locations of miscellaneous streamflow measuring sites between Lake McMillan and Lake Avalon are shown in plate 6. The stream was measured when the flow was relatively steady at several different rates Measuring conditions in this reach of the river are poor because the streambed contains many cobbles and boulders that cause error in measurement. Therefore, gains or losses measured at different rates of flow in the reach are inconsistent. Emphasis was given to the low-flow measurements in interpreting the results of the miscellaneous measurements. The Pecos River apparently loses about 10 cfs between Major Johnson Springs and damsite 3 gaging station when the flow of the springs is about 40 cfs The miscellaneous streamflow measurements between Major Johnson Springs and damsite 3 gaging station are listed in table 1.

Changes in the stage of Lake McMillan begin to affect the flow of the Pecos River at damsite 3 gaging station within a few hours, and are due to pressure effects transmitted through the permeable aquifer between Lake McMillan and Major Johnson Springs Major changes in the stage of the lake are reflected in measurable changes in water levels in wells near Major Johnson Springs about 10 days later. (See fig 5) The discharge of Major Johnson Springs, as measured at damsite 3 gaging station, is generally proportional to the stage of Lake McMillan but with a 10-day lag. The time needed for water to travel from Major Johnson Springs to damsite 3 gaging station does not appreciably affect the lag estimate because, as records indicate, only 5 to 15 hours is needed for water to travel from below McMillan Dam gaging station to damsite 3 gaging station.

The discharge of Major Johnson Springs is a combination of leakage from Lake McMillan and the base flow of the springs The amount of flow from each source is important to any water-budget study of the Pecos River. The discharge of Major Johnson Springs from each source is difficult to determine because of many variables in the hydrologic system, but it can be estimated by using available data and a few assumptions The results of this study indicate that all water leaking from Lake McMillan returns to the Pecos River at Major Johnson Springs; hence, the base flow of the springs equals the flow of the springs minus that part of the spring flow that leaked from Lake McMillan and from the river between Kaiser Channel gaging station and Lake McMillan

The gross flow of Major Johnson Springs is computed as the flow of the Pecos River at damsite 3 gaging station minus the flow at below McMillan Dam gaging station minus flood inflow between the gaging stations plus the loss from the river between the springs and damsite 3 gaging station. The part of the flow of Major Johnson Springs that is leakage from Lake McMillan can be determined from the graph in figure 3 The base flow of Major Johnson Springs was computed several times a year from 1953 through part of 1960, and is shown in figure 10 The base flow of Major Johnson Springs was determined by computing the flow of the springs when Lake McMillan was dry and no water leaked from the lake, or by subtracting the leakage from the total flow of the springs

TABLE 1 —*Miscellaneous streamflow measurements between Lake McMillan and Lake Avalon, Eddy County, N Mex*

Location	Streamflow, in cubic feet per second, on indicated dates																					
	11-28-51		8-4-54		11-15-56		3-1-57		12-17-57		11-30-59		12-22-59		1-15-60		1-18-60		1-21-60		12-1-60	
	Flow	Gain or loss	Flow	Gain or loss	Flow	Gain or loss	Flow	Gain or loss	Flow	Gain or loss	Flow	Gain or loss	Flow	Gain or loss	Flow	Gain or loss	Flow	Gain or loss	Flow	Gain or loss	Flow	Gain or loss
1 Pecos River at below McMillan Dam gaging station											0	0	0	0	34 6		72 8		0	0	81 9	
2 Pecos River 200 ft above mouth at Seven Rivers											0	0	0	0	32 8	−1 8	65 8	−7 0	0	0		
3 Seven Rivers 600 ft above mouth											12		08		16		21		10			
4 Pecos River at site of Old Major Johnson Springs gage	[1] 61 2		[2] 2								30 6	+30 6	30 7	+30 7	67 8	+35 0	92 2	+26 4	33 9	+33 9		
5 Pecos River below Major Johnson Springs											42 4	+11 8	43 7	+13 0	70 7	+2 9	[1] 99 4	+7 2	44 4	+10 5	[1] 158	+76 1
6 Pecos River above Hardesty's pump	72 0	+10 8	7 08	[2] +5 08			36 4		39 4		35 1	−7 3	35 8	−7 9	67 2	−3 5	106	+6 6	42 0	−2 4	[1] 157	−1
7 Hardesty's pump			1 76								0		0		0		0		0		0	
8 Pecos River at mouth of Rocky Arroyo	76 0	+4 0			36 0		33 0	−3 4	37 4	−2 0	34 6	− 5	34.7	−1 1	67 9	+ 7	105	−1 0	46 3	+4 3	[1] 148	−9
9 Pecos River at damsite 3 gaging station	73 2	−2 8	5 15	− 17	30 0	−6 0	33 0	0	40 3	+2 9	33 2	−1 4	33 2	−1 5	66 5	−1 4	100	−5 0	40 5	−5 8	[1] 156	+8
10 Pecos River at mouth of Soapberry Draw													34.7	+1 5	65 2	−1 3	103	+3 0	39 6	− 9		
11 Pecos River above mouth of Dagger Draw															58 8	−6 4	97 6	−5 4	36 6	−3 0		
12 Pecos River at mouth of Dagger Draw			4 30	− 85	28 7	−1 3	34.1	+1 1			[3] 24 2		[3] 19 8									

[1] Average of two measurements [2] Estimated [3] Measurement questionable because of backwater from Lake Avalon

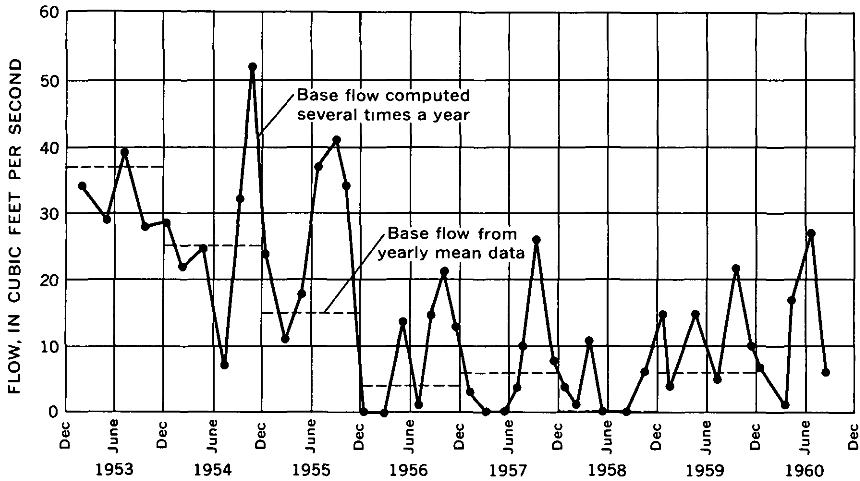

FIGURE 10 —Base flow of Major Johnson Springs

The computed base flow of Major Johnson Springs fluctuates throughout a year (fig. 10); so, the yearly mean data are probably more reliable for analyzing the base flow of the springs because they give an average flow The average base flow declined markedly from 1953 through 1956, and remained less than 10 cfs from 1956 through 1959

Leakage from the Pecos River between Artesia gaging station, 4 miles east of Artesia, and Lake McMillan is part of the base flow of Major Johnson Springs Leakage from the Pecos River between Kaiser Channel gaging station and Lake McMillan is included in this report in the leakage from the lake because Kaiser Channel gaging station was used to measure inflow into Lake McMillan for the purpose of determining leakage from the lake A net loss of about 5 cfs in the reach between Artesia gaging station and Kaiser Channel gaging station is water that has been measured previously at Artesia gaging station. This lost water probably returns to the Pecos River as part of the base flow of Major Johnson Springs The average base flow of Major Johnson Springs from 1953 through 1959, using yearly mean data, was 13 cfs The amount of the base flow of Major Johnson Springs which had not been measured as part of the Pecos River system upstream from damsite 3 gaging station averaged 8 cfs for the years 1953 through 1959

W E Hale, of the Geological Survey, reviewed the flow of Major Johnson Springs from 1947 through 1954 in a memorandum to the Pecos River Commission dated November 20, 1959. He computed the part of the base flow of Major Johnson Springs not previously recorded by gaging stations on the Pecos River during periods when Lake McMillan was dry for considerable time, and he established a relation between the water level in a well in the alluvium near the springs and the discharge of the springs not previously measured This index well is considered not close enough to the springs to be influenced by the total flow of the springs.

Hale's analysis of the base flow of Major Johnson Springs uses methods similar to those previously described by the author in this report. However, Hale assumed a loss of 2 to 4 cfs in the flow of the Pecos River between Major Johnson Springs and damsite 3 gaging station, whereas the author used a value of 10 cfs determined from measurements of four flows of about 40 cfs (table 1)

The Pecos River loses water between damsite 3 gaging station and Lake Avalon where the river is perched above the water table The loss in this reach appears to be about 5 cfs at normal low flows, based on miscellaneous streamflow measurements (See table 1) For the purpose of inflow-outflow studies, however, the loss between damsite 3 gaging station and Lake Avalon is included in the total leakage from Lake Avalon for convenience so that damsite 3 gaging station can be used to measure the inflow into Lake Avalon.

INFLOW-OUTFLOW RELATIONSHIPS FROM LAKE AVALON TO CARLSBAD SPRINGS

Inflow to Lake Avalon is that flow measured at damsite 3 gaging station and outflow from Lake Avalon is that flow measured at below Avalon Dam gaging station and Carlsbad main canal gaging station The Pecos River between Lake Avalon and Carlsbad Springs is dry except when water is spilled from Lake Avalon Carlsbad Springs issue along the river bottom and sides above and below the surface of the lake created by Tansill Dam. The flow of Carlsbad Springs is measured at Carlsbad gaging station about half a mile downstream from Tansill Dam.

Water leaks from Lake Avalon and moves through solution channels in the Tansill Formation into the limestone aquifer where it mixes with water from other sources and moves to Carlsbad Springs.

Bjorklund and Motts (1959, p. 187–188) listed the components of discharge from Carlsbad Springs as follows (1) Discharge due to leakage from Lake Avalon, including that from the Pecos River between damsite 3 gaging station and Lake Avalon, (2) seepage from the Pecos River between Major Johnson Springs and damsite 3 gaging station, (3) discharge due to leakage from canals, (4) discharge due to irrigation return flow, and (5) discharge due to natural recharge that results mostly from precipitation in the Guadalupe Mountain area west of Carlsbad. The rate of leakage from Lake Avalon ranges from a very small amount when the reservoir is almost empty at gage height 12 feet to more than 40 cfs when the reservoir is almost full at gage height 20 feet (Bjorklund, 1958, p 7). The net effect of leakage from Lake Avalon on the discharge of Carlsbad Springs probably lags 1 to 3 months (Bjorklund and Motts, 1959, p. 183). Most of the discharge of Carlsbad Springs from 1952 through 1956 was leakage from Lake Avalon (Bjorklund and Motts, 1959, table 7)

POSSIBLE DAM AND RESERVOIR SITES BETWEEN LAKE McMILLAN AND LAKE AVALON

The need for an additional storage reservoir on the Pecos River upstream from the Carlsbad Irrigation District has been recognized for many years. The original capacity of Lake McMillan was about 91,000 acre-feet, and the capacity of Lake Avalon was 7,600 acre-feet. Lake McMillan had a capacity of 61,500 acre-feet in 1910 and 45,200 acre-feet in 1915 The capacities of Lake McMillan and Lake Avalon in 1956 were 39,000 and 5,000 acre-feet, respectively The loss of storage capacity of the reservoirs is attributed to suspended sediment deposited in the reservoirs, especially during floods. Terminal storage is required for the Carlsbad Irrigation District to serve the 25,000 acres of land within the district.

In 1958 Congress authorized (Public Law 85–333) construction of a floodway through an area of intensive growth of saltcedar between Artesia gaging station and Lake McMillan with a stipulation that no money should be appropriated and that no work should be commenced on clearing the floodway until provision had been made to replace any terminal storage of the Carlsbad Irrigation District that might be lost as a result of clearing the floodway Floodwaters spread out in the saltcedar area upstream from Lake McMillan and lose most of the suspended sediment before reaching Lake McMillan A floodway through the saltcedar would increase the sediment load reaching Lake McMillan and would thus decrease the storage capacity of the lake, but a floodway would salvage water used nonbeneficially by evapotranspiration in the saltcedar area. Additional storage facilities between Lake McMillan and Lake Avalon would offset the decrease in storage in Lake McMillan.

Five possibilities for increasing terminal storage of the Carlsbad Irrigation District in the area between Lake McMillan and Lake Avalon are (1) dredge the sediment from the McMillan Reservoir and (or) raise McMillan Dam, (2) raise Avalon Dam, (3) construct a dam at the intermediate site, or No 3 site between McMillan Dam and Avalon Dam (pl. 1), (4) construct a dam at the Brantley site at the downstream end of Major Johnson Springs (pl 1), and (5) use underground storage, estimated to be 45,000 acre-feet, in the permeable Seven Rivers Formation between Lake McMillan and Major Johnson Springs in conjunction with a low dam at the Brantley site.

Raising McMillan Dam and dredging the reservoir would provide additional storage, but it would also increase leakage from the reservoir. The sediment accumulated in the bottom of the reservoir undoubtedly retards leakage; thus, removal of the sediment to provide storage would increase leakage considerably. The additional leakage from McMillan Reservoir would return to the Pecos River at Major Johnson Springs and most of it would flow into Avalon Reservoir. Because the storage capacity of Avalon Reservoir is small, much of the additional leakage from McMillan Reservoir would be lost to the Carlsbad Irrigation District.

Raising Avalon Dam would increase leakage from the reservoir because the leakage is directly proportional to the stage. In addition, sinkholes in gypsum along a flat north of the present reservoir may be inundated, and result in extremely large leakage rates. Leakage from Avalon Reservoir reappears in the Pecos River at Carlsbad Springs downstream from the diversion of the Carlsbad Irrigation District.

As early as 1905 consideration was given to construction of a dam on the Pecos River between McMillan and Avalon Dams This site has been called the "No. 3" site, the "third reservoir" site, the "intermediate" site, the "Carlsbad Reservoir" site, and perhaps other names. In this report the damsite shall be called the No. 3 damsite or simply the No. 3 site, and a reservoir that would be created by such a dam shall be called the No 3 Reservoir

The No. 3 site lies between two ridges of limestone conglomerate in sec. 6, T. 21 S., R. 26 E., where the Pecos River flows eastward. The flood plain of the river at the No. 3 site is underlain by a maximum of about 25 feet of silt, sand, gravel, cobbles, and quartzose conglomerate. This alluvium is underlain by clay of the Yates Formation. Unconsolidated alluvium lies directly on clay of the Yates on the north side of the flood plain A geologic section along the axis of the No. 3 damsite is shown in plate 6

A dam could probably be built at the No. 3 site without unusual difficulty. The limestone conglomerate ridges should make good abutments for the dam, and the quartzose conglomerate and clay or the unconsolidated alluvium should support the structure However, the problems of constructing a dam are beyond the scope of this investigation.

A dam 60 feet high at the No. 3 site, would create a reservoir extending nearly to the toe of McMillan Dam. Such a reservoir would have a capacity of at least 75,000 acre-feet.

To be effective, the No. 3 Reservoir should not leak excessively because leakage would not reappear in the Pecos River above the diversion of the Carlsbad Irrigation District. Leakage from a proposed reservoir can, at best, only be estimated, but a detailed examination of the geology and hydrology of the reservoir and surrounding area will give indications of the magnitude of leakage that might be expected.

The No. 3 Reservoir would inundate part of the Pecos River valley underlain by unconsolidated alluvium, limestone and quartzose conglomerates, and rocks of the Yates and Seven Rivers Formations The unconsolidated alluvium and the conglomerates are not widespread in the reservoir area, and leakage would not be large through these rocks unless they are hydraulically connected to aquifers in the Yates or Seven Rivers Formations Thus, leakage from the No 3 Reservoir would be controlled by hydrologic conditions in the Yates and Seven Rivers. The contact between the Yates and Seven Rivers Formations would almost bisect No 3 Reservoir; leakage from the upstream half of the reservoir would be controlled by hydrologic conditions in the Seven Rivers, and in the downstream half, by hydrologic conditions in the Yates.

Leakage from the upstream half of the No 3 Reservoir would enter the Seven Rivers Formation which is hydraulically connected with alluvium north and northwest of the springs between Lake McMillan and Major Johnson Springs A dam 60 feet high at the No 3 site would create a reservoir with a maximum or near maximum pool level at altitude 3,230 feet or approximately 20 feet above the altitude of Major Johnson Springs (See pl. 1.) Such a reservoir would reverse the flow of the springs until the water level in the Seven Rivers and nearby alluvium reached approximately 3,230 feet in altitude Maximum leakage from the No 3 Reservoir through Major Johnson Springs should approximate the maximum spring flow determined at full stage of Lake McMillan, or about 100 cfs. This additional water would remain in underground storage until released through the springs by lowering the level of the No. 3 Reservoir A geologic section across part of the Pecos River valley near the downstream end of Major Johnson Springs is shown in plate 6.

The downstream half of the No. 3 Reservoir would overlie rocks of the Yates Formation, and water from the reservoir would leak into that formation. The Pecos River is perched about 40 to 50 feet above the water table in the Yates from near the center of sec. 27, T. 20 S., R. 26 E., to the No 3 site (pl. 6), and the river is a losing stream from Major Johnson Springs to the No. 3 site. The altitude of the river ranges from 3,173 feet at the No. 3 site to 3,192 feet near the center of sec. 27; thus, a reservoir level at altitude 3,230 feet would increase the head above the aquifer in the Yates from 38 to 57 feet in the downstream half of the No. 3 Reservoir. When the reservoir is full or nearly full, the head differential between the reservoir level and the water table in the Yates would be more than 100 feet in places. Leakage from the reservoir would be large under these conditions. Leakage from the No 3 Reservoir into the Yates Formation would be expected to follow the path of water seeping from the Pecos River between Major Johnson Springs and the No 3 site and to discharge into the Pecos River at Carlsbad Springs.

A zone of perched water occurs near the base of the unconsolidated alluvium under the flood plain of the Pecos River in the downstream half of the No. 3 Reservoir. (See pl 6.) The zone of perched water also extends at least a quarter of a mile northward from the No. 3 site in clay of the Yates Formation (pl. 6). The composition of the confining bed beneath the perched-water zone is not known, although it is probably clay at the base of the alluvium or clay in the Yates. This confining bed could probably retard leakage from the No. 3 Reservoir if it is widespread. But, because it does not now prevent water from seeping from the river into the water-bearing zone in the Yates, the confining bed would probably not be an effective barrier to leakage from the reservior.

The downstream half of the No. 3 Reservoir might have leakage characteristics similar to those at McMillan Reservoir, which, when full, has a water level perched about 50 feet above the water table in the Seven Rivers Formation McMillan Reservoir has leaked a maximum of about 100 cfs since the construction of dikes that prevent water from entering most of the sinkholes along the eastern shore of the reservoir. Leakage from the downstream half of the No 3 Reservoir would be mostly through alluvium underlying the flood plain of the river and a low terrace west and southwest of the river into the Yates Formation, although leakage might occur through outcrops of fractured limestone conglomerate east and north of the river especially in the vicinity of the mouth of Rocky Arroyo Leakage through the unconsolidated alluvium can be demonstrated by the gage well at damsite 3 gaging station. More water leaks through the bottom of this well than can be siphoned from the river through a garden hose Attempts to seal the bottom of the well with bentonite and cement have failed Leakage from the downstream half of the No 3 Reservoir may be as much as 100 cfs.

The Brantley site is probably the most favorable damsite on the Pecos River in New Mexico between Alamogordo Dam and the Texas State line The Brantley site is just south of Major Johnson Springs near the downstream end of a canyon between the Seven Rivers Hills and the McMillan Escarpment (pl. 1) The flood plain at this point is less than a quarter of a mile wide, and dolomite of the Seven Rivers Formation is at or near land surface. A dam built here is capable of creating a reservoir having a capacity of at least 35,000 acre-feet and extending to the toe of McMillan Dam

The Bureau of Reclamation has made a reconnaissance study of the Brantley site, and tentative plans call for construction of a dam, 100 feet high, having a crest at altitude 3,303 feet The maximum normal reservoir level would be at altitude 3,268 5 feet; and the capacity, 121,200 acre-feet The maximum water surface during floods would be at altitude 3,296.5 feet

The geology and hydrology of the Brantley Reservoir site are identical with those for the upstream half of the No. 3 Reservoir site. That is, the reservoir would inundate Major Johnson Springs and alluvium upstream from the springs The flow of the springs would be reversed until the water level in the permeable aquifer in the Seven Rivers Formation and nearby alluvium rose to approximately the same altitude as the level of the surface reservoir The water level in the permeable aquifer would remain at this altitude until the level of the surface reservoir is lowered As much as 100 cfs of water could flow from the surface reservoir through the springs into the Seven Rivers and alluvium The relatively impermeable dolomite in the Seven Rivers would prevent water from moving eastward, southeastward, or southward from the permeable part of the Seven Rivers One of the geologic sections shown in plate 6 is near the Brantley damsite.

The geology and hydrology of the Brantley and No. 3 damsites are generalized, and the data presented in this report are not intended to establish the feasibility of either of these sites The Brantley site, however, appears to be the more favorable of the two sites insofar as avoiding excessive leakage from the reservoir. Extensive study of the geology and hydrology should be made of the dam and reservoir sites and of the surrounding areas before a dam is built

A dam at the Brantley site should be downstream from all the springs in the Major Johnson Springs area. The spring farthest downstream is apparently on the east bank of the river in the NW¼NE¼NE¼ sec. 28, T. 20 S., R. 26 E. Leakage would be large through this spring if the dam were built upstream from it The reach downstream from the damsite should be thoroughly examined for springs through which leakage from the reservoir could occur.

The dam should not be far enough downstream from Major Johnson Springs to overlie rocks of the Yates Formation. The Pecos River loses water to the Yates within half a mile downstream from Major Johnson Springs.

A dam capable of impounding about 300,000 acre-feet of water could be built so that it crosses the Pecos River in the NE¼ sec. 28, T. 20 S., R. 26 E Such a dam, with a crest altitude of 3,303 feet, would extend northeastward from a ridge in the NW¼ sec. 28, T 20 S., R 26 E., across the river to the end of a ridge in the NE¼ sec. 28, and thence northward up the ridge to higher ground in the NE¼ sec 21, T. 20 S., R. 26 E.

A well drilled into the Seven Rivers Formation between Lake McMillan and Major Johnson Springs might yield as much as 10,000 gpm. Five such wells would provide 100 cfs to the Carlsbad Irrigation District for release to farmland Pumping these wells would lower the water level not only in the Seven Rivers but also in the alluvium north of Major Johnson Springs. The Seven Rivers Formation and the alluvium to the north would be recharged by the Pecos River through sinkholes under Lake McMillan and through the openings of Major Johnson Springs Use of the 45,000 acre-feet of water in underground storage in the Seven Rivers Formation between Lake McMillan and Major Johnson Springs could supplement surface storage.

Underground storage could also be used in conjunction with a low dam at the Brantley site. A low dam could be built at the Brantley site in the NE¼ sec. 28, T. 20 S., R. 26 E., capable of forming a reservoir having a water surface at altitude 3,250 feet and a capacity of about 30,000 acre-feet. Water in the Seven Rivers Formation would also rise to altitude 3,250 feet, or about 40 feet above the present water level. About 150 feet of the Seven Rivers Formation presently contains 45,000 acre-feet; 40 additional feet of saturation might contain about 12,000 acre-feet. Thus, the combined surface storage in the low-dam reservoir and the underground storage, recoverable by lowering the reservoir level, would be about 42,000 acre-feet

Apparently, under present conditions, water does not leak from the evaporite facies of the Seven Rivers Formation east, southeast, and south of the Brantley Reservoir site, but this barrier, which results from the facies change in the Seven Rivers, might not be effective if the head on the system is raised as much as 60 feet when Brantley Reservoir is full.

Consideration has been given by the Bureau of Reclamation to provide flood storage and dead storage for fish propagation in Brantley Reservoir. Flood storage would not be feasible with the low dam Dead storage would not be possible if water were pumped from the Seven Rivers Formation.

SUMMARY AND CONCLUSIONS

Movement of ground water in part of the Pecos River valley between Lake McMillan and Carlsbad Springs is influenced by differences in permeability due to facies changes and differences in lithologic character of rocks of Permian age

Water leaks from Lake McMillan into evaporite rocks of the Seven Rivers Formation and moves under artesian pressure through interconnected solution channels to Major Johnson Springs. The hydraulic gradient of the piezometric surface in this aquifer is almost flat, a fact indicating that water moves with relative ease through highly permeable rocks Changes in pressure head on the aquifer caused by changes in the stage of Lake McMillan begin to affect the flow of Major Johnson Springs within a few hours

The flow of Major Johnson Springs represents discharge from the permeable aquifer in the Seven Rivers Formation which forms an underground reservoir between Lake McMillan and Major Johnson Springs The capacity of the underground reservoir is about 45,000 acre-feet Water in underground storage near Major Johnson Springs is mostly water that has leaked from Lake McMillan, but part of it is water that has discharged from the alluvium north of the springs.

All leakage from Lake McMillan apparently reappears in the Pecos River at Major Johnson Springs. The relatively impermeable carbonate rocks of the Seven Rivers Formation are a barrier to southward and southeastward movement of water from the gypsiferous rocks of the Seven Rivers between Lake McMillan and Major Johnson Springs If all the leakage from Lake McMillan does not reappear at Major Johnson Springs, the amount moving elsewhere is probably too small to be measured.

Most of the water in the alluvium in the southern part of the artesian area north of Major Johnson Springs moves southward to the springs, the natural discharge area for the alluvium This water and small amounts of water from alluvium to the west and possibly from the lower part of the Seven Rivers Formation, together with seepage from the Pecos River upstream from Lake McMillan, make up the base flow of Major Johnson Springs The base flow averaged 13 cfs from 1953 through 1959 Of this amount, about 8 cfs had not been measured upstream from damsite 3 gaging station and is considered as new water to the Pecos River

Part of the ground water in the shelf aquifers west of the Pecos River might discharge into the river at Major Johnson Springs, but most of it probably reaches the river at Carlsbad Springs. Water moves through the Capitan and Goat Seep Limestones and their back-reef equivalents, and enters the Pecos River at Carlsbad Springs. The water-bearing Capitan and its back-reef equivalents near Carlsbad is called the limestone aquifer.

Ground water in the Rustler Formation and alluvium north and northeast of Lake Avalon moves southeastward toward playas east of Lake Avalon. Water leaks from Lake Avalon and moves through solution channels in carbonate rocks of the Tansill Formation, mixes with water from other sources, and moves through the limestone aquifer and overlying alluvium to Carlsbad Springs.

Ground water moves through solution channels in the Yates and Tansill Formations east of the Pecos River between Major Johnson Springs and Lake Avalon and is believed to eventually discharge into the Pecos River at Carlsbad Springs Also, the river is perched above the water table in this reach and loses water to the underlying Yates and Tansill.

Generally, surface water has a much higher chloride content than ground water in that part of the Pecos River valley between Lake McMillan and Carlsbad Springs Therefore, aquifers having high chloride concentrations in this area are recharged by leakage from the Pecos River system. Water low in chlorides is known to occur within 5 miles of the river in places Wells yielding water moderately high in chlorides, not resulting from leakage from the Pecos River, are east of Fade-Away Ridge and in the irrigated areas along the lower reaches of north and south Seven Rivers and in the vicinity of Carlsbad

Construction of a dam at the Brantley site at the downstream end of Major Johnson Springs or use of underground storage in the Seven Rivers Formation between Lake McMillan and Major Johnson Springs in conjunction with a low dam at the Brantley site appears to be the most favorable means of increasing terminal storage for the Carlsbad Irrigation District. The most favorable site for a dam at the Brantley site would be in sec. 28, T. 20 S , R. 26 E., downstream from all springs in the Major Johnson Springs area but upstream from the point where the river begins losing water to the Yates Formation Removal of sediment from McMillan Reservoir and (or) raising McMillan Dam, raising Avalon Dam, or constructing a dam at the No. 3 site might result in excessive leakage from the reservoirs

REFERENCES CITED

Adams, J. E , 1944, Upper Permian Ochoa Series of Delaware basin, West Texas and New Mexico Am Assoc Petroleum Geologist Bull , v 28, no 11, p 1596–1625

Bjorklund, L J , 1958, Flow analysis of Carlsbad Springs, Eddy County, New Mexico U S Geol Survey open-file rept , 25 p , 5 figs , 1 table

Bjorklund, L J , and Motts, W S , 1959, Geology and ground-water resources of the Carlsbad area, New Mexico U S Geol Survey open-file rept , 322 p , 14 pls , 54 figs , 17 tables

DeFord, R K, and Riggs, G D, 1941, Tansill Formation, West Texas, and Southeastern New Mexico Am Assoc Petroleum Geologists Bull , v 25, no 9, p 1713–1728, 4 figs

Fiedler, A G , and Nye, S S , 1933, Geology and ground-water resources of the Roswell artesian basin, New Mexico U S Geol Survey Water-Supply Paper 639, 372 p , 46 pls , 37 figs

Hendrickson, G E , and Jones, R S , 1952, Geology and ground-water resources of Eddy County, New Mexico New Mexico Bur Mines and Mineral Resources Ground-Water Rept 3, 169 p , 6 pls , 11 figs

King, P B , 1948, Geology of the southern Guadalupe Mountains, Texas U S Geol Survey Prof Paper 215, 183 p , 23 pls , 24 figs

Lang, W B , 1937, The Permian formations of the Pecos valley of New Mexico and Texas Am Assoc Petroleum Geologists Bull , v 21, no 7, p 833–898

Meinzer, O E , 1923, The occurrence of ground water in the United States, with a discussion of principles : U S Geol Survey Water-Supply Paper 489, 321 p , 31 pls , 110 figs

Meinzer, O E., Renick, B C , and Bryan, Kirk, 1926, Geology of no 3 reservoir site of the Carlsbad irrigation project, New Mexico, with respect to water-tightness U S Geol Survey Water-Supply Paper 580–A, p 1–39, 2 pls , 2 figs

Morgan, A M , 1938, Geology and shallow-water resources of the Roswell artesian basin, New Mexico New Mexico State Engineer 12th–13th Bienn Repts 1934–38, p 155–249, 5 pls , 5 figs , also pub as New Mexico State Engineer Office Bull 5

Newell, N D , Rigby, J K , Fischer, A G , Whiteman, A J , Hickox, J E , and Bradley, J S , 1953, The Permian reef complex of the Guadalupe Mountains region Texas and New Mexico—a study in paleoecology San Francisco, Calif , W H Freeman and Co , 236 p

Theis, C V , 1938, Origin of water in Major Johnson Springs near Carlsbad, New Mexico New Mexico State Engineer 12th–13th Bienn Repts 1934–38, p 251–252

Theis, C V., Sayre, A N., Morgan, A M , Hale, W E , and Loeltz, O J , 1942, Geology and ground water, *in* [U S] Natl Resources Plan Board, Pecos River Joint Investigation—Reports of the participating agencies Washington, U S Govt Printing Office, p. 27–101

U S Bureau of Reclamation, 1957, Summary of geological material, terminal storage for the Carlsbad project Project Development Division, Albuquerque Project Office, U S Bur. Reclamation open-file rept , May 1957, 55 p

U S GOVERNMENT PRINTING OFFICE 1966 O - 231-544