An Appraisal of the Possibilities of Artificial Recharge to Ground-Water Supplies in Part of the Roswell Basin, New Mexico

By WARD S. MOTTS *and* R. L. CUSHMAN

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By WARD S. MOTTS and R. L. CUSHMAN

ABSTRACT

Since 1942, a persistent downward trend of water levels in wells tapping the two major aquifers (a main aquifer, consisting of consolidated rocks, and an alluvial aquifer) in the Roswell basin of southeastern New Mexico has indicated that the discharge of water from these aquifers has exceeded the replenishment. Although the supply of water in storage is not nearly exhausted, the decline in pressure in the artesian part of the main aquifer has disturbed the equilibrium of a fresh water–saline water interface in this aquifer, and saline water is gradually encroaching westward into the heavily pumped Roswell-Artesia sector of the basin.

The decline in water levels and the saline-water encroachment can be halted or retarded by reducing discharge, by increasing recharge, or by a combination of these two methods. The amount of recharge to the main and alluvial aquifers probably could be substantially increased by inducing additional infiltration of surface water through sinkholes and through permeable sections of stream channels.

The artificial-recharge potential was studied for an area that extends from the vicinity of Vaughn, N. Mex., southward to the Seven Rivers Hills and the Guadalupe Mountains, and westward from the Pecos River to the crest of the Jicarilla, Sierra Blanca, and Sacramento Mountains.

The Yeso Formation, San Andres Limestone (including its Hondo Sandstone Member), and the Artesia Group, all of Permian age, crop out extensively or have been tapped by wells in the basin west of the Pecos River.

Unconsolidated, and some consolidated, gravel, sand, and silt of Tertiary and Quaternary age compose the alluvium of the lowland area.

Major structural zones—the Border Hills, Sixmile Hill, Y–O, Fourmile, Vandewart-Cornucopia, and Huapache—are characterized in the study area by modified surface drainages and generally higher than average permeability.

Sinkholes and closed depressions, which are common in the study area, were formed by ground water moving upward under pressure in zones of weakness and dissolving the soluble rock; by surface water infiltrating the surface rocks, dissolving the soluble rocks, and carrying the dissolved materials to the water table; and by a combination of these two methods.

The principal aquifer of the basin, called in this report, the main aquifer, is within the Permian rocks. Water in most of the main aquifer west of the Pecos River is under water-table conditions. From 10 to 20 miles west of the river, the water table in the main aquifer intersects the base of semiconfining beds in the Artesia Formation, and from that area eastward the water in the main aquifer is under artesian pressure.

Artificial-recharge potentials of the main aquifer are more favorable where the aquifer is highly permeable. Areas of highest permeablity in the recharge area are along the major drainages, along structural zones, and in the vicinity of carbonate-evaporite facies boundaries.

The secondary aquifer of the basin is the alluvium along the Pecos River. Water in the alluvium is under water-table conditions. Recharge to the alluvium is inhibited in places by a layer of caliche.

The recharge area of the main aquifer is divided into seven subareas: the western limestone area; the eastern limestone area; the northern evaporite area; the southern evaporite area; the northern limestone area; the eastern evaporite-alluvial area; and the alluvial lowland area.

The artificial-recharge potential of the western limestone area is poor because much of the water put underground would appear as surface flow within that area.

The artificial recharge potential of the eastern limestone area is moderate to good. Dams could be constructed to impound water over the more permeable areas of stream channels to increase the length of time that water remains in contact with these areas of the channels. Some water probably could be diverted to sinkholes from drainages nearby.

In the northern part of the northern limestone area, the surface drainage is internal to sinkholes. Inducing additional recharge in that area would involve increasing the infiltration rate in sinkholes to reduce evaporation losses. Drainage is well integrated in the southern half of the northern limestone area, and small dams could be constructed to retard streamflow over the more permeable sections of streambeds.

The artificial-recharge potential of the eastern evaporite-alluvial area is probably poor. Water recharged to the main aquifer in the northern part of the area apparently moves east of the Pecos River and then southward; therefore, the water does not move directly to the Roswell-Artesia sector. Ground water moving into the Roswell-Artesia sector from much of the eastern evaporite-alluvial area is probably highly mineralized.

The artificial-recharge potential of both the northern evaporite area and the southern evaporite area is good.

The alluvial lowland is not a natural recharge area for the main aquifer; however, it has some potential for artificial recharge to the main and alluvial aquifers. Recharge water to the main aquifer in most places would have to be injected through recharge wells 400–1,000 feet deep. The most favorable places for wells recharging the main aquifer would be the western and southern halves of the alluvial lowland; there the static water level in the recharge well would be several tens of feet below the land surface.

The alluvial lowland is probably more favorable for artificial recharge to the alluvial aquifer than to the main aquifer. Wells injecting water to the alluvial aquifer could be less than 200 feet deep.

Waters in the Roswell basin that probably could be made available for artificial recharge are: floodwaters in Pecos River tributaries that would be lost by evapotranspiration on floodplains; floodwaters in tributaries that debouch onto lands at the terminus of well-defined channels and would be lost by evapotranspiration; water that would be saved by controlling saltcedar growth in the basin; and water that would evaporate from ponds in sinkholes. The right to use these apparently unappropriated waters would have to be established before proceeding with their use in artificial recharge.

INTRODUCTION

LOCATION AND EXTENT OF THE REPORT AREA

The area investigated for this report (pl. 1) is the major part of the recharge area of a large ground-water basin in southeastern New Mexico. This basin is bounded on the north by a ground-water divide in the vicinity of the town of Vaughn; on the west by ground-water divides near the crests of the Jicarilla, Sierra Blanca, Sacramento, and Guadalupe Mountains; and on the south by poorly permeable rocks underlying the Seven Rivers Hills and the Guadalupe Mountains. The eastern boundary of the basin is probably east of New Mexico. The area described in this report is that part of the basin west of the Pecos River in New Mexico and, in this report, is referred to as the Roswell basin.

PURPOSE OF THE INVESTIGATION

Large-scale development of ground water in the Roswell basin began in the early 1900's with the discovery of artesian water in carbonate rocks that form the main aquifer in the Roswell-Artesia sector of the lowland adjacent to the Pecos River. The water was used to irrigate fields on the alluvium along the river. Seepage of irrigation water into the ground raised the water table in the nonartesian alluvial aquifer and threatened to waterlog large parts of the alluvium near the river. Drains and shallow wells, constructed to counteract the rising water level in the alluvium, furnished water to irrigate additional acreage. Persistent downward trends in artesian and nonartesian water levels since 1942 indicate that the amount of ground water used and discharged naturally from the Roswell basin exceeds the average annual recharge to the ground-water basin.

The depletion of ground water in storage to an uneconomical pumping level is not imminent; however, the decline in artesian pressures has disturbed the equilibrium of a fresh-water–saline-water interface in the artesian system. In this report, water containing more than 1,000 ppm (parts per million) of dissolved solids is considered saline. This interface was at or slightly east of the Pecos River prior to the start of heavy pumping of artesian wells in the Roswell-Artesia sector. About 1952 the easternmost artesian wells in this sector began to yield increasingly saline water. A periodic water-sampling program was started in 1952 to monitor the change in the chemical quality of water from artesian and nonartesian wells. Hood, Mower, and Grogin (1959, p. 33) indicated that if saline water continued to encroach as it did between August 1952 and September 1957, artesian wells along the eastern city limits of Roswell probably would begin pumping water with a chloride content of at least 500 ppm sometime in 1960. By 1960 a few artesian wells east of Roswell were abandoned and plugged because they were yielding saline water. Saline water is encroaching westward in several areas between Roswell and Artesia. The most rapid encroachment is toward the centers of heaviest pumping from artesian wells.

Most of the water recharging the nonartesian alluvial aquifer in the Roswell-Artesia sector is from the artesian system, either as seepage from irrigated fields or as upward leakage through the formation that separates the artesian main aquifer and the nonartesian aquifer. Thus, deterioration in chemical quality of the artesian water results in deterioration in chemical quality of the nonartesian water.

The westward encroachment of saline water must be halted, and, if possible, the saline-water–fresh-water interface must be pushed back to the east if the Roswell-Artesia sector is to be assured a perennial supply of ground water of suitable quality for irrigation. This can be done by reducing discharge, by increasing recharge, or by a combination of these two.

Studies are being made in the Roswell basin to determine ways of restoring the balance between recharge and discharge. Some reductions in discharge are being effected by improved irrigation practices and the retirement from cultivation of lands that do not have legal ground-water rights. The discharge of water by nonbeneficial vegetation in the bottom land of the Pecos River and its tributaries is being studied to determine how much the discharge of ground water can be reduced by eradicating the nonbeneficial bottom-land vegetation. The investigation described in this report was concerned with methods of increasing recharge to the basin.

SCOPE AND METHODS OF INVESTIGATION

This investigation, made in cooperation with the Pecos Valley Artesian Conservancy District and the New Mexico State Engineer, was a study of the physical and geologic features in the Roswell basin to determine whether or where artificial recharge would be possible. The study was to define areas in which artificial recharging might be done and in which intensive studies of some features should be made before artificial-recharge projects were started. Some opinions are expressed about the general type of recharge works that might be suitable in some areas.

Most of the area shown on plate 1 was included in a reconnaissance; (study) however, sinkholes, streams, and geologic formations in the area bounded by the Pecos River, Cienega del Macho, long 105°00′′ W., the Seven Rivers Hills, and the Guadalupe Mountains were studied more intensively.

Literature describing the geology and hydrology of the basin was studied and revealed that sinkholes were numerous in parts of the basin. Holes were augered in a few of these sinkholes to obtain soil samples for permeability studies and to determine the thickness of sediments in the sinkholes. The length of time that water remained in sinkholes after rains was noted by periodic flights over sinkhole areas and was measured in detail in a few selected sinkholes by periodic reading of staff gages set in the ponds. Sinkholes in which changes in pond levels were measured in detail were mapped topographically using a plane table to determine the volume and rate at which the ponded water entered the ground.

A geologic map was compiled of a part of the area using available geologic data. Some geologic mapping was done to delineate the more permeable geologic formations that crop out in the area.

Flood flows in a few tributaries entering the Pecos River from the Sacramento Mountains were measured or estimated to determine natural seepage losses in the middle and upper reaches of those streams. Flow losses were studied in relation to the character and type of rock in which the channel was cut to assist in classifying the relative permeability and recharge potential of certain geologic formations.

Tributaries that occasionally flood, overflow their banks, and lose water by evapotranspiration were studied to locate sites for small dams upstream from the overflow areas. The small dams could be used either for diversion of water into canals leading to suitable sites for artificial recharge or for temporary impoundment of water in a section of the channel overlying a permeable formation.

Water levels were measured in numerous wells outside the cultivated areas in the Roswell-Artesia sector to define better the position and form of the water table and the general pattern of ground-water movement between the recharge and discharge areas. Knowledge of the pattern and rate of ground-water movement is important in selecting sites for artificial recharge. A place from which the ground water neither moves to the Roswell-Artesia sector within a reasonable time nor increases the artesian pressure in the cultivated area would not be a suitable site for artificial recharge.

PREVIOUS INVESTIGATIONS

The following is a brief summary of the reports that were especially helpful in the recharge study. Fisher (1906) reported on the hydrologic and geologic features of the artesian main aquifer of the basin and outlined the area in which flowing wells were being developed. Renick (1926) described briefly the geology of the Rio Penasco drainage above Hope, N. Mex. Fiedler and Nye (1933) described in considerable detail the hydrology and geology of that part of the entire Roswell basin west of the Pecos River. That study led to the enactment of ground-water laws for the State of New Mexico and the Roswell basin. Morgan (1938) described the nonartesian-water resources of the Roswell basin. A discussion of the geology and ground water of the basin was included as a part of the comprehensive study of the Pecos River system (Theis and others, 1942). Bean (1949) made an intensive study of the Hondo Reservoir. Theis (1951) reported on the effects of storing floodwater in the Hondo Reservoir. Hendrickson and Jones (1952) discussed the geology and ground-water resources of Eddy County, which includes the southern part of the Roswell basin. Hantush (1955) presented quantitative estimates of the amount of recharge and discharge, ground water in storage, and perennial yield for the Roswell basin. Hood, Mower, and Grogin (1959) pointed out that saline water in the artesian aquifer east of the Pecos River was encroaching westward toward areas in which artesian wells are pumped heavily for irrigation supply.

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WELL-NUMBERING SYSTEM

The system of numbering wells in New Mexico is based on the land-survey system of the Federal Government. The well number, in addition to designating the well, locates its position to the nearest 10-acre tract in the land net. The first segment of the well number denotes the township, the second denotes the range, the third denotes the section, and the fourth denotes the location within the section. In the project area, townships are north and south of the base line and east of the principal meridian; however, all the wells discussed in this report are in townships south of the base line.

The fourth segment of the number, which consists of three digits, with a lowercase letter sometimes added, denotes the particular 10-acre tract in which the well is situated. For this purpose, the section is divided into four quarters, numbered 1, 2, 3, and 4 in the normal reading order for the northwest, northeast, southwest, and southeast quarters respectively. The first digit of the fourth segment gives the quarter section, which generally is a tract of 160 acres. Similarly, the quarter section is divided into four 40-acre tracts numbered in the same manner, and the second digit denotes the 40-acre tract. Finally, the 40-acre tract is divided into four 10-acre tracts, and the third digit denotes the 10-acre tract. Thus, well 11.25.13.344 in Chaves County is in the SE¼SE¼SW¼ sec. 13, T. 11 S., R. 25 E. If the well cannot be located accurately within a 10-acre tract, a zero is used as the third digit, and if it cannot be located accurately within a 40-acre tract, zeros are used for both the second and the third digits. If the well cannot be located more closely than the section, the fourth segment of the well is omitted. When it becomes possible to locate more accurately, a well in whose number zeros have been used, the proper digit or digits are substituted for the zeros. Lowercase letters a, b, c, and so on are added to the last segment to designate the second, third, fourth, and succeeding wells investigated in the same 10-acre tract. The following diagram shows the method of numbering the tracts within a section (fig. 1).

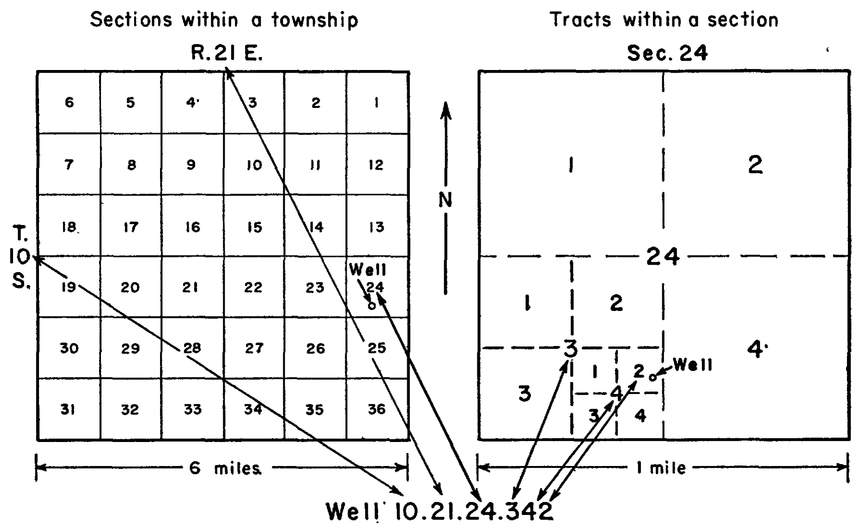

FIGURE 1.—System of numbering wells in New Mexico.

TOPOGRAPHY

The project area is characterized by mountains along much of the western margin, a bedrock surface that dips gently eastward from the crest of these mountains, and a relatively flat alluvial plain near the Pecos River. (See pl. 1.) The average altitude at the crest of the Sacramento Mountains is about 9,000 feet; however, individual peaks rise considerably higher. The altitude of the highest peak, Sierra Blanca, is about 12,000 feet. The lowest point in the project area, at an altitude of about 3,300 feet, is where the Pecos River crosses the southeastern boundary of the Roswell basin.

The broad alluvial plain in the eastern part of the project area is referred to in this report as the lowland area, and the rocky slope that descends from the crest of the mountains on the west to the lowland area is referred to as the upland area. (See pl. 2.)

LOWLAND AREA

The lowland area is characterized by three constructional terraces named the Lakewood, the Orchard Park, and the Blackdom Terraces by Fiedler and Nye (1933, p. 10, pl. 4).

The Lakewood terrace is a flat plain adjacent to the Pecos River and is 10–25 feet above the bed of the river. Parts of this terrace are inundated when the Pecos River is in high flood stage, and the terrace is commonly referred to as river-bottom land. The water table is at a shallow depth beneath most of the terrace, and much of the terrace is covered by a lush growth of water-loving vegetation.

The Orchard Park terrace extends as a strip along the west side of the Lakewood terrace and for considerable distances westward along the valleys of the major tributaries. The terrace rises 5–10 feet above the Lakewood terrace, and it has an eastward slope of 20–30 feet per mile. Almost all the irrigated fields of the Roswell-Artesia sector are on the Orchard Park terrace.

The Blackdom terrace rises 30–50 feet above the Orchard Park terrace, and it has an eastward gradient of 30–40 feet per mile. It is the most dissected of the constructional terraces because of its greater age. The relief is generally 20–35 feet. Low rolling hills generally capped by resistant caliche are characteristic of many parts of the terrace. The caliche cap and the deposits underlying the Blackdom terrace are excently exposed in a cliff along the Rio Felix in the NW¼ sec. 21, T. 14 S., R. 23 E.

UPLAND AREA

In this report the upland area is divided into five areas or surfaces: Sacramento plain, Diamond A plain, upland surface of the Guadalupe Mountains, embayment plain, and Vaughn-Macho plain. These are shown on plate 1 and are referred to as geomorphic surfaces because the division of the upland area was based on the similarity in land forms and their geologic history. Fiedler and Nye (1933, p. 13–14) described only three surfaces in the upland area; from highest to lowest, they are: Sacramento plain, Diamond A plain, and gravel-capped mesas. In this report the gravel-capped mesas are included in the embayment and Vaughn-Macho plains.

SACRAMENTO PLAIN

Remnants of an ancient surface cut mainly on carbonate rocks of the San Andres Limestone occur near the crest of the Sacramento Mountains. Fiedler and Nye (1933) referred to this surface as the

Sacramento plain. Near the crest of the mountains, the major streams are entrenched more than 800 feet below the surface of the plain. In places the plain is indistinct because of its advanced stage of dissection and because of structural deformation. The eastern limit of the Sacramento plain was not shown in figure 1 north of the Rio Ruidoso because the plain could not be identified.

The altitude of the plain ranges from 8,400 to 8,500 feet from Ruidoso southward to Cloudcroft. In this area the plain is flat. South of Cloudcroft the altitude of the plain ranges from 9,200 to 9,600 feet along the crest of the mountains and decreases eastward about 70–75 feet per mile to an altitude ranging from 8,200 to 8,600 feet along the eastern margin of the plain.

DIAMOND A PLAIN

A peneplain that now exists only as a few remnants preserved on the tops of the higher hills and interstream valleys was referred to as the Diamond A plain by Fiedler and Nye (1933, p. 14). The area shown as the Diamond A plain on plate 1 was once covered by a part of that peneplain.

The area is well dissected and has a well-integrated drainage system. The interstream divides are generally sharp; however, a few small divides are flat. The surface of the plain ranges from an altitude of about 7,500 feet on the west side to about 4,000 feet on the east side.

In general, the plain is cut on the San Andres Limestone; however, in places the bedrock surface is masked by a thin mantle of soil, gravel, and boulders. Sinkholes, formed by the solution of the underlying rocks by surface and ground waters, are common on the Diamond A plain, although not as numerous as in other parts of the project area.

UPLAND SURFACE OF THE GUADALUPE MOUNTAINS

The upland surface of the Guadalupe Mountains is an erosional surface bounded on the west by a prominent escarpment called The Rim, which forms the western slope of the Guadalupe Mountains, and on the east by a less prominent break in topography that marks a monocline. (See Huapache structural zone in pl. 1.) The surface between The Rim and the monocline is a tableland characterized by broad swales and rolling divides. The altitude of the tableland ranges from about 6,000 feet at The Rim to less than 5,000 feet at the monocline. Canyons are incised in the tableland, some to depths of more than 600 feet. The surface of the tableland cuts across several geologic formations. The missing strata for the most part consisted of rock that was more easily eroded than the present limestone surface.

EMBAYMENT PLAIN

The embayment plain, as referred to in this report, consists of two separate units. (See pl. 1.) The larger unit, in the southern part of the project area, is characterized by shallow swales and gently rounded hills, which trend northeast, and commonly has less than 50 feet of relief. The altitude of the land surface in the embayment plain ranges from 4,500 to 3,200 feet. The hills are capped by rock, generally dolomite, that is more resistant to erosion than the underlying gypsum and sandy and silty red beds. Some sinkholes have formed within the swales. Many of the swales have no exterior surface drainage.

The smaller unit of the embayment plain is mainly in Tps. 15 and 16 S., R. 23 E. In this area the plain is capped by gravel, which forms a protective cover for the underlying rocks, and is one of the areas referred to by Nye (Fiedler and Nye, 1933, p. 13) as gravel-capped mesas.

VAUGHN-MACHO PLAIN

The Vaughn-Macho plain is cut on soft and easily erodible rock. The plain is characterized by low rolling hills, swales, large closed depressions, and sinkholes. Sinkholes and depressions are more numerous in this area than in other parts of the Roswell basin. Drainage channels are poorly formed, except in the eastern and southern parts of the plain because the runoff is to sinkholes and closed depressions. The altitude of the plain ranges from 3,500 to 6,500 feet.

SINKHOLES AND CLOSED DEPRESSIONS

Sinkholes and closed depressions (depressions having no external surface drainage) are common. A few were studied in detail, but many were only reconnoitered.

Some sinkholes resemble shallow basin and range from a few feet to several hundred feet across the top. The depths of the floors of most sinkholes range from 10 to 50 feet below the land surface, although some are more than 50 feet deep. The bottoms of most sinkholes are covered with silt, clay, and rock rubble. Some have no visible openings through which water could drain; others have small cavelike openings in the sides and bottoms. Some are almost circular, whereas others are very irregular. The sides of some are almost vertical, and the sides of others slope gently from the rim to the bottom.

In places several sinkholes formed within a small area, and subsequent erosion destroyed the rock barrier between them and formed a single large irregularly shaped depression. Some of these depressions are as much as 1 mile across.

Ephemeral ponds and small lakes appear in some sinkholes and closed depressions in the upland area after rains. The water stands until evaporated in sinkholes whose bottoms are impermeable. In sinkholes having permeable bottoms, the water drains underground before much is lost by evaporation.

Permanent ponds and lakes occupy some sinkholes in the lowland near the Pecos River. The water surface in some of these coincides with the water table; in others the water surface is above the water table and indicates a probable connection with the artesian system.

The formation of sinkholes is described in this report in the section on structural features resulting from solution. The water-retaining and recharge characteristics of some sinkholes and depressions are described in the hydrology section of this report.

DRAINAGE

The Pecos River is the master stream of the area; it originates north of the Roswell basin and flows southward through the basin. The principal tributaries to the Pecos River from the eastern and southern parts of the Vaughn-Macho plain are Yeso Arroyo, Arroyo de la Mora, Cienega del Macho, and Salt Creek. North of the drainage divide in the northern part of the Vaughn-Macho plain, drainage is internal to sinkholes and closed depressions. (See pl. 1.) The principal tributaries draining the Sacramento and Diamond A plains and most of the lowland are the Rio Hondo, Rio Felix, Cottonwood Creek, Eagle Creek, and Rio Penasco. The principal tributaries draining the upland surface of the Guadalupe Mountains and the embayment plain are North, Middle, and South Seven Rivers and Rocky Arroyo.

Streams in the Roswell basin, including the Pecos River, are intermittent in much of their reaches in the basin. The Pecos River generally is dry in much of its reach between the northern limit of the Roswell basin and Salt Creek, principally because flow from upstream areas is controlled by Alamogordo Reservoir. Springs and seeps in the river channel and man-made drains in the irrigated area discharge to the river and maintain some flow in the reach of the river between Salt Creek and the southern limit of the basin. The Rio Hondo, Rio Penasco, and some of their tributaries are perennial in their upper reaches. The Rio Hondo, Rio Felix, Cottonwood Creek, and Rio Penasco are perennial near their confluence with the Pecos River.

Drainage and drainage patterns in the Roswell basin are related to the type of rocks in the basin and to structural and topographic features. The ancestral streams of the major tributaries draining the east slope of the Sacramento Mountains probably originated on a fairly smooth eastward-sloping plain, probably post-Cretaceous in age. As the streams flowed across this plain, they cut into it and helped erode the surface. Before this surface was completely eroded, streams had cut into the underlying Permian rocks, which form the present-day surface of the area, and the drainage patterns that

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had formed on the original surface were superimposed on the Permian rocks. The Rio Hondo and Rio Penasco are superimposed on the Sacramento and Diamond A plains, and the Rio Felix is superimposed on the Diamond A plain.

At places the Rio Penasco, Rio Hondo, and Rio Felix have been deflected by major structural and topographic features. The Rio Penasco flows northward for 3 miles along the Vandewart-Cornucopia structural zone (pl. 1), the Rio Hondo flows northward for several miles along the Sixmile Hill structural zone, and the Rio Felix flows northward along the Y–O structural zone for about 5 miles before turning eastward. Bean (1951, p. 5) stated that the major streams cross the Y–O, Border Hills, and Sixmile Hill zones at points of structural weakness that were topographically low. He also indicated that the Rio Hondo crosses the Border Hills zone where part of the flexure is offset to the west and where the displacement along faults is reversed with respect to upthrown and downthrown sides. Two alternate explanations can be advanced. After consequent drainage had been established and the post-San Andres rocks had been eroded, movement occurred along the structural zones. This temporarily disrupted the drainage and forced the streams to flow along the structural zone until an exit across the zone was reached at a topographic low. On the other hand, the streams may have been deflected in the following manner without antecedent movement: As the streams were incised into the bedrock, ground water was moving generally eastward and was dissolving large quantities of soluble gypsum. Ground water may have been deflected along the Sixmile Hill, Border Hills, and Y–O structural zones. The ground water would have formed permeable zones in the soluble gypsum along the flanks of the structures more easily than in the less soluble limestone in the anticlinal hills. Collapse of gypsum along the flanks of the zones may have deflected the streams into courses parallel to the structural zones.

After the principal superimposed drainage was established in the hard limestone, subsequent streams formed along the trends of both major and minor structural features. The following are examples of the subsequent drainage. A tributary to Blackwater Draw flows northeastward for several miles parallel to the Border Hills structural zone in Tps. 10–11 S., Rs. 20–21 E. A tributary of the Rio Hondo parallels the Border Hills zone for 5 miles in T. 12 S., Rs. 19–20 E. (pl. 1). Tributaries of the Rio Penasco and Bluewater Creek flow for several miles along the Vandewart-Cornucopia zone. Soon after the establishment of subsequent drainage, a well-integrated pattern of resequent and obsequent drainage was formed on the slopes. The subsequent, obsequent, and resequent streams have greatly dissected the

Sacramento and Diamond A plains; however the main structural and topographic trends have not been obliterated. The trellis drainage pattern is typically formed on anticlines in the area.

In places the drainage pattern is not the same on the western and the eastern sides of the structural zones. For example, along the Border Hills structural zone from Blackwater Draw in T. 10 S., R. 21 E., to the northwestern part of T. 13 S., R. 19 E., the drainage west of the structural zone consists of numerous shallow drainage lines, whereas east of the zone the drainage consists of a few deeply incised drainage lines. The difference in drainage patterns reflects the difference in size of the drainage areas west and east of the structural zone.

CLIMATE

The Roswell basin is semiarid. Precipitation is scant but falls mainly in summer, relative humidity is low, daily temperature fluctuations are large, and most of the days are clear and sunny. The average annual rainfall at Roswell, which is in the lowland area, is about 12 inches. In the period 1878–1959 the annual precipitation at a weather station in Roswell ranged from 32.92 inches in 1941 to 4.35 inches in 1956. Precipitation is greater in the upland area than in the lowland area; the average annual precipitation is 15 inches at Picacho, 19 inches at Mayhill, 21 inches at Ruidoso, and 26 inches at Cloudcroft.

More than 50 percent of the annual precipitation at Roswell occurs as showers and thundershowers between July 1 and September 30. Summer temperatures in the lowland are high and at times, from May to September, exceed 100°F. The average annual temperature at Roswell is 59.5°F. Average monthly temperatures range from 41°F in December to 83°F in July. The high temperatures and low humidity in combination with a high rate of wind movement cause high rates of evaporation. The evaporation for 1958 was 86.14 inches at Bitter Lake National Wildlife Refuge and 98.41 inches at Lake Avalon. Precipitation and evaporation data for the years 1957–59 are given in table 1 for selected stations in the Roswell basin.

VEGETATION

The study of vegetation is of considerable help in delineating which sinkholes, depressions, flood plains, and other areas are covered with water infrequently and which are covered with water frequently. Areas that are frequently covered with water have a darkened appearance when viewed from the air and are green if water has covered them recently and the vegetation has has benefited from the moisture. The areas appear black if water has not covered the area for a considerable time and the vegetation is dead or dormant.

TABLE 1.—*Climatological data from selected stations in the Roswell basin, Chaves and Eddy Counties, N. Mex.*

[Compiled from U.S. Weather Bur. records]

Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Precipitation, in inches, at Roswell													
Long term mean	0.42	0.46	0.53	0.75	1.28	1.47	1.81	1.45	2.00	0.98	0.39	0.53	12.07
1957	.09	.64	.80	.31	.43	.06	.87	1.23	1.18	2.91	.80	.00	9.32
1958	1.57	.84	1.93	.84	.77	.20	.66	1.27	3.56	.98	.19	.25	13.06
1959	.02	.10	.03	.59	1.44	.82	2.98	1.87	.16	.52	.24	.75	9.52
Evaporation, in inches, at Bitter Lake National Wildlife Refuge													
1957	2.88	3.82	7.32	9.10	11.39	14.70	15.02	11.94	8.91	5.09	2.24	3.32	95.73
1958	2.26	3.74	3.61	9.54	10.66	13.50	13.78	11.69	7.97	3.77	3.24	2.38	86.14
1959	2.81	3.91	8.50	8.91	12.30	12.72	11.26	10.42	9.08	4.96	3.65	2.36	90.88
Evaporation, in inches, at Lake Avalon													
1957	4.87	5.24	9.15	11.51	13.59	14.73	15.77	13.38	10.47	5.73	3.33	4.04	111.81
1958	3.20	4.88	5.37	11.25	12.26	14.72	14.36	12.65	7.48	4.77	4.10	3.37	98.41
1959	4.02	5.17	9.56	9.62	12.35	11.23	10.66	10.82	9.77	6.05	4.34	3.17	96.76

Quick-growing plants can thrive in depressions and sinkholes that contain water for short periods of time, even in those depressions that receive water infrequently, possibly once every few years. Some of the quick-growing plants of the area are pigweed (*Amaranthus* sp.), ragweed (*Ambrosia* sp.), lambs quarter (*Chenepodium alba*), kochia (*Kochia scoparius*), and russian thistle (*Salsola pestifer*).

Flood plains of some of the tributaries of the Pecos River and some sinkholes receive enough water every year to support perennial plants. Some of the perennial plants are tobosa grass (*Helaria mutica*), buffalo grass (*Buchlolo dactylordes*), burro grass (*Sclerapogon brevifolious*), cholla cactus (*Opuntia arborescens*), bitterweed (*Hymenoxys odacata*), and creeping muhly (*Muhlenburgia repens*). Phreatophytes such as saltcedar (*Tamarix gallica*) and mesquite (*Prosopes juliflora*) grow along the flood plain of the Pecos River and the lower reaches of some tributaries.

Sacaton (*Sporobolus wrightii*) and alkali sacaton (*Sporobolus anoides*) are perennial plants that formerly were common in southeastern New Mexico. Sacaton grew abundantly along many of the flood plains and in some sinkhole areas. In these areas, other native grasses such as blue gramma (*Bouteloua gracilles*) also were abundant. The dense growths of high native grasses not only retained much of the runoff but also collected considerable amounts of silt and prevented erosion. Overgrazing by cattle and sheep resulted in the removal of the protective ground cover at many places. The sacaton, alkali sacaton and blue gramma grasses have been replaced by shorter grasses, such as buffalo grass, that have shallower and weaker root systems.

Runoff has increased in some of the tributaries, channels have deepened and gullies have formed as a result of overgrazing and changes in grass cover. The deepened channels and gullies date from the late 1800's when grazing began in the Roswell area. Flood water flows in the deeper channels in some streams rather than over the shallow flood plains. The result is not only increased erosion and gullying but also a decreased amount of growth of forage plants. A decrease in frequency of rainfall (Leopold, 1951) could also account for the modern epicyle of erosion. Leopold believed that the decrease in the number of light rains reduced the vegetation cover and, in turn, resulted in less infiltration and greater runoff.

Hills as seen from the air commonly are lighter colored than nearby flatter areas owing to a sparser growth of plants such as creosote bush (*Larrea tridentata*). Also, the native blue and black gramma grass (*Bouteloua gracilles* and *Bouteloua eriopoda*) now are not as common as the lighter colored invading fluff grass (*Tredeus puclchellus*) and hairy tridon (*Tridens pelosus*) on the hilly areas. In the southern part of the project area, the beds of silt and sandstone along the hills can be traced readily on aerial photographs by vegetation. One of the common plants growing in the silt along the benches of limestones is the tar bush (*Flourencia* sp.).

Gyp gramma (*Bouteloua breviseta*) and gyp grass (*Sporobolus neeleyi*) are two common grasses growing in depressions underlain by gypsum.

GEOLOGY

In most of the project area consolidated rock at the surface and to a depth considerably below the bottom of the deepest water well consists chiefly of a complex accumulation of marine rocks of Permian age deposited in various environments (fig. 2). Consolidated rocks of the Triassic and Cretaceous age crop out in a small area; however, they are unnecessary for this report because they do not have an appreciable potential for additional recharge.

Unconsolidated gravel, sand, and silt deposited by the Pecos River and its tributaries in the Tertiary and Quaternary Periods overlie the stratified bedrock with profound unconformity. These alluvial deposits are only a veneer on the Permian rocks in most of the upland area but range in thickness from a fraction of a foot to more than 300 feet in the lowland area.

ROCKS OF PERMIAN AGE

The rocks of Permian age that crop out in the Roswell basin comprise the Yeso Formation (the stratigraphically lowest formation that

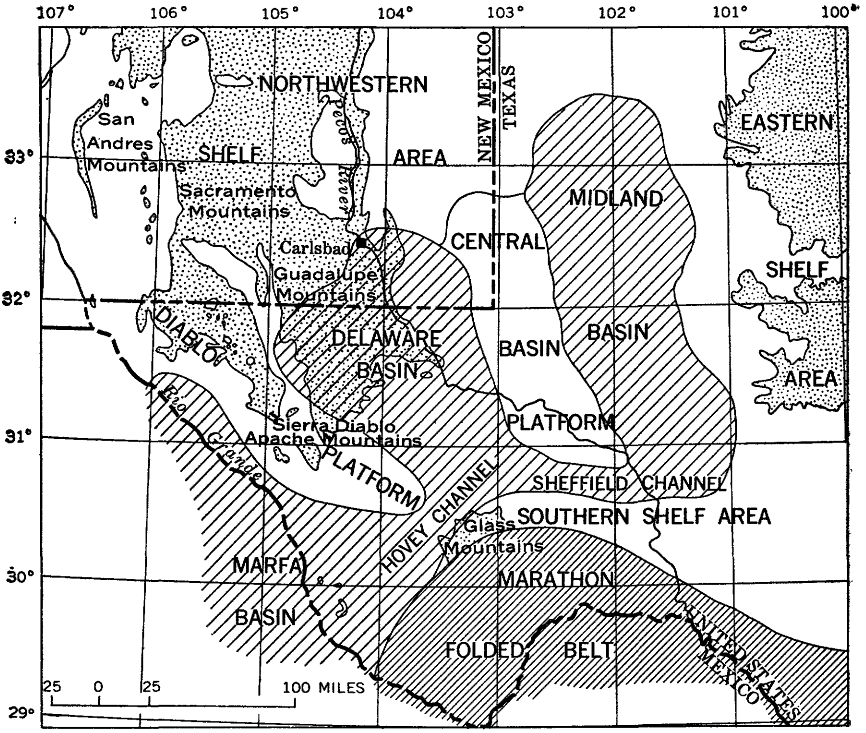

FIGURE 2.—Structural provinces during Permian time in southeastern New Mexico and western Texas. The wide-spaced slanted lines delineate the basins, and the close-spaced slanted lines delineate the area of deformed pre-Permian rocks; the remaining areas are shelf and platform provinces. The stippled areas delineate outcrops of Wolfcamp, Leonard, Guadalupe, and Ochoa Series of Permian age, and their equivalents (after King, 1948, p. 25).

is an aquifer on the east slope of the Sacramento Mountains), the San Andres Limestone, and the Artesia Group. The Artesia Group includes the carbonate and evaporate facies of the back-reef deposits of the Guadalupe Series. The Guadalupe Series in southeastern New Mexico is characterized by four major facies: a basin facies consisting of quartzose sandstone interbedded with limestone which was deposited in the deep waters of the Delaware basin southeast of Carlsbad; a reef facies consisting of massive limestone of the reef complex of Guadalupe age; a carbonate facies consisting of carbonate rocks interbedded with sandstone which was deposited landward from the reef complex of Guadalupe age in back-reef waters; and an evaporite facies consisting of gypsum, anhydrite, and other evaporite rocks interbedded with red sandstone and shale which was also laid down in back-reef waters. Each of these rock types was deposited at the same time but in different environments.

YESO FORMATION

The Yeso Formation is the lowest stratigraphic unit of Permian age that crops out extensively in the Roswell basin. The Yeso is overlain by the Hondo Sandstone Member of the San Andres Limestone and underlain by the Abo Sandstone. It is exposed where the large tributaries of the Pecos River have cut deeply into the uplands of the Sacramento Mountains and where the overlying San Andres Limestone has been stripped from local uplifts (pl. 2).

The Yeso Formation in southeastern New Mexico consists of anhydrite and gypsum interbedded with sandstone, siltstone, shale, and carbonate rocks. Sandstone and siltstone become progressively more abundant in the formation northwestward across the Roswell basin. The formation contains salt beds in the subsurface near and east of the Pecos River. The lack of salt in the formation west of the Pecos River may be the result of solution by ground water. The removal of salt from the section also could account for the thinning of the Yeso Formation west of the river. The Yeso is about 1,800 feet thick in the Sacramento Mountains and more than 2,000 feet thick east of the Pecos River in the vicinity of Roswell.

The Yeso Formation on the east slope of the Sacramento Mountains consists of brown and yellow sandstone, siltstone, shale, limestone, and gypsum. The sandstone and siltstone which are cemented by calcium carbonate near the top of the Yeso, are similar in most respects to sandstone and siltstone in the Hondo Sandstone Member of the San Andres. Drill cuttings of the Yeso from a hole in the NE¼ sec. 10, T. 18 S., R. 21 E., consisted of light-greenish-gray shale, siltstone, mudstone, limestone, and anhydrite. The calcium-carbonate-cemented quartzose siltstone ranged from yellowish brown to light yellow. Much of the shale was dark gray, and some was black and had laminae less than 1 mm in thickness. Cuttings from well 7.20.16.333, PVACD 1 (Pecos Valley Artesian Conservancy District), show the upper 235 feet of the Yeso Formation to consist principally of yellow and red sandstone and siltstone, some white chalky gypsum, and light-gray-brown anhydrite containing minor amounts of claystone (Crawford and Borton, 1961, p. 263–269).

The Yeso Formation is the most extensive aquifer in the area. The permeability of the Yeso is low, especially where the formation underlies the San Andres Limestone. Ground water is in the coarser grained siliceous clastic rocks and in solution channels in the carbonate rocks and evaporite rocks. The sandstones and siltstones are confining beds where they are cemented by calcium carbonate. Perched water on top of these impermeable sandstone beds discharges as springs where canyons cut into the Yeso Formation in the Sacramento Mountains. Wells generally tap the Yeso Formation west of R. 21 E., and most of them yield less than 10 gpm (gallons per minute). The water in the Yeso is potable to impotable but is generally suitable for stock use.

SAN ANDRES LIMESTONE

The Hondo Sandstone Member, the basal unit of the San Andres Limestone, is generally defined as a sandy unit that is overlain by carbonate rock of the San Andres Limestone and underlain by the gypsum and red siltstone of the Yeso Formation. Locally it is difficult to distinguish the Hondo from the Yeso and the upper part of the San Andres; for example, on the east slope of the Sacramento Mountains, sandstones similar to those of the Hondo occur in a zone about 150 feet thick in the overlying parts of the San Andres Limestone.

The Hondo Member is exposed in canyons on the east slope of the Sacramento Mountains where the tributary streams of the Pecos River have cut deeply into the Permian Rocks. This member is mapped with the San Andres Limestone on pl. 2.

In a well in the NE¼ sec. 10, T. 18 S., R. 21 E., the Hondo Sandstone Member consists of three units: an upper yellow-orange quartzose-sandstone unit 20 feet thick, a middle siltstone unit 10 feet thick, and a lower sandstone unit 10 feet thick. The upper sandstone unit is composed of fine- to medium-grained well-rounded sand cemented with calcium carbonate; however, many of the grains are poorly cemented. The lower part of this unit contains considerable amounts of silt. The siltstone unit is light yellow to yellow brown and is cemented with calcareous cement. The lower sandstone unit is silty and generally light yellow brown and is interbedded with some light-gray shale.

The Hondo Sandstone Member of the San Andres is about 150 feet thick in the upper reach of the Rio Hondo and consists of an upper quartzose sandstone unit 40 feet thick; a middle silty limestone, siltstone, gypsum, and anhydrite unit 90 feet thick; and a lower quartzose sandstone unit 20 feet thick (W. A. Mourant, oral communication, July 1958). The quartzose sandstone typically consists of sand that is well rounded and well sorted and has an average grain size ranging from medium to coarse on the Wentworth scale. In places it contains considerable silt. The sand generally is reddish brown owing to a coating of limonite on the grains. Where the Hondo is adjacent to intrusive rocks, the sandstone may have been metamorphosed to quartzite.

The Hondo Sandstone Member is an aquifer in large areas of the east slope of the Sacramento Mountains. Its water-yielding properties are variable, and it may be a confining bed where the member is very silty. In parts of the embayment plain in Tps. 20, 21, and 22 S., the upper sandstone of the Hondo forms the lower confining bed for water in the overlying part of the San Andres Limestone. Wells generally tap the Hondo Sandstone Member west of R. 21 E., and most of them yield less than 10 gpm. The water from these wells is chemically suitable for livestock and domestic use.

The San Andres Limestone above the Hondo Member is the most widely exposed stratigraphic unit in the area of investigation and caps large areas of the Sacramento and Guadalupe Mountains. North and west of the town of Artesia, the upper part of the San Andres Limestone grades laterally into evaporite rocks.

The upper part of the San Andres Limestone is overlain by the Artesia Group and underlain by the Hondo Sandstone Member and Yeso Formation. The San Andres–Artesia Group contact used in this report is a carbonate rock–sandstone contact, as mapped by Hayes and Koogle (1958). The contact between the upper part of the San Andres Limestone and Hondo Sandstone Member is also a carbonate rock–sandstone contact, and it is exposed in the deeper ravines in the Sacramento and Guadalupe Mountains.

Rocks of the carbonate facies of the San Andres Limestone have not been studied in detail, but dolomitization in the upper part of the carbonate facies is probably similar to that in the carbonate facies of formations of late Guadalupe age in the southern Guadalupe Mountains (Newell and others, 1953, p. 131–140) and the northern Guadalupe Mountains (Motts, in Bjorklund and Motts, 1959, p. 58–61). Bean (1949, p. 13) pointed out that the upper part of the carbonate facies of the San Andres Limestone has a greater amount of dolomite than the lower part. The relationship of the upper dolomite to the lower limestone is shown on plate 3. Thin bedding is more common in the upper part than in the lower part. Fiedler and Nye (1933, p. 64–70) and Bean (1949, p. 9–14) noted and described the "worm-eaten" or "honeycombed" appearance of the upper part of the San Andres Limestone. This appearance is characteristic of rocks of the carbonate facies where they are subjacent to evaporite rocks of the San Andres and younger rocks.

The vacillating front between the areas of deposition of carbonate and evaporite rocks of the San Andres Limestone resulted in the interbedding of evaporite rocks and dolomitic rocks, particularly north and west of Roswell. Test holes in the NW¼ sec. 33, T. 4 S., R. 21 E., penetrated numerous beds of anhydrite and gypsum interbedded with dolomite.

Variations in thickness of the carbonate facies of the San Andres Limestone are rather consistent. The carbonate facies decreases in thickness to the north and west at right angles to the regional facies changes. However, some anomalies occur west and southwest of Roswell. A study of well logs compiled by Crawford and Borton (1961) indicates that the San Andres Limestone above the Hondo Member is

243 feet thick in well 13.20.13.22 (PVACD 4), 380 feet thick in well 11.21.18.333 (PVACD 8), and 500 feet thick in well 10.21.16.222 (PVACD 3). The apparent differences in thickness may result from the presence of lenses of sandstone in the lower part of the San Andres Limestone or from local structural deformation and truncation.

Intraformational breccias or rubble zones (pl. 3) are common in the San Andres Limestone. The breccias consist of tilted and rotated blocks of carbonate rocks as much as 2 feet in diameter in a silt matrix. The breccias probably formed when the Permian seas withdrew temporarily and left the topographically high areas subject to erosion. Many of the large cavernous openings in the San Andres are in the brecciated zones. A terrace generally has formed where the brecciated beds are exposed. Weathering by slope retreat eroded the weaker beds of breccia and formed a bench on the underlying hard carbonate rocks. The "worm-eaten" and "pinhead" type of porosity is more common in the San Andres Limestone than in the stratigraphically higher carbonate rocks of the Guadalupe Series. The size of openings ranges from that of a pinhead to more than 1 foot in diameter. Many of the openings are interconnected.

The carbonate rocks of the San Andres Limestone are highly permeable in many areas west of the Pecos River and readily yield water to wells. In the Roswell-Artesia cultivated sector, the yields of irrigation wells generally range from 40 to 70 gpm (gallons per minute) per foot of drawdown, and the average discharge is about 1,300 gpm.

Water in the San Andres Limestone in the recharge area and in most of the cultivated area is low in dissolved solids and is generally potable. Adjacent to and east of the Pecos River, the water in the San Andres is saline.

ARTESIA GROUP

The Artesia Group extends from the top of the Tansill Formation to the base of the Grayburg Formation and includes (in descending order) the Tansill, Yates, Seven Rivers, Queen, and Grayburg Formations. The formations of the Artesia Group crop out as easily identifiable formational units immediately outside the southeastern margin of the Roswell basin. The Tansill, Yates, and Seven Rivers cannot be identified as separate formations in the Roswell basin, and equivalents of these formations may be absent in the basin. The Queen Formation crops out as an identifiable unit only in the extreme southeastern part of the basin. The Grayburg Formation crops out in the southeastern part of the basin and, through a facies change to the northwest, becomes an evaporite unit along a line extending from about Dayton toward Texas Hill. Recharge to the Queen, in large part, moves from the Roswell basin. The Queen, being of limited hydrologic importance to the Roswell basin, does not warrant a detailed discussion in this report.

For the purposes of this report, the name Artesia Group will be used where the formations are well defined, and the name Artesia Formation will be used where the units are not separable. The Artesia Formation as used in this report includes the evaporite facies of the Artesia Group, may include the evaporite rocks of the San Andres Limestone, and is the equivalent to the Chalk Bluff Formation of former usage.

GRAYBURG FORMATION

The Grayburg Formation, as defined from exposures, is a thick accumulation of interbedded dolomite and sandstone that occupies the interval between the Queen Formation and the San Andres Limestone. It is a rock sequence about 435 feet thick (Hayes and Koogle, 1958) that differs lithologically from the Queen Formation and the San Andres Limestone, and its carbonate facies grades into evaporite rocks farther west than does the carbonate facies of the Queen.

The Grayburg is exposed in the project area in T. 21 and 22 S., Rs. 22 and 23 E., and Tps. 19 and 20 S., Rs. 23 and 24 E. North and west of the carbonate-evaporite facies boundary, the formation grades abruptly into exaporite rock which consists chiefly of gypsum and forms the basal part of the evaporite facies of the Artesia Formation.

The carbonate facies of the Grayburg Formation consists of interbedded sandstone and carbonate units. The Grayburg contains rubble zones (pl. 3), but they are not as common as in the San Andres Limestone. Many of the sandstone beds in the lower part of the Grayburg Formation can be traced only short distances. The interbedded reddish-brown siliceous sandstone units in places show fluvial cross bedding.

Bjorklund and Motts (1959, p. 92) concluded that the Grayburg Formation has two aquifers. The aquifers are beds of dolomite separated by relatively impervious beds of sandstone. How far north into the Roswell basin the two aquifers extend is conjectural. Bjorklund and Motts (1959, fig. 26) indicated that water in the upper aquifer moves east toward Carlsbad and that water in the lower aquifer and underlying San Andres Limestone moves northeast toward Lakewood. A large amount of ground water moves into the Grayburg from the San Andres west and southwest of Artesia.

Stock and domestic wells in the Grayburg in the outcrop area generally yield from 5 to 10 gpm. Irrigation wells in the Grayburg in the vicinity of Artesia yield as much as 1,000 gpm.

The total dissolved-solids content in water in the Grayburg in the outcrop area ranges from 300 to 400 ppm. Northeast and east of Artesia the dissolved-solids content may be greater than 1,000 ppm (J. W. Hood, oral communication, 1960).

ARTESIA FORMATION

The Artesia Formation (Chalk Bluff Formation of former usage) crops out in the vicinity of Hope, between Eagle and Walnut Creeks, and in a large area north of Roswell. (See pl. 2.) The formation underlies much of the alluvium along the Pecos River and, in part, forms the upper confining bed for the artesian water in the San Andres Limestone.

The formation ranges in thickness from about 1,500 to 1,800 feet in the subsurface east of the Pecos River. West of the river its thickness is considerably less, owing to erosion and to solution of the evaporite rocks.

The Artesia Formation is chiefly gypsum and anhydrite interbedded with red siltstone and sandstone. The lithologic characteristics of the formation vary with stratigraphic position. For example, in the upper and middle parts of the formation, the equivalents of the Yates and Queen Formations contain more sand and silt than do the equivalents of the Tansill and Seven Rivers Formations. The Artesia Formation is poorly resistant to erosion. Exposures are poorly preserved and show evidence of considerable solution by ground water.

The Artesia Formation is highly permeable at some places and poorly permeable at others. It commonly is highly permeable in its outcrop because ground water has dissolved large amounts of gypsum along interconnected solution channels. The formation generally is poorly permeable where it underlies several feet of alluvium. Ground water under artesian head in the underlying San Andres Limestone rises through the Artesia Formation and slowly dissolves the gypsum but leaves the silt and sand behind. This process of selective removal results in a relatively impermeable silt and sand blanket that retards the movement of ground water. The wide range in permeability of the formation is reflected by the yield of its wells. Wells that produce water where the permeability is low yield only a few gallons per minute; but wells in the highly permeable areas yield as much as 1,000 gpm (J. W. Hood, oral communication, 1959). The water generally is impotable because of the high dissolved-solids content, and in some places it is unsuitable for irrigation.

ROCKS OF MESOZOIC AGE

Rocks of Triassic and Cretaceous age are in the Ruidoso-Capitan area. (See pl. 2.) The rocks of Triassic age are the Dockum Group. In the study area the Dockum Group includes a lower unit probably equivalent to the Santa Rosa Sandstone and an upper unit probably equivalent to the Chinle Formation. The Santa Rosa equivalent is about 295 feet thick (Allen and Jones, 1951) and consists mostly of interbedded sandstone, siltstone, and minor amounts of chert pebble conglomerate. The Chinle equivalent is about 180 feet thick (Allen and Jones, 1951) and consists of interbedded shale, siltstone, and mudstone. The rocks of Cretaceous age include the Dakota Sandstone, the Mancos Shale, the Mesaverde Group, and possibly the Cub Mountain Formation of Bodine (1956). The Dakota Sandstone, which is about 135 feet thick, is chiefly quartzose sandstone and interbedded shale. The Mancos Shale is about 390 feet thick and consists of interbedded shale and limestone. Bodine (1956, p. 6) divided the Mesaverde Group into three units: a lower sandstone unit about 156 feet thick, a middle shale unit about 275 feet thick, and an upper sandstone unit about 60 feet thick. The Cub Mountain Formation of Bodine (1956) is at least 500 feet thick in the Capitan area (Bodine, 1956, p. 8–11) and is sandstone interbedded with some conglomerate, shale, and clay. According to Bodine, the Cub Mountain Formation may be either Late Cretaceous or early Tertiary in age.

In the general area of Ruidoso, Capitan, and Carrizozo, the rocks of Triassic and Cretaceous age are preserved in a synclinorium that has been perforated by igneous intrusions. South of the synclinorium on the Sacramento plain, rocks of Triassic and Cretaceous age have been removed by erosion except for a small area of rocks of Cretaceous age in Tps. 14–15 S., R. 13 E. (Pray and Allen, 1956). Little is known about the water-bearing characteristics of the rocks of Triassic and Cretaceous age because only a few wells have been drilled in them (W. A. Mourant, oral communication, 1959). Artificial recharge to these rocks would not be effective recharge to the Roswell-Artesia sector of the Roswell basin.

ROCKS OF TERTIARY AND QUATERNARY AGE

Unconsolidated and some consolidated gravel, sand, and silt of Tertiary and Quaternary age compose the alluvium (pl. 2) of the project area. Small thin deposits of gravel at places on the Diamond A plain and on the higher surfaces of the Sacramento plain of the upland area are of Tertiary or Quaternary age. The well-cemented conglomerate, gravel, sand, and clay on the gravel-capped mesas were called limestone conglomerate by Nye (Fiedler and Nye, 1933, p. 38). The limestone conglomerate caps hills and mesas near Melena in the extreme southeastern part of the Vaughn-Macho plain and along Eagle and Cottonwood Creeks north of Hope in the northern segment of the embayment plain.

The consolidated gravel, sand, and silt underlying the younger alluvium of the Blackdom, Orchard Park, and Lakewood terraces of the lowland area was called quartzose conglomerate by Nye (Fiedler and Nye, 1933, p. 35–37). Nye pointed out that the quartzose conglomerate generally is well stratified, firmly cemented, and, in some places, deformed; whereas the younger material is commonly structureless, unconsolidated, and undeformed. Nye considered the limestone conglomerate of the upland area to be younger than the quartzose conglomerate in the lowland area; however, Morgan (1938) considered the two deposits to be the same age.

Morgan (1938, p. 17) estimated that the thickness of the alluvium ranges from a few feet to more than 300 feet and averages about 150 feet in the cultivated part of the basin. Thicknesses greater than 300 feet have been reported. Oil-test wells in secs. 25 and 27, T. 17 S., R. 26 E., reportedly penetrated about 900 feet of alluvium—an unusually thick sequence for the Roswell basin. This excessive thickness may be the result of incorrectly identifying a thick rubble bed of breccia in the Artesia Formation as alluvium. Fielder and Nye (1933, p. 35) wrote that the maximum thickness of the deposits of the Blackdom terrace where they are exposed is at least 80 feet and may be considerably more. Morgan (1938, p. 14), however, believed that the actual thickness of the Blackdom sediments probably is less than 20 feet and that the 80-foot thickness ascribed to the deposits by Nye includes material belonging to the underlying quartzose conglomerate. Morgan considered that the thickness of the deposits underlying the Orchard Park terrace ranges from a few feet to 20 feet. The deposits underlying the Orchard Park terrace are flood-plain and channel deposits of the Pecos River and its tributaries and consist of beds of interfingering gravel, sand, and silt. The deposits underlying the Lakewood terrace are generally similar to those underlying the Orchard Park terrace and range in thickness from a few feet to about 25 feet. The alluvium in the lowland area is second to the main aquifer as a source of water to irrigation wells in the basin.

IGNEOUS AND METAMORPHIC ROCKS

Intrusive and extrusive igneous rocks are mostly in the northern part of the Sacramento Mountains (pl. 2). The Sierra Blanca and Capitan Mountain area were sites of extensive igneous activity. The Sierra Blanca extends about 20 miles north of the Sacramento Mountains and consists of a complex of intrusive and extrusive rocks. The Capitan Mountains are about 20 miles long and extend eastward from the north end of the Sierra Blanca. The Capitan Mountains are composed chiefly of microgranite. Pajarito Mountain, an intrusive mass on the east slope of the Sacramento Mountains (pl. 2), in T. 12 S., Rs. 15–16 E., is composed mainly of syenite (which crops out in an area slightly more than 1 mile square). The crystalline rocks of the Pajarito Mountain area are intrusive rocks of Tertiary age.

These igneous rocks have no apparent potential for artificial recharge.

GEOLOGIC STRUCTURE

Major geologic structures in the project area trend northwestward, northward, northeastward, and eastward. The six major structural zones—zones along which joints, small faults, and flexures have a similar or parallel trend—are the Huapache, Fourmile, Vandewart-Cornucopia, Border Hills, Sixmile Hill, and Y–O structural zones. (See pl. 2.)

NORTHWESTWARD-TRENDING FEATURES

The major structural features that trend northwestward are the Huapache structural zone (pl. 2) and the faults that delimit the west side of the Guadalupe Mountains. Structural features that trend northwestward can be traced into Tps. 19 and 20 S. where they intersect structural features that trend northward and eastward. The area of intersection is highly fractured and structurally complicated.

A prominent structural feature that forms an escarpment at the eastern boundary of the upland surface of the Guadalupe Mountains is a monocline (not mapped) in the Huapache structural zone. The axis of the monocline is parallel to major faulting to the west. The monocline is the result of deep-seated faulting in the Precambrian basement during pre-Abo time. Faulting in the Huapache structural zone probably was active in Late Pennsylvanian time and throughout Early Permian time.

More than 4,500 feet of Upper Mississippian and Pennsylvanian rocks are missing west of the monocline but are present east of the monocline. The Abo Sandstone and Yeso Formation are thin west of the monocline. The San Andres Limestone is 1,100 feet thick east of the monocline and 900 feet thick west of the monocline. Thinning of the San Andres Limestone might be attributed to faulting during Permian time; however, it may be the result of changes of facies in the San Andres between the carbonate and evaporite facies and subsequent erosion of the rocks of the evaporite facies. Removal of these rocks would produce the thinning of the San Andres.

The Guadalupe Mountains were elevated to their present topographic position in Tertiary time. The Permian rocks in that area dip to the northeast as a result of the uplift. The northeastward dip controls the surface drainage and the movement of ground water in that area.

NORTHWARD-TRENDING FEATURES

Large structural features that trend northward are the faults at the west edge of the Sacramento Mountains (west of area mapped in pl. 2) and the Vandewart-Cornucopia structural zone. The eastward dip of the rocks of Permian age is the result of the uplift that raised the Sacramento Mountains to their present altitude. This eastward dip controls the surface drainage and the movement of ground water on the east side of these mountains.

The trend of the Vandewart-Cornucopia structural zone probably is related to deep-seated basement faulting. The trend is characterized by faults, folds, and numerous subsidiary structural features west and east of the major structural zone. West of the structural zone, in Tps. 16 and 17 S., several faults (not mapped) follow the trend of the zone. East of the structural zone, in Rs. 17 and 18 E., a series of gently dipping folds (dip 5° or less) parallel the trend of the zone. The limiting fold of this series crosses approximately through the eastern half of Tps. 16 and 17 S., R. 18 E., and extends northward into Tps. 14 and 15 S., Rs. 19 and 20 E. The Manning anticline is at the northern end of the Vandewart-Cornucopia structural zone. (See pl. 2.)

NORTHEASTWARD-TRENDING FEATURES

The Border Hills, Sixmile Hill, and Y–O structural zones are major structures that trend northeastward. These structural zones consist of long linear sharply folded anticlines that pass into faults in places.

The Border Hills structural zone is marked by a prominent topographic ridge. On the west and east sides of the ridge, strata probably have buckled upward at places. Fielder and Nye (1933, p. 78) quote K. H. Crandall as saying that the Border Hills fault reverses itself at several places and that for a few miles south of the Rio Hondo the beds on the east side are downthrown relative to those on the west side. At most places, however, the beds on the west side of the zone appear to be downthrown in relation to the beds on the east side. West of the Border Hills structural zone and south of the Rio Hondo, several faults follow the trend of the structural zone. These faults are in a series of grabens and horsts.

The Sixmile Hill and Y–O structural zones are sharply folded and faulted anticlines that are not as well expressed topographically as the Border Hills structural zone.

The origin of the structural zones that trend northeastward probably is related to deep-seated basement faulting and to slipping along bedding planes in gypsum of the Yeso Formation during Tertiary time. The Huapache and the Y–O structural zones intersect at about right angles. West of the Huapache structural zone, Pennsylvanian strata are missing and Lower Permian strata have been thinned. West of the Y–O, Sixmile Hill, and Border Hills structural zones, the Pennsylvanian and Lower Permian strata seem to thin in steps. Basins formed during Pennsylvanian time trend northeastward and northwestward. These data suggest that the Huapache structural zone and the structural zones which trend northeastward may be related and possibly were active in Late Pennsylvanian and Early Permian time.

The uplift of the Sacramento fault block during Tertiary time produced an eastward-directed force on the east slope of the Sacramento Mountains, and the contraction and subsidence that resulted from cooling of the Capitan Mountains igneous mass may have produced a northeastward-directed force. These two forces may have resulted in slipping of the San Andres Limestone across the gypsiferous beds of the Yeso Formation. If slipping occured, the gypsum in the Yeso acted as a lubricant for movement of the carbonate rocks of the San Andres. The establishment of a water table in the Yeso Formation and the conversion of anhydrite to gypsum probably facilitated the movement. The movement probably was northeastward along old fault zones that formed in Pennsylvanian time. This movement in places caused buckling of both flanks of the linear sharply folded anticlines and caused thrusting of gypsum and sandstone of the Yeso and San Andres Formations toward the surface. There may have been a strike-slip movement also, and the western side of the slip moved northeastward relative to the eastern side.

The Border Hills, Y–O, and Sixmile Hill structural zones seem to be areas of high permeability. The fracturing, buckling, and dislocating of the bedrock within these structural zones increased the permeability in the bedrock. Easier movement of ground water in those areas accelerated solution activity. Many sinkholes are along the Sixmile Hill structural zone. The cavernous sinkhole in which the Hondo Reservoir was formed is between two limbs of the Sixmile Hill structural zone (Bean, 1949, p. 7).

EASTWARD-TRENDING FEATURES

The intrusion that forms the Capitan Mountains and two dikes (not mapped) (Dane and Bachman, 1958) a few miles northeast of Roswell trend eastward. A general eastward trend could be inferred because the Capitan Mountains and the two dikes are alined.

Fourmile structural zone is between Fourmile Draw and North Seven Rivers (pl. 2). Complex faulting and jointing occur at many places along this zone west of R. 19 E., and in places the extensive fracturing has a herringbone pattern. The shattering of the Hondo Sandstone Member and Yeso Formation may have increased the permeability of those formations in the Fourmile structural zone. Information from well logs indicates an area of higher permeability along this zone. This eastward-trending zone of fracturing may be the result of differential uplift of the Guadalupe and Sacramento fault blocks during Tertiary time.

FEATURES RESULTING FROM SOLUTION

Sinkholes and closed depressions in the Roswell basin were formed by ground water moving upward under pressure through zones of structural weakness and dissolving the soluble rocks, by surface water percolating downward and laterally and dissolving the soluble rocks, and by a combination of these two processes.

Sinkholes formed by the upward movement of ground water are commonly characterized by a high degree of roundness and a lack of surface drainage area. A sinkhole of this type may have three or

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four smaller sinkholes on its periphery, thus forming a compound sinkhole.

Some of the sinkholes penetrating the San Andres Limestone in the area west of R. 21 E. probably were formed by water in the Yeso Formation moving upward under pressure along structural zones and dissolving large quantities of the San Andres Limestone. At places in these structural zones, faulting has raised the lower confining beds in the Yeso against the permeable upper beds that compose the principal water-bearing beds in the Yeso, and water in the Yeso moves upward in the structural zone. Where the Hondo Sandstone Member, overlying the Yeso Formation, is silty adjacent to the structural zones, the water in the Yeso is confined by the Hondo.

The most accessible sinkholes in the Roswell basin, of the type formed by upward movement of artesian water, are those forming Bottomless Lakes (pl. 1) just east of the Pecos River near Roswell.

Sinkholes formed by infiltrating surface water may be classed as collapse sinkholes, which have steepsided walls, or as broad depression sinkholes, which have gently sloping sides and generally are partly filled with alluvium.

Some collapse sinkholes in the Roswell basin are as much as 200 feet in diameter; in general, however, they are small compared with other types of sinkholes. Many collapse sinkholes contain silt and large tilted blocks of gypsum that have slumped and subsided. Collapse sinkholes are common in the Vaughn-Macho plain and in parts of the embayment plain.

The broad depression sinkholes are most common where rocks of the evaporite facies are covered by a thick blanket of alluvium. As the gypsum is removed by solution, silt and clay fill the solution openings, and there is little or no slumping of the bedrock. An example is Juan Lake sinkhole (pl. 4), where solution has been slow and a thick layer of silt and clay has accumulated on the bottom of the sinkhole. There is no visible opening in the bottom of this sinkhole. Solution almost stops when the silt and clay layer becomes very thick.

If the alluvium is thin, the solution openings in the soluble bedrock do not become filled with silt and clay. An example is Antelope sinkhole (pl. 4), in which the alluvial fill is less than 25 feet thick and which has open solution cavities in the bottom. Sinkholes of the broad depression type having open solution channels in their bottoms are referred to in this report as open sinkholes, and those having a thick silt and clay layer and no visible openings are referred to as tight sinkholes.

Intermediate between the open sinkholes and the tight sinkholes are sinkholes having tight bottoms but permeable sides. These may form if the sinkhole is bottomed in permeable material, and the sinkhole has a large drainage area from which detrital material is washed into the sinkhole. An example of this type of sinkhole is Marley sinkhole (pl. 4) in the Blackwater Draw drainage area. The permeability of the bottom of this sinkhole is low because silt and clay cover the bottom to a depth of about 50 feet; however, large solution cavities in the evaporite rock of the San Andres Limestone are in the sides of the sinkhole above the silt and clay floor.

The Antelope sinkholes, like some others, are bottomed in thin alluvium and nonresistant evaporite rocks and red beds of the Artesia Formation, whereas sinkholes in other areas are bottomed in carbonate rocks of the San Andres Limestone. Some sinkholes shown on plate 4 are on topographic benches that also are structural benches. The Pajarito sinkholes, for example, are on a flat structural bench which is the limiting area of nearby folds. The Flying H sinkholes are on a bench east of the Vandewart-Cornucopia structural zone, and the high area east of these sinkholes may be the approximate location of a fault trending north. The Mayhill sinkholes are on the west side of the Vandewart-Cornucopia structural zone on another topographic bench.

The sinkholes shown on plate 4 occur over such a large area that it was not possible to visit and classify all of them. Parts of the project area were studied only by using aerial photographs and by making observations from an airplane, and, thus, the sinkholes in these areas could not be classified with any degree of assurance. All the sinkholes within the project area are not shown on plate 4.

HYDROLOGY

The description of the hydrology is given in greater detail for the area between Tps. 7 and 22 S. and between R. 19 E. and the Pecos River, because this part of the project area was studied more intensively than other parts. Principally those elements of hydrology are described that relate to natural and artificial recharge of the two chief aquifers in the basin. The reader is referred to other publications on the water resources of the basin for a more complete description of all hydrologic elements.

Most of the ground water in the basin is in a main aquifer, consisting of consolidated rocks, and an alluvial aquifer. The alluvial aquifer is secondary to the main aquifer because much of the water that recharges the alluvial aquifer comes from the main aquifer.

MAIN AQUIFER

The main aquifer is beneath the upland and lowland areas and extends eastward beyond the Pecos River, the eastern limit of the project area. This aquifer is within the Yeso Formation, the Hondo Sandstone member, the San Andres Limestone, the Grayburg Formation, and the evaporite facies of the Artesia Formation. These formations dip gently eastward from the crest of the Guadalupe and Sacramento Mountains at the western margin of the basin; the dip is modified in the vicinity of the structural zones described in the section on geology.

OCCURRENCE OF WATER IN THE MAIN AQUIFER

Most of the ground water in the main aquifer between the western margin of the basin and R. 21 E. is in the Yeso Formation and the Hondo Sandstone Member of the San Andres Limestone. West of R. 21 E. the main aquifer is ground-water province A of this report (pl. 5). Ground water in this province generally is unconfined (nonartesian), but it may be confined under artesian pressure beneath the Hondo in the vicinity of structural zones at places where the Hondo is highly silty. At the eastern boundary of ground-water province A, the water table in the main aquifer intersects highly permeable beds in the San Andres Limestone; from this boundary eastward to the Pecos River the main aquifer is referred to in this report as ground-water province B. The upper part of the San Andres Limestone is the major source of ground water in ground-water province B, although south of Artesia the water is principally in the Grayburg Formation. Aquifers in the Artesia Formation at places form a part of ground-water province B. Ground water in this province generally is unconfined from the western boundary of this province to within 10–20 miles of the Pecos River. At approximately this distance west of the river, the water table intersects the base of beds of low permeability in the Artesia Formation. Water in ground-water province B from this point of intersection eastward is under artesian pressure.

HYDRAULIC PROPERTIES OF THE MAIN AQUIFER

Information is meager about the water-transmission and storage properties of much of the main aquifer. Hantush (1955, p. 28) estimated that the average coefficient of transmissibility of the aquifer in the recharge area (ground-water provinces of the Hondo and Yeso and the upper part of the San Andres) is approximately 75,000 gpd per ft. (gallons per day per foot). This implies that 75,000 gpd of water would move through an average section of the aquifer 1 mile wide under a hydraulic gradient of 1 foot per mile. The value was computed from an estimate of the average annual recharge to the aquifer and the average slope of the water table in the aquifer.

Theis (1951, p. 2) estimated that the porosity of the main aquifer is about 4 percent in the principal intake area and that the porosity in the vicinity of Roswell is 5 percent or possibly higher. He estimated that the coefficient of transmissibility of the aquifer in this latter locality is between 1 and 3 million gpd per ft.

Fiedler and Nye (1933, p. 145–146, 183–185, and pl. 41) concluded that the permeability of the main aquifer between Tps. 9 and 20 S. is greater in five areas than in the intervening areas—based on a comparison of well yield and drawdown in wells. Their observations were made on wells tapping the main aquifer within province B; no observations were made in province A. They noted that the areas of apparent greater permeability are along major surface drainage lines. Where the permeability of the main aquifer is greater, the coefficient of transmissibility probably is greater also, as the coefficient of transmissibility is equal to the average permeability of the aquifer times its thickness.

Coefficients of transmissibility derived by Hantush (1955, p. 29) from tests in a few wells in the artesian part of the ground-water province of the upper part of the San Andres were about 1,400,000 gpd per ft near Roswell, about 75,000 gpd per ft near Dexter, about 150,000 gpd per ft near Artesia, and about 66,000 gpd per ft near Lakewood. These tests were made in segments of the basin described by Fielder and Nye (1933, p. 145–146, 183–185, and pl. 41) as areas of large yields from wells and areas of greater permeability than intervening areas. These coefficients can be used to make a general comparison between the transmissibility in one segment and that of other segments; however, the tests were too few and too widely spaced to give any assurance of a true sampling of the transmissibility in any one segment.

The average permeability of the main aquifer in province A seems to be less than that of province B. This difference is indicated by the smaller yield per foot of drawdown in wells in province A than in province B. The smaller yield-drawdown ratio is principally the result of lower permeability in the aquifer.

The water-transmission properties of the main aquifer in provinces A and B is indicated also by a difference in hydraulic gradients between province A and B. The average hydraulic gradient is about 70 feet per mile in that part of province A on plates 5 and 6 and less than 10 feet per mile in province B. The area having the lower hydraulic gradient has the higher transmissibility because the same or larger quantity of water must be moving through province B as through province A.

The permeability of the main aquifer is not uniform within province A. The permeability of the aquifer in province A along Fourmile and Vandewart-Cornucopia structural zones is above average for that province. The above-average permeability in the Fourmile structural zone probably resulted from fracturing of the Hondo Sandstone Member of the San Andres and Yeso Formation and, in places, from reef zones that cross the structural zone. This area of above-average permeability extends into province B. Above-average permeability in the Vanderwart-Cornucopia structural zone probably resulted from uplift of the upper confining bed in the Yeso Formation. In places along this structural zone, ground water has discharged from the Hondo Sandstone Member and Yeso Formation into large solution openings in the San Andres Limestone. The permeability may not be above average everywhere along this structural zone.

CAUSES OF DIFFERENCES IN HYDRAULIC PROPERTIES IN THE MAIN AQUIFER

The high permeabilities of rocks that compose the main aquifer in the ground-water province B are the result of the original structure, porosity, and sedimentary characteristics of the carbonate rocks of Permian age; the position of the carbonate-evaporite facies boundaries of the Permian shelf rocks; and the erosion of Permian rocks in Tertiary and Quaternary time.

Chemical and textural subfacies (the term "subfacies" is used to differentiate rock units either by chemical composition or by texture) influenced the extent and amount of original porosity and permeability of the carbonate rocks of Guadalupe and Leonard age in the shelf area. The chemical and textural subfacies correlate to some extent. Adjacent to the reef zone in most rocks of post-San Andres age, the deposits of the carbonate facies primarily are coarse calcarenite and coquina, and the composition is dominantly calcareous. Shelfward the coarse calcareous materials grade into a fine-grained calcarenite whose composition is dominantly dolomitic. Rocks having the greatest original permeability and porosity are adjacent to the reef front. Most of the reef and adjacent shelf rocks of the San Andres Limestone probably have been dolomitized.

The deposition of Upper Permian, Triassic, and younger rocks over the rocks of the Leonard and Guadalupe Series protected the older rocks from erosion. As a result, highly mineralized water probably was entrapped in the zones of original porosity in the Permian rocks. During the late Pliocene and Pleistocene, the Guadalupe and Sacramento Mountains were uplifted, the San Andres Limestone was exposed on the mountain slopes, and the Pecos River cut into the younger rocks and broke the artesian seal. The hydrostatic pressure of the water entrapped in the rocks was considerably increased in the Pecos Valley by the uplift. Water moved downdip owing to gravity and was partly confined under pressure beneath the Artesia Formation, though some water leaked upward through the Artesia Formation and drained into the Pecos River. Much of the highly mineralized water west of the river was flushed from the main aquifer by fresh water entering the rocks on the mountain slopes. Water then had an entrance to, a passageway through, and an outlet from the main aquifer.

As the mountains were uplifted and the level of the Pecos River was lowered, streams that drained areas of evaporite rocks formed on the east slope of the Sacramento Mountains. Few solution channels formed in the carbonate rock, and most of the water flowed over rather than infiltrated the surface. In addition, water infiltrating from the surface probably could not move to any great depth because of the entrapped highly mineralized water at shallow depth in the main aquifer. The Rio Hondo, the Rio Felix, and the Rio Penasco formed large drainage systems, which were superimposed on the carbonate rocks before the evaporite rocks were stripped from much of the area.

The evaporite rocks in the east slope of the Sacramento Mountains were stripped away, and a great amount of the carbonate rocks was dissolved along the present large drainage systems because infiltration of water was greater along these drainages.

High porosity and permeability formed in rocks of the main aquifer in the vicinity of boundaries of the carbonate-evaporite facies. The carbonate and evaporite facies of the San Andres Limestone and Grayburg Formation interfinger in the area of gradation between the gross carbonate facies and gross evaporite facies. Thus, for a given stratigraphic interval, dolomite generally grades into a sequence of dolomite interbedded with gypsum which in turn grades into anhydrite. The upper part of the San Andres Limestone begins to grade into anhydrite a few miles north of Artesia, and, farther to the north, progressively more and more anhydrite is in the section.

The permeability of the San Andres Limestone is greatest in the Roswell area. Water that infiltrated from the Rio Hondo, Blackwater Draw, and Salt Creek probably caused much of the solution. The permeability is lower toward Artesia and is much lower north of Salt Creek than near Roswell. The relatively low permeability in this northern area may be related to the lack of streams. Precipitation on the Vaughn-Macho plain between Salt Creek and Vaughn flows short distances, usually in small rivulets or as sheet runoff, to ponds and small lakes in depressions, where much of the water evaporates and only small amounts enter the ground.

RECHARGE AREA OF THE MAIN AQUIFER

The recharge area of the main aquifer is herein divided into seven subareas on the basis of rock type and surface-drainage features that might affect recharge. These subareas are shown on plate 4 and are referred to in this report as the western limestone area, the eastern limestone area, the northern evaporite area, the southern evaporite area, the northern limestone area, the eastern evaporite-alluvial area, and the alluvial lowland area.

WESTERN LIMESTONE AREA

The Sacramento plain and the western part of the Diamond A plain compose the western limestone area. The western limestone area is underlaid primarily by carbonate rocks of the San Andres Limestone.

Most of the area is highly dissected; however, some undissected remnants remain. Many of the undissected areas are structural benches in which sinkholes have formed. The deeper drainages have cut into the gypsum and red beds of the Yeso Formation within the western limestone area.

Precipitation is the only source of water entering the area. Precipitation on the western limestone area discharges from the area as runoff, discharges from the general land surface by evapotranspiration, infiltrates the rock surface to a depth below the zone affected by evapotranspiration, or drains to sinkholes.

The permeability of the San Andres Limestone on the land surface is moderate to low; water infiltrates principally through joints and faults. Water that infiltrates this limestone surface and passes to depth recharges either small perched bodies of water or the main ground-water body in province A. Some of the water in the perched bodies percolates to the main ground-water body, but much of it discharges as seeps and springs in the canyons. In areas where deep canyons intersect the water table in province A, ground water discharges from the main ground-water body to the stream channels and maintains perennial flow. Some of the water reaching the water table may move eastward in province A into province B.

Some of the water that drains to sinkholes evaporates from open-water surfaces of lakes and ponds in the sinkholes, and some water infiltrates to the subsurface through the bottom and sides of the sinkholes.

The Pajarito sinkholes in T. 13 S., Rs. 16 and 17 E., and the Mayhill sinkholes in T. 17 S., R. 16 E. (pl. 4), are the major sinkholes in the western limestone area. The Pajarito sinkholes, the largest sinkhole area in the western limestone area, consist of approximately 100 sinkholes. This sinkhole area is on a structural bench capped by carbonate rocks of the San Andres Limestone and underlain by sandstone and evaporite rocks of the Hondo and the Yeso Formation. The sinkholes probably are the result of solution of the evaporite rock in the Hondo Sandstone Member and Yeso Formation and slumping of the overlying San Andres.

Red Lake, in secs. 9 and 10, T. 13 S., R. 16 E., and Deadman Lake, in sec. 25, T. 12 S., R. 16 E., are in the largest of the Pajarito sinkholes. Deadman Lake, the largest, is about 2,500 by 1,300 feet and has a drainage area of about 4 square miles. Red Lake is about 1,300 by 1,000 feet and has a drainage area of about 2 square miles. About 10 of the Pajarito sinkholes are from 17 to 22 acres in extent, and their drainage areas range from a quarter to a half square mile. The floor in most of the Pajarito sinkholes is 20–40 feet below the general land surface.

About 10 sinkholes compose the Mayhill sinkholes. They range in size from a fraction of an acre to about 20 acres. The floor of the sinkholes ranges between 10 and 50 feet below the general land surface. The sinkholes were formed in carbonate rock of the San Andres Limestone.

The floor of most sinkholes in the western limestone area consists of silty sand, which is moderately permeable, and silty clay, which has a relatively low permeability. If the permeability of the floor is high, water infiltrates the bottom and drains from the sinkhole in a few days. If the permeability is low, most of the water evaporates.

Infrequent observations were made of the approximate rate at which water discharged from sinkholes in Pajarito and Mayhill sinkhole area; the observations were made during flights in 1958 and 1959. About 25 lakes in the Pajarito sinkhole area were full of water on August 8, 1958; about the same number still contained water on November 2, 1958; and by February 3, 1959, only 2 sinkholes contained water. No water entered the sinkholes during this period. Some of the water in these sinkholes was consumed by the 6,000–8,000 cattle in that area. Mr. Fred Pellman, of the Mescalero Apache Tribe, informed the senior author that 20–25 years ago many of these sinkholes contained water throughout the year. This probably can be attributed to greater precipitation rather than lower permeability of the sinkhole floors at that time. The Mayhill sinkholes reportedly filled with water during July and August 1958; four of them still contained water on November 2, 1958; and on February 3, 1959, all the sinkholes were dry. Mr. Fisher, a local farmer, informed the senior author that if these lakes fill with water in July and August, they generally hold water about 3 months. He also reported that the maximum depth of the water in these sinkholes is about 5 feet, as indicated by high-water marks on fence posts in the sinkholes.

The great length of time that water remained in these sinkholes indicates that several tens of acre-feet of water are discharged by evaporation. Although large amounts of water enter the rocks of the western limestone area, and some additional water could be added by artificial recharge, probably only a small percentage of the additional water would be effective recharge for the limestone aquifer in the Roswell-Artesia sector of the basin. Most of the water probably would appear as seepage to streams in the western limestone area. The artificial-recharge potential of the area is poor.

EASTERN LIMESTONE AREA

The upland surface of the Guadalupe Mountains and much of the eastern part of the Diamond A plain compose the eastern limestone area. North of State Highway 83, the eastern limestone recharge area is underlain primarily by carbonate rock of the San Andres Limestone; south of that highway the area is underlain primarily by carbonate rock of the Grayburg Formation. Ground-water province A underlies all the area except the extreme eastern part, which is underlain by ground-water province B.

The area is highly dissected, and the drainage system is well integrated. In general, the interstream divides are sharp, but a few small flat interstream areas remain. Sinkholes occur on some of the interstream areas. The Flying H sinkholes in T. 15 S., R 18 E., constitute the major sinkhole area. (See pl. 4.) The largest sinkhole of this group is about a third of a mile in diameter, and its floor is about 25 feet below the general land surface. This sinkhole is partly filled by silty sand and sandy silt and, in places, by a black organic silty clay.

Water enters the eastern limestone area directly as precipitation and indirectly as surface and ground-water flow from the western limestone area. The precipitation that neither evaporates from nor infiltrates the land surface reaches stream channels quickly because of the sharp interstream divides and well-integrated drainage. Little of the precipitation drains to sinkholes. The permeability of the carbonate rock on the surface is moderate to low, and surface water infiltrates these rocks primarily through joints and faults. The amount of recharge to the main ground-water body from the interstream areas is probably small. The main ground-water body in the eastern limestone area is recharged principally along the major streams. Much of the eastern limestone area was described by Fiedler and Nye (1933, pl. 2) as being the principal recharge area for the main aquifer. Recharge along the stream channels could be increased if the streamflow were retarded.

The quantity of water infiltrating to the subsurface through sinkholes in the eastern limestone area is small, because the amount of water draining into the sinkholes is small. The bottoms of the sinkholes in this area are permeable, and water goes underground quickly. Water accumulating in the Flying H sinkholes after thundershowers, discharges in 1–2 months, mostly to the subsurface.

The artificial-recharge potential of this area is moderate to good. Good sites for small dams would not be difficult to find. Dams constructed where their reservoirs would inundate the more permeable areas of the channel would increase the recharge from streams. If sites for dams to impound water on the permeable areas could not be found, water could be impounded upstream from the more permeable areas and released at a rate that would increase the amount of recharge over that of uncontrolled flow in those areas. Diverting streamflow to sinkholes would increase recharge in the sinkhole areas. The greatest problem would be in getting the water from the streams to the sinkholes. A detailed study of the recharge characteristics of Hope sinkhole in sec. 33, T. 16 S., R. 19 E., is described in the section on water-loss studies in selected sinkholes.

NORTHERN EVAPORITE AREA

The extreme southern part of the Vaughn-Macho plain composes the northern evaporite area. The area is characterized by rolling hills and valleys, broad flats, and well-integrated drainage. Sinkholes are numerous, but they are localized by structural and lithological variations in the evaporite rocks.

The northern evaporite area is underlain by the evaporite facies of the San Andres Limestone and, to a minor extent, by the evaporite facies of the Artesia Formation. The permeability of the surface and subsurface rocks is moderate to high. Many of the hills are capped by carbonate rocks and underlain by gypsum that is poorly resistant to erosion.

Some of the hills are expressions of anticlines. The cores of some of the anticlines consist of gypsum in which water has dissolved channels and caverns. Large open solution channels in the gypsum and older solution channels filled with angular slump and detrital material occur along the Sixmile Hill structural zone.

Water enters the northern evaporite area as precipitation and as surface- and ground-water flow from the eastern limestone area and adjacent parts of the Vaughn-Macho plain. Much of the precipitation on the interstream areas is discharged by evapotranspiration, and some infiltrates to the subsurface. Most of the precipitation that is not discharged by evapotranspiration drains to stream channels and sinkholes.

Blackwater Draw, Salt Creek, and the tributaries of Cienega del Macho drain a large part of the northern evaporite area as well as transport water into this evaporite area from upstream sources. These drainages lose a considerable amount of water by infiltration in the northern evaporite area. Small cavelike solution holes are common in the channels of several drainages, and streamflow enters the subsurface readily through these openings. Quantitative studies were not made to determine the amount of loss, but the seepage loss per mile of channel is probably greater in the northern evaporite area than in other parts of the project area.

In some areas, silt beds at shallow depth prevent the deep percolation of water entering the ground. At places, streamflow entering the subsurface through the solution holes in the channel reappears as streamflow emerging from other solution holes in the channel downstream. This was observed in Middle Arroyo, where flow disappeared in solution holes in sec. 19, T. 7 S., R. 21 E., and reappeared about 1,000 feet downstream. Wet-weather springs are numerous in the northern evaporite area.

The permeability of the floors of sinkholes in the northern evaporite area ranges from very low to high. Many sinkholes floored by thick silt beds of low permeability have solution channels in the sides. The solution channels in the side of a sinkhole may be from a fraction of a foot to a few feet above the floor, and a considerable volume of water must pond on the floor before the water surface reaches the mouth of the solution channel. If the permeability of the floor is very low, most of the water ponded below the level of the channel mouth is discharged by evaporation.

The artificial-recharge potential of the northern evaporite area is good to excellent, and recharge to the main aquifer might be increased substantially. All the streamflow in the major drainages that cross the area is not lost, so more water might be put underground if the flow could be impounded and then released at a rate that would allow infiltration through the permeable streambeds. The stream channels are narrow, and the reservoir capacity behind a dam would be small; consequently, numerous dams would be required to provide sufficient storage capacity.

Some streamflow could be diverted to sinkholes having permeable floors; however, the sinkholes selected should be in areas where the water put into the subsurface would not emerge from solution holes in nearby stream channels. Sinkholes floored by material of low permeability and located where streamflow could be diverted to them easily probably could be used for artificial recharge if recharge wells were constructed in the sinkholes. Some sinkholes in which large quantities of water collect below the level of solution channels in the sides probably could be made more efficient recharge points by lowering the mouths of the solution channels.

SOUTHERN EVAPORITE AREA

Both segments of the embayment plain and a small part of the lowland area compose the southern evaporite area. The surface of the area is characterized by shallow swales and gently rounded hills. The drainage is well integrated. Collapse and broad-depression sinkholes are common on the interstream areas; however, the broad-depression type is the most common. Most of the broad depressions are open sinkholes because of solution channels in their floors.

The main aquifer in the southern evaporite area is a part of groundwater province B. The transmissibility of the aquifer in the southern evaporite area seemingly is higher in the northern part than in the southern part. The reason for this difference is not entirely clear; however, it may be the result of a greater thickness of the aquifer and more brecciated zones in the northern part of the southern evaporite area.

The southern evaporite area is underlain primarily by rocks of the middle and lower parts of the Artesia Formation (equivalents of the

Seven Rivers, Queen, and Grayburg Formations) and, to a minor extent, by evaporite rocks of the San Andres Limestone. Gypsum is the major constituent of the rocks of the southern evaporite area. The permeability of the carbonate rocks is high in parts of the area because of interformational breccias consisting of angular to subangular blocks of carbonate material in a calcareous silty matrix. Solution by water readily removes the carbonate and creates many interconnected channels in the brecciated zone.

Water enters the area as precipitation and as surface- and groundwater flow from the eastern limestone area. Some recharge to the main aquifer is from precipitation infiltrating the surface of the interstream areas; however, most of the recharge is from water that reaches sinkholes and stream channels. Considerably more water recharges the aquifer through streambeds than through sinkholes.

The streams in the area are not gaged; therefore, how much surface water is discharged is not known. None of the streams are perennial within the southern evaporite area, and most of the streamflow originates from precipitation on areas upstream. Much of the streamflow entering the southern evaporite area is depleted by infiltration within the area. Estimates were made of streamflow losses in Rio Penasco and Fourmile Draw after a thunderstorm on May 7, 1959. Streamflow estimated as between 80 and 90 cfs (cubic feet per second) was lost by infiltration through the bed of Rio Penasco in a 1-mile reach within secs. 16 and 21, T. 17 S., R. 21 E. Streamflow estimated as about 200 cfs diminished to about 125 cfs in an 8–mile reach downstream from sec. 22, T. 18 S., R. 20 E. (this 8–mile reach is within the eastern limestone area), and disappeared completely in a total channel distance of about 14.5 miles (the last 6.5 mile reach is within the southern evaporite area). Much of the water lost from streamflow enters the alluvium in the streambed and then infiltrates the underlying evaporite rocks. Parts of some streambeds are directly on evaporite rocks that contain solution channels, through which the streamflow disappears underground. A local rancher reported that small streamflows will not get past solution openings in the bed of Johnston Draw in the NE¼ sec. 23, T. 16 S., R. 21 E.

Antelope, Tank Mill, and Fanning sinkholes (pl. 4) form the three largest groups of sinkholes in the southern evaporite area. Antelope sinkholes are in a 4-square-mile tract in T. 18 S., R. 23 E.; however, most of the sinkholes in this group, including the largest, are entirely within sec. 23, T. 18 S., R. 23 E. The Antelope sinkholes are actively growing, as indicated by fractures around them. Their growth is by subsidence as a result of solution of the gypsum bedrock. During growth, some sinkholes have joined and formed one large compound sinkhole. One compound sinkhole of the Antelope group has an area of about 0.4 square mile. The material on the floor of many of the sinkholes in the Antelope group is a granular coarse-grained silt that is friable. The permeability of this material is moderately high. Much of the water entering the Antelope sinkholes goes underground quickly, generally in less than 1 month, because of the permeable material and solution channels in their floors.

In general, the material flooring the Tank Mill sinkholes (T. 18 S., R. 24 E.) probably is less permeable than that of the Antelope sinkholes. Some of the sinkholes having floors of low permeability are adjacent to sinkholes having floors of high permeability. When the sinkholes having floors of low permeability become filled with water, the overflow may drain into nearby sinkholes having more permeable floors.

The Fanning sinkholes in T. 22 S., R. 22 E., consist of about 10 sinkholes. Bone Tank (T. 21 S., R. 23 E.) and Tule Lake (T. 22 S., R. 23 E.) are two of the largest sinkholes in the southern evaporite area. Bone Tank sinkhole is about 1,800 feet long and 800 feet wide; Tule Lake sinkhole is roughly square, and each side is about 1,000 feet long. These were not visited but were observed from an airplane.

The artificial-recharge potential of the southern evaporite area is good to excellent. The larger sinkholes in the area generally hold water for less than 2 weeks and rarely for more than a month. The amount of water that would be saved from evaporation by putting the water underground faster artificially by wells probably would be too small to justify the construction of recharge wells in sinkholes of the southern evaporite area. It might be advantageous, however, to construct drains and channels in some of the larger sinkholes to connect ponds within a sinkhole to openings in the sinkhole. Dams either to impound water in permeable areas of stream channels or to divert water from streams to sinkholes may be feasible in the western part of the area. Streambeds in the eastern part of the southern evaporite area are broad and shallow; therefore, few places would be satisfactory for dams and reservoirs.

Some of the water infiltrating to the subsurface in the southern part of the area enters an upper aquifer in the Grayburg and Queen Formations and moves southeastward from the Roswell basin into the Carlsbad area. This water is not effective recharge to the Roswell-Artesia sector.

NORTHERN LIMESTONE AREA

The western part of the Vaughn-Macho plain composes the northern limestone area. The northern part has no integrated drainage, and drainage is internal to numerous sinkholes. The southern part of the northern limestone area is well dissected by streams. A surface drainage divide (pl. 4) is between the northern part, which has internal drainage, and the southern part, which has well-integrated drainage. Precipitation directly on the northern limestone area is the only water entering the area. Much of the precipitation evaporates from the land surface, some infiltrates the surface, and some drains to sinkholes and stream channels. Most of the recharge to the ground-water body is by infiltration through sinkholes and streambeds.

Carbonate rocks of the San Andres Limestone are exposed in the area except where they are covered by a veneer of soil and gravel. The carbonate rocks are 450–650 feet thick in the southern part of the area and thin northward to about 20–30 feet near Vaughn. Generally, the carbonate rocks of the San Andres Limestone are more permeable than the sandstone, siltstone, and evaporite rocks of the underlying Hondo Sandstone Member and Yeso Formation.

Sinkholes are more common in the northern limestone area than in any other recharge area of the main aquifer. Although sinkholes are scattered throughout the northern limestone area, they are more numerous and closer spaced in the following four major groups: Vaughn sinkholes, Richards sinkholes, Hasparos sinkholes, and Bogle sinkholes. (See pl. 4.) The northern limestone area was not studied in detail, and most observations of the sinkholes were made from an airplane and by studying aerial photographs. The sinkholes seem to be of the collapse and broad-depression type, and many have solution openings in their sides and floors. The diameter of the sinkholes in the Vaughn group ranges from 100 to 1,000 feet. Within the Vaughn group, sinkholes occupy less than 10 percent of the land in some parts, whereas in the other three groups, sinkholes occupy about 50 percent of the land. Sinkholes other than the Vaughn group are circular, are bottomed with green vegetation, and seem to be deeper than those in areas in which the areal density of sinkholes is less. No attempt was made to compare physical characteristics of sinkholes in the Richards, Hasparos, and Bogle groups.

Two less well defined sinkhole areas, the Western and Eastern Capitan sinkholes, are a few miles north of Capitan Mountain (pl. 4). Samples of soil from the floors of the Eastern Capitan sinkholes consist of a poorly permeable silty clay.

The permeability of the materials flooring the Vaughn, Richards, Hasparos, and Bogle sinkholes was inferred from observation of the length of time water remained in the sinkholes after rains. The conclusions are approximate because flights were not made over the areas after each rain. Many of the Vaughn sinkholes contained water in the period July–December 1958 and were dry by early February 1959; consequently, the permeability of the floors probably is low. None of the Richards, Hasparos, and Bogle sinkholes contained water, although sinkholes adjacent to these three major sinkhole areas contained water after heavy rains in July and August 1958. The floors of the Richards, Hasparos, and Bogle sinkholes probably are highly permeable.

A considerable volume of water is evaporated from sinkholes floored by material of low permeability. Recharge wells constructed in the larger sinkholes of the Vaughn group and in other sinkholes in which water collects and evaporates would increase the recharge in the northern limestone area. Many sinkholes have solution openings that are higher than much of the floor. Water collected in the sinkholes below the solution openings could be drained underground by lowering the mouths of the solution openings and constructing drainage channels to these openings.

In that part of the northern limestone area having well-integrated drainage, dams could be constructed on some streams either to impound water over a permeable area or to divert water to sinkholes. The southern half of the northern limestone area seems to be well suited to artificial recharge because of the great thickness of the San Andres Limestone. The artificial-recharge potential of the northern limestone area seems to be moderate to good.

EASTERN EVAPORITE-ALLUVIAL AREA

The eastern part of the Vaughn-Macho plain composes the eastern evaporite-alluvial area. The area is underlain by evaporite rocks of the San Andres Limestone and younger rocks of Permian age and by alluvium of probable late Tertiary age. The areas of evaporite rock and areas of alluvium are not differentiated on plate 4.

Drainage is well integrated in much of the area; however, in the northwestern part of the area, drainage is internal to sinkholes. Some water drains to sinkholes on the interstream areas.

Precipitation on the area and surface- and ground-water flow to the area from the northern limestone area are the sources of water. Water moving downward may enter aquifers at shallow depth in the alluvium and Artesia Formation and then move eastward and discharge as seeps and springs along the Pecos River. Little is known about these shallow aquifers. In general, water moving to the subsurface in the western part of the area probably recharges the main aquifer, and water moving to the subsurface in the eastern part recharges the shallow aquifers.

Sinkholes are common in the eastern evaporite-alluvial area. Broad-depression sinkholes that have solution holes in their floors drain water to the subsurface quickly (large solution holes are in Lewis sinkhole T. 4 S., R. 22 E.), whereas water collects and evaporates from broad-depression sinkholes floored by material of low permeability. The Steel, Wright and Yeso sinkholes (pl. 4) compose the major sinkhole areas; however, there are many isolated sinkholes throughout the eastern evaporite-alluvial area. The area was studied principally during flights over the area.

The possibilities for recharge of the main aquifer by artificial means are poor in the eastern evaporite-alluvial area. In the western part of the area some additional water could be put underground through recharge wells and by channeling water to solution channels within these sinkholes. Some water might be diverted to sinkholes in the western part of the area.

ALLUVIAL LOWLAND AREA

The alluvial lowland is not a natural recharge area for the main aquifer because water spread on the ground cannot move downward from the land surface to the main aquifer. The natural hydraulic gradient is upward from the main aquifer to the alluvial aquifer. Water could be induced to enter the main aquifer through recharge wells in the alluvial lowlands.

The altitude of the artesian-pressure surface of water in the main aquifer in the alluvial lowland might make certain areas of the lowland more favorable than others for recharge wells. In areas where the artesian-pressure surface is near the land surface, water would have to be pumped into the well under pressure to reverse the pressure gradient in the well. This would be necessary in wells near the Pecos River in the vicinity of Roswell. Where the artesian-pressure surface is several feet below the land surface, water discharged into the mouth of the well would move downward into the aquifer by gravity. Recharge wells south of Dexter would be in this category.

The most favorable sites for recharge wells in the alluvial lowland would be in the western and southern halves, where the water level would be several tens of feet below the land surface.

MOVEMENT OF WATER IN THE MAIN AQUIFER

The direction of water movement and the rate that the water or the pressure effects move are major factors to consider in selecting recharge sites for the main aquifer. The pressure effects move much faster than the water. Favorable recharge sites are those where the recharge would increase the artesian pressure in the Roswell-Artesia sector of the basin within a reasonable length of time and where the recharged water could move to the artesian aquifer without gaining an undesirable concentration of dissolved solids.

If the main aquifer is recharged at a site overlying the nonartesian part of the aquifer, the rise in the water table as the result of recharge will cause some rise in the artesian pressure in the Roswell-Artesia sector long before the water reaches the artesian part of the aquifer. The difference between the travel time of the pressure effect and that of the water may be days, months, or years—depending in part on the distance of the recharge site from the artesian part of the aquifer in the Roswell-Artesia sector. In general, the closer the recharge site is to the artesian part the less time it will take for the recharge to benefit the artesian part of the aquifer.

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The arrows on plate 4 represent the general direction of ground-water movement. The water that enters the main aquifer in the northern quarter of the northern limestone area and the northern half of the evaporite-alluvial area probably moves east of the Pecos River and then southward, rather than directly to the Roswell-Artesia sector. Water entering the main aquifer in the southern quarter of the eastern limestone area and in the southern half of the southern evaporite area may be intercepted by wells in the Dayton-Lakewood area, but some probably moves out of the Roswell basin underground and discharges from Major Johnson Springs. Most of the water that enters the main aquifer at other points eventually reaches some part of the Roswell-Artesia section. Artificial recharge to the main aquifer at sites within the alluvial lowland would be effective immediately in the Roswell-Artesia sector.

In the Roswell-Dexter area, where the encroachment of saline water has been most pronounced, benefits from recharge would arrive faster from recharge sites in the northern evaporite area, the northern half of the eastern limestone area, and the extreme southern part of the eastern evaporite-alluvial area. The benefits from artificial recharge would arrive quicker in the area between Dexter and Lakewood from recharge sites in the southern evaporite area and the eastern limestone area; however, water recharged to the upper aquifers of the Grayburg and Queen Formations would move eastward from the Roswell basin. Most of the western limestone area, the northern limestone area, the eastern evaporite-alluvial area, and the western half of the eastern limestone area probably are too remote to be considered for initial sites for artificial recharge. Sites in those areas would not be excluded, however, in a complete and long-term program of artificial recharge for the basin.

The velocity at which water moves through an aquifer is directly proportional to the permeability and hydraulic gradient and inversely proportional to the porosity of the aquifer. Because of the high permeability of the main aquifer in the vicinity of some of the major drainages, artificial recharge in parts of those areas might reach the pumped area as quickly as recharge in areas closer where the permeability is less. Distance, permeability, hydraulic gradient, and porosity of the aquifer should be considered together in evaluating sites for artificial recharge.

ALLUVIAL AQUIFER

The alluvial aquifer is within the alluvial-lowland area shown on plate 4. The alluvium is not saturated in the western part of the alluvial-lowland area. The alluvial aquifer consists of irregular beds of gravel, sand, silt, and clay. The various beds of gravel and sand are in part poorly connected, but these permeable beds probably are sufficiently interconnected to form a common aquifer.

OCCURRENCE OF WATER IN THE ALLUVIAL AQUIFER

Water in the alluvial aquifer generally is not confined, although it may be confined locally by beds of silt and clay.

The average thickness of the alluvium in the alluvial lowland is about 150 feet, but the average thickness of the zone of saturation is considerably less. The depth to the water table ranges from a fraction of a foot near the Pecos River and the lower reaches of major tributaries to more than 100 feet in the western part of the aquifer and in some areas of heavy withdrawal south of Hagerman. The water table in the alluvial aquifer is being lowered further each year in the areas of heavy withdrawal.

HYDRAULIC PROPERTIES OF THE ALLUVIAL AQUIFER

Hantush (1955, p. 27) used several irrigation wells that tap the alluvial aquifer for aquifer tests and computed an average coefficient of transmissibility of about 100,000 gpd per ft for the part of the aquifer near those wells. The coefficients for individual wells ranged from 36,000 to 139,000 gpd per ft. A few tests made during the study period of this report indicated a wider range in coefficients of transmissibility in the alluvial aquifer. The transmissibility of the aquifer varies within short distances, probably because of the erratic occurrence of gravel, sand, and silt. Transmissibilities probably are larger near major streams crossing the alluvial lowland than in the interstream areas.

The apparent wide range in transmissibility of the aquifer is reflected in the wide range in well yields in small areas. Irrigation wells in use yield from less than 500 gpm to as much as 1,500 gpm; the average yield is between 800 and 1,000 gpm. Specific capacities between 10 and 80 gpm per foot of drawdown, averaging between 40 and 50 gpm per foot of drawdown, were obtained during a random sampling of wells in the alluvium. These yields probably are reasonable indicators of the range in rates at which water can be recharged through wells to the alluvial aquifer. Sites for large-capacity recharge wells probably would not be too difficult to find in spite of the apparent large differences in the aquifer's hydraulic properties from place to place.

RECHARGE TO THE ALLUVIAL AQUIFER

The recharge area of the alluvial aquifer in the Roswell-Artesia sector is the alluvial lowland. Natural recharge to the alluvial aquifer consists of (1) artesian water leaking upward through the Artesia Formation from the main aquifer, (2) infiltration of irrigation water applied to cultivated fields, (3) infiltration of surface water from stream channels and flood plains, (4) infiltration of precipitation on the land surface, and (5) ground-water flow entering the area in the alluvium of stream channels. Only inducing more infiltration of precipitation and surface water could increase the ground-water supply.

Infiltration of water to the alluvium is governed primarily by (1) water-infiltration characteristics of the alluvium, (2) topography of the alluvial surface, (3) thickness of the alluvium, and (4) location in relation to the Pecos River and its tributaries.

FACTORS AFFECTING WATER INFILTRATION TO THE ALLUVIUM

In the arid climate of the Roswell basin, geologic processes retard and, in places, prevent the passage of water from the land surface to the water table in alluvial deposits. Particularly, the formation of caliche tends to reduce the amount of recharge.

In general, caliche forms when water removes calcium carbonate from the soil in the A horizon (the zone of leaching in the soil) and deposits it in the B horizon (the zone of deposition in the soil); therefore, the accumulation of caliche in the B horizon depends on a source of calcium carbonate in the A horizon and sufficient movement of water through the A horizon to the B horizon without much water passing below the B horizon. Soils in the Roswell basin are rich in calcium-bearing materials. When the quantity of water is sufficient to pass through the B horizon, some of the calcium carbonate is leached from that horizon and carried to greater depth.

The thickest caliche deposits are in undrained areas, in flood plains, near the apex of alluvial fans, on floors of intermittent streams, and in some irrigated areas—these are areas where water in addition to direct precipitation is available to further the weathering processes.

Caliche in interstream areas in the alluvium of the Blackdom, Orchard Park, and Lakewood terraces is the cause of differences in permeability and infiltration capacity of soils of those terraces. Soils underlying the Blackdom and Lakewood terraces are, in general, more permeable than those underlying the Orchard Park terrace.

A sample of the silty clay and caliche cap (fig. 3; table 2) that forms the B horizon of the soil of the Blackdom terrace contained 47 percent clay and 36 percent silt. The permeability of such materials is low and has been decreased further by cementation with calcium carbonate. Solution channels ranging in diameter from a fraction of a foot to several feet have formed in this cap on the flanks of hills, and surface water enters these openings readily.

Soils underlying the Lakewood terrace have, at places, a well-formed B horizon consisting of clay and silt; at other places the soils have a poorly formed B horizon. The permeability of the soils of the Lake-

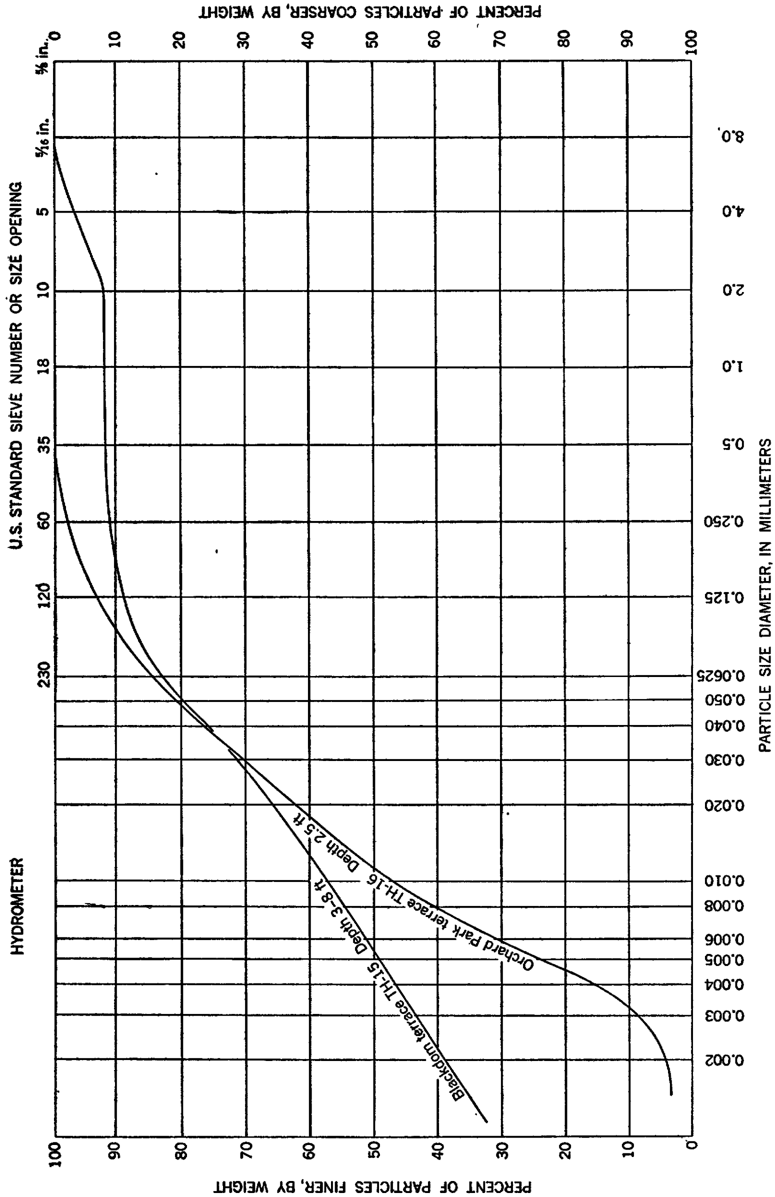

FIGURE 3.—Particle-size distribution in soil samples from the B. horizon of Blackdom and Orchard Park terraces.

TABLE 2.—*Particle-size distribution in soil samples from the B horizon of Blackdom and Orchard Park terraces*

[Analysed by Geol. Survey, Denver hydrologic laboratory]

Sample site	Weight percents of samples in indicated size range									
	Clay sizes (mm) <0.004	Silt sizes (mm) 0.004–0.0625	Sand (mm) sizes: Very fine 0.0625–0.125	Sand: Fine 0.125–0.25	Sand: Medium 0.25–0.5	Sand: Coarse 0.5–1	Sand: Very coarse 1–2	Gravel (mm) sizes: Very fine 2–4	Gravel: Fine 4–8	Gravel: Medium 8–16
Blackdom terrace, SW¼ sec. 31, T. 12 S., R. 23 E.	47.0	36.1	6.0	1.5	0.8	0.3	0.2	4.6	2.9	0.6
Orchard Park terrace, SW¼ sec. 24, T. 12 S., R. 25 E.	15.3	69.3	8.2	5.2	2.0	-------	-------	-------	-------	-------

wood terrace probably has a greater range than that of the other two terraces.

Much of the Orchard Park terrace is underlain by a thick B horizon consisting of clay and caliche. The permeability of this material is low and is further decreased by cementation.

Most of the irrigated land in the Roswell-Artesia sector is on the Orchard Park terrace, and the low permeability of the soil prevents a high rate of recharge to the alluvial aquifer as seepage loss from irrigation water. Hantush (1955, p. 57) estimated that about 20 percent of the irrigation water applied to the land recharges the alluvial aquifer. This estimate may be too large. The coefficient of permeability of the B horizon was estimated to be about 0.01 gpd per sq ft (gallons per day per square foot). Computations based on this coefficient indicate that the recharge from irrigation water probably is 10 percent or less of the water applied.

The formation of caliche in the B horizon reduces the infiltration capacity of soils in interstream areas; and cementation of gravel, sand, and silt in streambeds in the alluvium by calcium carbonate reduces the infiltration capacity of those streams. Surface water in contact with large volumes of calcareous rocks takes quantities of calcium carbonate and calcium bicarbonate into solution. Calcium carbonate precipitating from solution where water accumulates and evaporates along intermittent streams cements the streambed materials and forms hard, impermeable conglomerate. Conglomerate formed in this manner is common in the streambeds of the Roswell basin.

A cemented deposit of gravel, sand, and silt also is present in the alluvium at depths below the B horizon beneath streamways. The downward percolation of water is obstructed at places by confining beds of silt and clay. If the downward movement of water is stopped at a shallow depth, the water may accumulate and evaporate. The deposition of calcium carbonate further lowers the permeability of the bed. The accretions of calcium carbonate may fill the beds of gravel and sand to the extent that the material becomes a hard cemented conglomerate. Later, water may form solution channels in the conglomerate similar to those in limestone. These processes of cementation and solution probably produce the greatest differences in permeability between the areas underlying streams of large flow and the areas underlying streams of small intermittent flow. The permeability is greatly reduced in the areas underlying the smaller streams.

The amount of recharge from streams has not been determined, but it may not be large. Long reaches of the main tributary streams crossing the alluvium are silty in places and apparently of low permeability. Rio Felix, one of the largest and deepest of the streams crossing the alluvial recharge area, is underlain at places by well-rounded sand and gravel that is permeable. At other places the sand and gravel is impermeable owing to a matrix of silt and clay.

Two normally perennial ponds and an intermittent pond lie above the water table in parts of the Rio Felix channel having low permeability. The largest of the perennial ponds, in the NW¼ sec. 29, T. 14 S., R. 23 E., is 400–500 feet long, 40 feet wide, and, in places, 5–10 feet deep. The other perennial pond is 2 miles upstream, in the SE¼ sec. 25, T. 14 S., R. 22 E., and is 600–750 feet long and 7–8 feet deep. A local rancher reported that the latter pond normally holds water all year; however, during the drought in the early 1950's it was dry. An intermittent pond in the NE¼ sec. 22, T. 14 S., R. 23 E., holds water during and after floods. In October 1958 this pond was 800 feet long, about 50 feet wide, and 5–6 feet deep. Other temporary ponds, lasting 1 to 2 months, form along the channels of the Rio Felix, Rio Penasco, Seven Rivers, and Rio Hondo after large floods. The channels of the smaller streams also have many impermeable reaches on which water accumulates after floods. Infiltration of water from the smaller tributaries seems to be much less per unit wetted area than that from the larger streams.

The apparent poor infiltration characteristics of interstream areas and of long reaches of the streams crossing the alluvial lowland indicate that artificial recharge by ponding water on the land surface in those areas would not be efficient. Much of the water would be evaporated. Periodically scarifying these surfaces in areas where a surface-water supply is available for recharge might increase the water-infiltration potential of those areas. Additional study would be necessary to evaluate the feasibility of such an operation.

TOPOGRAPHIC FEATURES THAT AFFECT RECHARGE OF THE ALLUVIAL AQUIFER

Topographic features influence the recharge characteristics of the alluvial lowland. Most of the lowland is on the Blackdom and Orchard

Park terraces; a minor part is on the Lakewood terrace. Topographic features superimposed on the terraces are broad shallow swales and depressions, broad flood plains along drainages tributary to the Pecos River, stream channels that are entrenched a few feet below the flood plains, and some sinkholes. Swales and depressions are very shallow but at many places they are more than 1,000 feet wide and extend downslope several miles.

Most of the sinkholes are dry much of the time, although some contain small perennial lakes. Lake Van and several of the Bitter Lake sinkholes (pl. 4) contain water all year; Prichard Lake sinkholes contain water diverted from the lower end of the Hagerman Canal; and Juan Lake, Felix, and Clarks Lake sinkholes contain water only after heavy rains in their vicinity.

Most of the sinkholes in the alluvial lowland are less than 200 feet in diameter and are shallow; however, a few are larger. The long time that water remains in the sinkholes after rains indicate that much of the water in sinkholes in the alluvial area evaporates. Studies made of infiltration and evaporation of water from Juan Lake sinkhole in the alluvial area are described in section on water-loss studies in selected sinkholes.

Many of the streams in the alluvial area have flood plains 1,000–3,000 feet wide, and overflow onto the flood plains is common. The inability of the stream channels to contain flood flows is more pronounced on the east side of the alluvial lowland than on the west. The permeability of the flood plains is low, and much water is lost from them by evapotranspiration. Drainages such as Thirteenmile Draw, Greenfield Draw, and Eagle Creek do not have well-defined channels in their lower reaches near the Pecos River. Floods in such drainages spread over large areas and damage croplands.

WESTERN LIMIT OF THE RECHARGE AREA OF THE ALLUVIAL AQUIFER

The alluvium is thin in much of the western part of the alluvial lowland, and the saturated alluvium does not extend to the western margin of the lowland. Most of the water that infiltrates the alluvium in that area passes through the alluvium to the underlying Artesia Formation and the San Andres Limestone, and only a small part of the water moves eastward in the alluvium.

BOTTOM LANDS OF THE PECOS RIVER AND LOWER REACHES OF ITS TRIBUTARIES

Most of the water that enters the alluvial aquifer in the bottom lands of the Pecos River and its tributaries in the Roswell-Artesia sector is discharged in a short time, either through seeps and springs to those drainages or as evapotranspiration. The water table of the alluvial aquifer intersects the channels of the Pecos River and the lower reaches of its major tributaries. Dense growths of saltcedar and other forms of water-loving vegetation consume large quantities of water annually, and much of this water is obtained directly from the capillary fringe above the water table. Additional recharge to the alluvial aquifer that would increase the natural discharge of ground water would not add to the usable water supply in the aquifer; and, therefore, the bottom lands would be poor areas for artificial recharge of the alluvial aquifer.

POSSIBILITIES FOR ARTIFICIAL RECHARGE OF THE ALLUVIAL AQUIFER

The widespread caliche at shallow depth in the interstream areas, the materials in streambeds, and the low permeability of sinkhole floors would retard recharge to the alluvial aquifer except through artificial openings. The location of recharge wells would not be limited to any one part of the alluvial lowland but could be anywhere that an irrigation well can be developed in the alluvial aquifer.

Water injected through wells to recharge the alluvial aquifer should be free of suspended sediment and algae-forming bacteria that eventually would clog the well screen and aquifer near the well if not removed from the water. If recharge wells were constructed in sinkholes, the sinkholes could serve as natural settling basins for the sediment; however, settling and filtering basins could be constructed where needed.

WATER-LOSS STUDIES IN SELECTED SINKHOLES

Studies of infiltration, evaporation, and chemical quality of water were made at four sinkholes—Juan Lake, Hope, Marley, and North Marley (pl. 4). These sinkholes were chosen for study because of their area, depth, and accessibility.

Topographic maps of these sinkholes were prepared. Staff gages installed in the sinkholes were read periodically to measure the change in water level. Samples of the alluvial sediments underlying the floor of the sinkholes were collected by augering and were analyzed for particle size and permeability. Samples of the water ponded in the sinkholes were collected periodically and analyzed to determine kinds and concentrations of dissolved solids in the water.

The topographic maps of the sinkholes (pl. 7) do not include the entire sinkhole. Only that part of a sinkhole was mapped that seemed likely to be inundated by water during the study period. The contours for the topographic may of Marley sinkhole are referenced to mean sea-level because a bench mark of known altitude was near the sinkhole. Contours shown on maps of the other sinkholes are referenced to assumed datums.

The volume of water that would be in a sinkhole at various altitudes of the water surface was computed from the contour maps and plotted on a graph. The volume of water in the sinkhole was determined by periodic readings of the water-surface altitude. A second graph was prepared showing the volume of the water in the sinkhole in respect to time.

The loss of water from the sinkhole was considered to be entirely by infiltration and evaporation. Infiltration was not measured directly but was computed as the difference between total water loss and water loss by evaporation. The evaporation rate from Juan Lake and Marley and North Marley sinkholes was computed as 0.7 of rate measured in an evaporation pan near Bitter Lake, northeast of Roswell. The evaporation rate from Hope sinkhole was computed as 0.7 of the rate from a pan near Lake Avalon, south of Artesia. The evaporation rate of water standing in sinkholes may be more than 0.7 of the pan evaporation. Additional studies are needed to determine a more nearly exact evaporation rate.

JUAN LAKE SINKHOLE

Juan Lake sinkhole is in secs. 30 and 31, T. 12 S., R. 23 E., in the western part of the alluvial lowland area (fig. 8). Most of the water enters the sinkhole from Thirteenmile Draw, which has about 20 square miles of drainage area upstream from the sinkhole. Water flows in Thirteenmile Draw only after moderate to heavy precipitation on its drainage area. Apparently, all the water from small flows drains into Juan Lake sinkhole, but some of the water from large flows bypasses the sinkhole.

Test holes were augered 10–13 feet into the floor of Juan Lake sinkhole to obtain samples of the fill. None of the holes penetrated the full thickness of the fill. Analyses of these samples indicated that the fill is a uniform dark-brown to black clay and silty clay. (See table 5, test hole 12.) The clay has high plasticity, compactness, cohesiveness, and dry-breaking strength. Laboratory tests using variable-head permeameters indicated that the coefficient of permeability of the alluvial fill is 0.01 gpd per sq ft. This low permeability is the result of the high percentage of clay (58 percent) and fine silt (29 percent) in the fill. (See fig. 4 and table 3).

TABLE 3.—*Particle-size distribution in soil samples of alluvium in Marley, North Marley, and Juan Lake sinkholes*

[Analysed by Geol. Survey, Denver hydrol. lab.]

Sinkhole	Test hole	Depth (feet)	Weight percents of samples in indicated size ranges									
			Clay sizes (mm) <0.004	Silt sizes (mm) 0.004–0.0625	Sand sizes (mm)					Gravel sizes (mm)		
					Very fine 0.0625–0.125	Fine 0.125–0.25	Medium 0.25–0.5	Coarse 0.5–1	Very coarse 1–2	Very fine 2–4	Fine 4–8	Medium 8–16
Marley	2	3–5	62.1	32.9	2.8	1.8	0.4	------	------	------	------	------
Juan Lake	12	0–3	57.8	29.4	6.9	1.7	.6	0.8	1.4	1.3	0.1	------
Marley	3	0–3	33.5	31.6	14.2	10.8	2.8	.2	.2	2.0	2.4	2.3
North Marley	10	3–8	------	------	30.5	15.5	11.3	.4	------	4.5	2.9	3.6

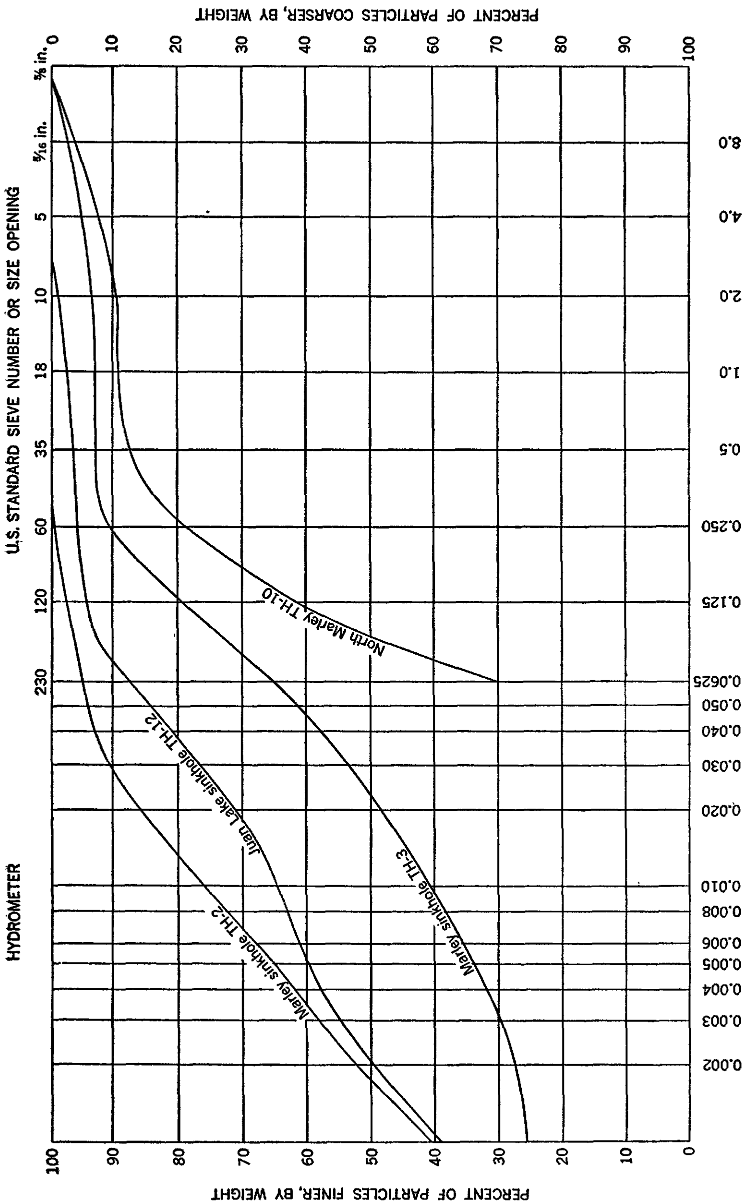

FIGURE 4.—Particle-size distribution in soil samples of alluvium in Marley, North Marley, and Juan Lake sinkholes.

Juan Lake sinkhole, if filled with water to the 52-foot contour (pl. 7), would contain 995 acre-feet of water, have a water surface area of 236 acres, and have a maximum depth of 9 feet. If the water level in the sinkhole were to rise above the 52-foot contour, the water would spill northward into North Juan Lake sinkhole. North Juan Lake, if filled to the 46-foot contour, would contain 130 acre-feet of water, have a water surface area of 17 acres, and have a maximum depth of 11 feet.

Although water entered Juan Lake sinkhole in September 1958, observations of the water level in the sinkhole were not started until October 9. The water level on that date was 46.31 feet. Figure 5 shows the change in volume of water in the sinkhole from October 1, 1958, to March 7, 1959; the graph was extrapolated to include the period October 1–9. Approximately 33 acre-feet of water, or about 30 percent of the amount in storage on October 1, was evaporated; and 87 acre-feet, or 70 percent, infiltrated the bottom of the sinkhole.

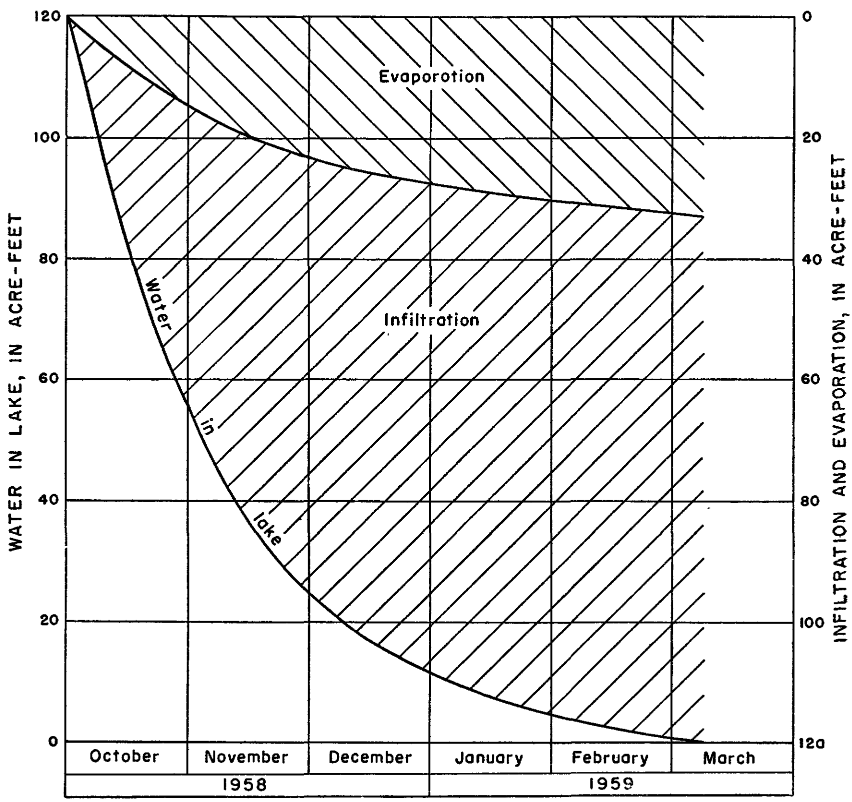

FIGURE 5.—Depletion of water in Juan Lake sinkhole by evaporation and infiltration in the period October 1, 1958, to March 7, 1959.

Infiltration data obtained for the area of the part of the sinkhole inundated during the study period probably should not be extrapolated to the area of the part above the high water level of the study period. The surface material semed to be more permeable at the higher levels in the sinkhole; therefore, water loss by infiltration probably would be larger per unit wetted area along the flank than in the lower areas of the sinkhole. Also, the infiltration rate per unit wetted area increases as the depth of water, or pressure head, increases. If the infiltration rate is comparable throughout the sinkhole, a recharge well could put several tens of acre-feet of water underground each year that under natural recharge conditions would be lost by evaporation.

MARLEY SINKHOLE

Marley sinkhole, the largest of the four sinkholes studied in detail, is a compound sinkhole in T. 10 S., R. 22 E. The shape of the sinkhole, as shown by a topographic map (pl. 7), indicates that it was formed by the coalescing of three sinkholes. The sinkhole, if filled to the 4,016-foot contour, would contain 2,000 acre-feet of water, have a water surface of 530 acres, and have a maximum depth of 9 feet.

Test holes were augered in the sinkhole area to sample the subsurface materials. Studies of the surface of the sinkhole and analyses of the subsurface materials revealed that in the southern two-thirds of the sinkhole the permeability of the floor is low within the area that would be encircled by the 4,011-foot contour. The permeability of the floor above the 4,011-foot contour is somewhat greater.

The soil in the area of low permeability is predominately a silty clay that has high plasticity and high dry-breaking strength. Laboratory tests showed that the coefficient of permeability of the silty clay is 0.007 gpd per sq ft. A particle-size analysis for this silty clay is shown in figure 4.

The area of higher permeability is underlain in part by sand and silt having high permeability and in part by silty clay having low permeability. The coefficent of permeability of a soil sample was 0.2 gpd per sq ft.

In places the silty clay is at least 48 feet thick. (See table 5, test hole 2.) This large thickness of material suggests that the deposits of silty clay settled from flood waters that ponded in the sinkhole.

Marley sinkhole is in rocks of the evaporite facies of the San Andres Limestone. A prominent escarpment east of the sinkhole has a dolomite cap overlying gypsum. The gypsum contains numerous solution openings into which water flows when Marley sinkhole is filled to capacity.

Marley sinkhole receives large quantities of water when Blackwater Draw overflows during high floods. Water entering the sinkhole from Blackwater Draw flows into the southern part of the sinkhole. When the water surface in that part of the sinkhole rises above the 4,014-foot level, water spills into the northern part of the sinkhole.

Measurements of infiltration and evaporation in the sinkhole could not be made during the study because so little water entered. A local rancher reported that the sinkhole fills about twice in a 10-year period, and, as of March 1959, the sinkhole had not filled since 1954. When the sinkhole is filled with water, the water level reportedly recedes to about the level of the 4,010-foot contour within a few weeks, but water remains for several months in parts of the sinkhole below the 4,010-foot contour. Studies should be made when the sinkhole contains water to obtain more reliable infiltration characteristics.

NORTH MARLEY SINKHOLE

North Marley sinkhole, in T. 10 S., R. 22 E., is underlain by carbonate rocks of the San Andres Limestone. These carbonate rocks are interbedded with evaporite rocks and indicate that the sinkhole area is in the evaporite facies of the San Andres. Solution channels in rocks of the evaporite facies of the San Andres exposed in adjacent areas indicate that the rocks underlying the sinkhole probably are highly permeable.

Areas along the flanks of North Marley sinkhole, particularly in the northwestern and southeastern parts, are underlain by sandy silt that was transported and deposited by the streams entering the sinkhole. Laboratory analyses indicate that the coefficient of permeability of the sandy silt is 0.4 gpd per sq ft. This coefficient is high for alluvium in the Roswell basin and is due to the large percentage of coarse silt and sand as shown in the analysis of a sample from test hole 10 (fig. 4). The central part of the sinkhole is underlain by clayey silt having a coefficient of permeability of 0.1 gpd per sq ft. The log of a test hole augered in North Marley sinkhole is given in table 5.

North Marley sinkhole, if filled with water to the 130-foot contour (pl. 7), would contain 3,700 acre-feet of water, have a water surface area of 228 acres, and have a maximum depth of 31 feet.

North Marley sinkhole, whose drainage area is about 5 square miles, seldom contains much water. Observation of the water level in this sinkhole was started on October 3, 1958. On that date the sinkhole contained 120 acre-feet of water and had a water-surface area of 50 acres. Water remained in the sinkhole 84 days. During that period, 30 acre-feet of water was evaporated and 90 acre-feet infiltrated to the subsurface. The natural rate of infiltration for that part of the sinkhole inundated during the study period was lower than anticipated. The sinkhole if filled with water to a higher level probably would have a much higher rate of infiltration per unit area, partly because the rock forming the sinkhole walls is more permeable than the alluvium in the low area of the sinkhole.

The great depth and small surface area exposed to evaporation in relation to the volume of water contained would make North Marley sinkhole an excellent site for artificial recharge.

HOPE SINKHOLE

Hope sinkhole, in sec. 33, T. 16 S., R. 19 E., is in carbonate rock of the San Andres Limestone. The walls of the sinkhole consist of carbonate rock; the floor is alluvium consisting of compact silty clay. The silty clay has high plasticity and a high dry-breaking strength. Samples of the silty clay taken from test holes in the sinkhole are similar to samples of clay from Marley sinkhole that have a coefficient of permeability of 0.007 gpd per sq ft.

The area of Hope sinkhole within the 106-foot contour is 85 acres; the area of alluvium (70 acres) corresponds to the area within the 104-foot contour. The total volume of water required to inundate the area of alluvium is 163 acre-feet. Water in excess of that amount would be in contact with carbonate rock that contains joints and solution channels.

Water entered Hope sinkhole from widespread rains on September 7, 1958, and filled the sinkhole to the 103.5-foot level, equivalent to 130 acre-feet of water. Water remained in Hope sinkhole for 179 days. Evaporation from a pan near Lake Avalon, which is 50 miles southeast of Hope sinkhole and 1,500 feet lower in altitude, was 27.6 inches, or 2.3 feet, during the 179-day period. Assuming that the evaporation loss at Hope sinkhole is 70 percent of that amount, the total evaporation loss from Hope sinkhole would be 1.6 feet. Therefore, 80 acre-feet of water evaporated from Hope sinkhole, and 50 acre-feet infiltrated the floor.

Hope sinkhole contained water part of each year during the 3 years of the investigation, and local ranchers reported that the sinkhole contains water every year. Hope sinkhole fills more often than the other three selected sinkholes.

During the senior author's visits to Hope sinkhole, the water level was never higher than the 104-foot contour (top of the alluvium). The water level probably was higher immediately after heavy rains, but it lowered quickly to the level of the upper limit of the alluvium because of the rapid infiltration of water into the joints and solution channels of the carbonate rock in the sinkhole walls above the alluvium.

A recharge well would put water underground faster than it infiltrates under natural conditions through the alluvium. The 130 acre-feet of water that was in the sinkhole at the start of the 1958–59 study period probably could have been put underground by a recharge well within 1 month, and evaporation could have been reduced to no more than 15 acre-feet. A recharge well in Hope sinkhole probably would increase the recharge to the main aquifer by at least 100 acre-feet of water in a year of normal precipitation.

PROBABLE SOURCES OF WATER FOR ARTIFICIAL RECHARGE

Low flows and most of the flood flows in the Pecos River and its tributaries have been appropriated. Under the laws and compacts, these waters probably are not available for artificial recharge of the ground-water reservoir in the Roswell basin. For the purposes of this report, the appropriated waters are not considered as a source of water for artificial recharge; however, if some of these waters were available, the size and scope of the plans for artificial recharge in the basin could be increased enormously.

Some of the flood water in tributaries normally is not a part of any appropriator's supply and might be considered as unappropriated water. Those waters not appropriated are waters that overflow the banks of tributaries and are lost by evapotranspiration before reaching a point of beneficial use. The amount of water lost in this way is unknown because flows in the tributaries are not measured in sufficient detail. This loss might be several thousand acre-feet in some years, and in other years the loss might be negligible. Additional information on tributary flows would be required to determine the volume of flow certain tributaries could transport without wasting onto flood plains.

If certain tributaries could contain a specified rate of flow within their banks and if flow in excess of that spills and is lost, then facilities could be built on those tributaries to impound or divert the surplus water for artificial recharge. In this manner the appropriator's rights would not be impaired, and water waste would be reduced.

Drainages such as Thirteenmile Draw, Zubi Draw, Greenfield Draw, Fourmile Draw, and Eagle Creek do not have well-defined channels near the Pecos River. Floods in these drainages spread over cropland and do much damage. Much of this flood water is lost by evapotranspiration. The water lost, like the water lost by evapotranspiration on flood plains, might be considered as unappropriated water and probably could be used for artificial recharge if salvaged.

Water that accumulates naturally in sinkholes may or may not be available for artificial recharge. The water that collects in some sinkholes forms natural stockwatering ponds, and depleting the water of those ponds at a faster rate than by natural means might require the construction of a facility that would make water available to stock in lieu of the pond water.

Another probable source of water for artificial recharge is that which might be salvaged after eradicating water-loving vegetation, particularly saltcedar, from the bottom land along the Pecos River and its tributaries in the Roswell-Artesia sector. Mower and others

(1964) estimated that saltcedars consumed about 52,000 acre-feet of water in 1958 in the area extending from where U.S. Highway 70 crosses the Pecos River north of Roswell to where State Highway 83 crosses the river east of Artesia. The water was derived principally from precipitation and from the alluvial aquifer. If the saltcedar were eradicated, not all the 52,000 acre-feet could be recovered and used for artificial recharge. Some measure would have to be taken to prevent saltcedar's regrowth, and most plans to do that would require some water. One plan would be to plant the denuded area with grasses whose water requirements would be less than that of saltcedar. The amount of water annually saved by this method might be put to beneficial use if it could be recovered.

Reducing water consumption in the bottom land probably would necessitate pumping some water from wells in the alluvial aquifer in the bottom land to prevent ground-water levels from rising too high. Water pumped during the summer probably would be used for crop irrigation, and water pumped in the winter might be used to artificially recharge either the main aquifer or the alluvial aquifer where the water table is several feet below the land surface. The amount of water that might be available from this operation is unknown. The ownership and probable disposal of water salvaged by control of saltcedar has not been determined.

QUALITY OF WATER WITH RESPECT TO ARTIFICIAL RECHARGE

The concentration of suspended sediments and the dissolved-solids content of surface water used for artificial recharge should be within limits that are dictated by the particular recharge operation, otherwise the efficiency of the recharge works would be impaired. Ideally, water used for artificial recharge should be free of suspended sediment and low in dissolved-solids content. Most of the surface water that might be available for artificial recharge in the Roswell basin would be low in dissolved-solids content and, therefore, would be acceptable chemically for recharge. The concentration of sediment in these waters is light to moderate in comparison with that in other New Mexico streams.

SUSPENDED SEDIMENT

Large quantities of water containing low to moderate concentrations of suspended sediment probably could be drained underground through solution holes and channels and through recharge wells in highly permeable limestone; however, the recharge efficiency of those facilities would deteriorate more slowly if the sediment load in the water was reduced. Temporary storage of the water in settling basins (sinkholes and reservoirs behind impoundment dams) would result in the settling of most of the sediment, except the colloidal materials.

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Surface water injected into the alluvial aquifer through recharge wells probably would require filtering in addition to a settling period to remove much of the very fine material that would fill the interstices of that aquifer in the vicinity of the well. Periodic pumping of alluvial recharge wells would help remove the sediment that enters the aquifer through the wells.

DISSOLVED-SOLIDS CONTENT

The dissolved-solids content of much of the potential recharge water is low and would not be a recharge problem. Water artificially recharged in some areas would reach the Roswell-Artesia sector with a dissolved-solids content too high for most uses because of the large amount of minerals taken into solution en route. Artificial recharge in such areas would not be desirable. Natural recharge should be retarded by artificial means where the water recharged gains too high a mineral concentration en route to the Roswell-Artesia sector. If water artificially recharged to the main aquifer in the northern part of the northern limestone area (pl. 4) and in the eastern evaporite-alluvial area moved to the Roswell-Artesia sector, it probably would increase the amount of highly mineralized water in that part of the main aquifer. Additional study of water quality is needed for the northern limestone and eastern evaporite-alluvial areas to determine what areas would be less likely to contribute highly mineralized water to the Roswell area. Water entering the main aquifer in most of the other recharge areas would not adversely affect the chemical quality of the water in the Roswell-Artesia sector.

The water that accumulated in the four sinkholes selected for water-loss studies was analyzed for its chemical constituents at various times. The results of these analyses show some anomalies. The sulfate content of water in Juan Lake and Hope sinkholes decreased soon after the water entered the sinkholes and then increased during the interval in which no additional water entered. The initial decrease of sulfate content may have been the result of ion-exchange from the water to clay on the floor of the sinkholes or may have been the result of the absorption of the sulfate constituents by plants and algae in the sinkhole. Specific conductance and concentrations of sodium, calcium, and potassium decreased with time in the water in North Marley sinkhole. Normally the dissolved-solids content of the water in the sinkhole should increase with time as the result of evaporation of the water. Ion exchange between the dissolved solids in water, and clay or ion absorption by plants and algae in the sinkhole, may explain the anomaly. North Marley sinkhole contains more vegetation than either Hope or Juan Lake sinkholes.

In the Roswell basin, water for recharge should be stored above ground only for short periods of time. The principal objective would be to put the water underground quickly to reduce evaporation losses; consequently, the water probably would enter the aquifer with about the same low dissolved-solids content as it had when it entered the surface-storage basin.

Certain bacteria will produce slime and algae that quickly clog screens of recharge wells and interstices of the aquifer near the well. These bacteria can be controlled by chemical treatment of the water. Additional study would be needed to determine the extent of this problem, particularly in surface basins in which recharge wells would be used. Public health agencies would have to be assured beyond doubt that bacterial contamination of the ground water would not result if surface waters were placed underground through wells.

CONCLUSIONS

Artificial recharge is one of several methods that might assist in either counterbalancing or reversing the trend of declining water levels in the main and alluvial aquifers and in combatting the deterioration of the chemical quality of ground water in the Roswell-Artesia sector of the Roswell basin. The scope of an artificial-recharge program in the basin would be governed by the amount of water that could be made available for use in recharge of the ground-water system and by the location of the water available.

Waters that probably could be made available for artificial recharge in the Roswell basin are (1) flood waters in Pecos River tributaries that are lost by evapotranspiration on flood plains, (2) floodwaters in tributaries that debouch onto lands at the terminus of the well-defined channels and are lost by evapotranspiration, (3) water that could be saved by controlling saltcedar growth in the basin, and (4) water that evaporates from ponds in sinkhole areas. For the purposes of this report, these waters are assumed to be unappropriated. The right to these apparently unappropriated waters would have to be established before proceeding with their use in artificial recharge. The scope of an artificial-recharge program could be increased if some of the appropriated water in the basin—low flows and much of the flood flows in the Pecos River and its tributaries—could be used for recharge.

Most of the waters that might be made available for artificial recharge would be obtained by salvage methods; consequently, it would be desirable to have the points of recharge at or adjacent to the points of salvage. Floodwater that would be lost on flood plains and below the terminus of well-defined channels would be salvaged upstream from the area of potential loss. One method of salvaging the water would be to restrict the streamflow to a rate at which the water would be contained within the stream banks and would infiltrate as recharge before reaching the terminus of well-defined channels. Control facilities to assist in the salvage of water from floodflows would be required on Cienega del Macho in the eastern evaporite-alluvial area; Salt Creek and Blackwater Draw in the northern evaporite area; Rio Hondo in the eastern limestone area; Thirteenmile, Zubi, and Greenfield Draws in the alluvial-lowland area; Rio Felix in the eastern limestone and alluvial-lowland areas; and Eagle Creek, Rio Penasco, Fourmile Draw, and North Seven Rivers in the eastern limestone and southern evaporite areas. The amount of water that could be salvaged from these for artificial recharge is unknown.

Salvage of water by the control of saltcedar growth would be in the bottom land along the Pecos River and lower reaches of some tributaries within the alluvial lowland. The amount of water consumed in the saltcedar areas less the amount consumed in the control of saltcedar would be the maximum amount that a water-salvage operation could undertake to recover without infringing on established water rights. Not all the water recovered would be available for artificial recharge because some would be needed for irrigation.

The amount of water lost annually by evaporation from open-water surfaces in sinkholes in the recharge area of the Roswell basin was not determined during this investigation; however, it probably is several tens of thousands of acre-feet. Computations of evaporation and infiltration losses in three sinkholes in the 6-month period, September 1958–February 1959, indicated that of about 370 acre-feet of water in those sinkholes about 163 acre-feet (44 percent) discharged by evaporation. Evaporation from individual sinkholes ranged from 40 to 65 percent. Data were inadequate to compute the evaporation from those sinkholes for a complete year of normal precipitation.

Only a fraction of the water that might be recharged artificially to the main aquifer in some areas would reach the main aquifer beneath the Roswell-Artesia sector. Most of the water recharged to the main aquifer in the northern quarter of the northern limestone area and in the northern half of the eastern evaporite-alluvial area probably would move east of the Pecos River instead of to the Roswell-Artesia sector. Some, if not most, of the water put underground in much of the western limestone area would discharge through seeps and springs within the area. Some of the water recharged to the main aquifer in the southern quarter of the eastern limestone area would move through the Dayton-Lakewood area and discharge from the Roswell ground-water basin through springs in the Pecos River. Water recharged to the upper aquifer in the Grayburg and Queen Formations in the southern part of the area would move southeastward from the Roswell basin. Water entering the main aquifer at most other points in the seven recharge areas (pl. 4) eventually would be effective recharge for the main aquifer beneath the Roswell-Artesia sector.

The question of the length of time required for water or its pressure effects to move from a point of recharge to the Roswell-Artesia sector can be answered only in terms consistent with the knowledge available when this report was prepared. In general, the elapsed travel time increases with distance from the Roswell-Artesia sector; however, travel time from recharge points equidistant from the Roswell-Artesia sector probably would be different because of permeability differences in the aquifer. The rate of water or pressure movement in an aquifer generally is more rapid along areas of greater permeability, thus the benefits of water recharged to the main aquifer along the major tributary drainages, along major structural zones, and in the vicinity of carbonate-evaporite facies boundaries in the Roswell basin probably would move faster toward the Roswell-Artesia sector than from recharge sites elsewhere in the basin. Water recharged to the main aquifer in the alluvial lowland, the northern and southern evaporite areas, and the southern quarter of the eastern evaporite-alluvial area would provide effective recharge faster to the Roswell-Artesia sector than to other recharge areas.

Solely because of speed in getting the benefits of recharge to the main aquifer in the Roswell-Artesia sector, the full recharge potential of the alluvial-lowland, the northern and southern evaporite areas, and the southern quarter of the eastern evaporite-alluvial area should be developed first. That development probably would require water-impoundment structures in upstream areas, particularly in the eastern limestone area. Development of the full recharge potential of the eastern limestone area and the southern half of the northern limestone area would be next. Development of the full recharge potential of the remainder of the recharge area would follow; however, the elapsed time necessary for recharge benefits to move from the more distant areas probably would put plans for artificial recharge in those areas only in a long-range recharge program.

In general, the dissolved-solids content in the water that might be available for recharge would be less than that in the water in the main aquifer in the Roswell-Artesia sector. The highest dissolved-solids content would be in the water salvaged in a saltcedar-control program.

Water recharged in some areas probably would increase the amount of highly mineralized water reaching the Roswell-Artesia sector because of the large mineral content gained enroute. Additional recharge in the northern halves of the northern limestone and eastern evaporite-alluvial areas probably would result in such recharge of highly mineralized water; additional recharge in all other areas probably would not. Some consideration should be given to retarding natural recharge in areas where the recharging waters bring highly mineralized water to the Roswell-Artesia sector.

The concentration of suspended sediment in floodwaters used for artificial recharge should be reduced before putting the water underground. Temporary storage in settling basins probably would reduce the sediment load to an acceptable concentration for recharge through solution openings in highly permeable limestone. Water injected through recharge wells, particularly to the alluvial aquifer, would require filtering to obtain a sediment-free water and chemical treatment to control slime, algae, and bacteria.

The alluvial aquifer can be artificially recharged directly only in the alluvial lowland. Water recharged to the alluvial aquifer in the vicinity of the Pecos River and its tributaries probably would discharge in part to those drainages through seeps and springs and, therefore, would be inefficient recharge of the aquifer. Water put into the alluvium in that part of the alluvial lowland beyond the western limit of the main ground-water body in the alluvial aquifer would move, in part, downward to the main aquifer, and, in part, move laterally eastward to the alluvial aquifer. Substantial quantities of water can be put into the alluvial aquifer through recharge wells in the general vicinity of irrigation wells that tap the alluvial aquifer.

Natural topographic features in the Roswell basin that would be useful in an artificial-recharge program are sinkholes and closed depressions and parts of stream channels where several tens or hundreds of acre-feet of water could be impounded temporarily behind small dams. Man-made facilities that could be constructed to improve the recharge capacity of these natural features are recharge wells, diversion channels between streams and nearby sinkholes, and channels within the sinkholes to obtain a more rapid distribution of water to solution openings and other permeable areas of the sinkholes.

Wells through which water could be injected into the alluvial aquifer should be of sufficient depth to permit pumping water from the aquifer to remove slime, sediment, and algae that might accumulate in the well screen and aquifer as a result of the recharge operation. The depth of wells recharging the main aquifer outside the artesian area probably can be less than the depth to the main water table if most of the well bore is in highly permeable limestone.

SUGGESTED SITES FOR ARTIFICIAL RECHARGE

The sites described in this section are the most promising ones observed during the field study. The reconnaissance allowed time for a detailed inspection in areas of the Guadalupe and Sacramento Mountains, but only a general inspection in the Vaughn-Macho plain; therefore, sites as well suited as or better suited than some of those suggested for artificial recharge probably could be found during a more intensive study.

The sites suggested are in two categories: sinkholes and impoundment areas along drainages. The sites are identified by numbers on plate 6—the numbers are for convenience of identification and do not denote a priority preference.

SINKHOLES

MARLEY SINKHOLE—SITE 1

The principal source of water for recharge in Marley sinkhole would be flows in Blackwater Draw. Blackwater Draw and associated tributaries upstream from Marley sinkhole have a drainage area of about 270 square miles. Marley sinkhole receives water from Blackwater Draw only during high floods—low floods bypass the sinkhole in a low-flow channel. When the amount of water entering the sinkhole exceeds the storage capacity of the sinkhole, water flows southward over the south rim of the sinkhole to rejoin Blackwater Draw. Downstream from Marley sinkhole, flows from Blackwater Draw pass through parts of Eightmile Draw, South Berrendo Creek, and the Rio Hondo before reaching the Pecos River. Large floods from Blackwater Draw cannot be contained within the channels of Eightmile Draw and South Berrendo Creek, and much water is lost by evapotranspiration on their flood plains. If the water lost by these means were considered to be unappropriated water if salvaged, then withholding some of the water and artificially recharging the main aquifer in an upstream area to reduce the stage of the floods to the amount that would pass through the downstream drainages without spilling onto flood plains would be a method of salvaging the unappropriated water.

The water stage in Blackwater Draw immediately downstream from Marley sinkhole could be regulated by constructing the mouth of a diversion channel leading to Marley sinkhole at an altitude that would allow floods below a certain size to pass Marley sinkhole but would divert water from floodflows that would spill over banks if permitted to pass downstream. The construction of an adequate diversion facility probably would be simple.

Better distribution of the water in the sinkhole might increase the recharge efficiency of the sinkhole. The large part (southern two-thirds) of the sinkhole fills to above the 4,014-foot contour before water flows into the smaller part (northern one-third) of the sinkhole. If a channel was cut through the divide between these two parts, water would fill the northern part of the sinkhole at the time the southern part is filling, thus putting water in contact with a larger area more quickly. Water enters the solution openings along the base of the escarpment at the east side of the sinkhole only when the water surface in the sinkhole is near the 4,016-foot level. The mouths of these openings could be lowered and channels cut to the openings to drain water to them before the water surface in the sinkhole reached the 4,016-foot level.

If water would not go underground at a sufficient rate by natural infiltration of the sinkhole floor and the solution openings, the rate could be increased by using recharge wells. Test drilling would help locate the best sites for recharge wells within the sinkhole. Large-capacity recharge wells probably could be developed at a shallow depth, probably less than 200 feet.

Marley sinkhole is close to the area of heavy pumping from the main aquifer in the vicinity of Roswell. According to the water-movement pattern shown on plate 4, water entering the main aquifer at Marley sinkhole would move directly toward the heavily pumped area.

NORTH MARLEY SINKHOLE—SITE 2

North Marley sinkhole seems to have a high potential for draining water underground if water were ponded at a high level in the sinkhole. The chief problem of artificial recharge in this sinkhole is an inadequate water supply, because the sinkhole's 5-square-mile natural drainage area does not supply much water. Some of the floodwaters in Blackwater Draw could be diverted to North Marley sinkhole. The diversion could be from the draw at a point upstream from Marley sinkhole. The diversion channel from Blackwater Draw would need to extend only to a place in the drainage area of North Marley sinkhole from which the water would drain naturally to the sinkhole. Another method of diversion would be to pump water from Marley sinkhole to the nearest place in the drainage area of North Marley sinkhole when water is in Marley sinkhole. The particular route and method of transporting water from the draw to the sinkhole could be decided after a detailed topographic survey was made of the area between the draw and the sinkhole.

If discharge studies of Blackwater Draw indicated that the amount of water available for recharge frequently would exceed the natural recharge capacity of the sinkhole, it might be feasible to increase the recharge capacity of the sinkhole by constructing recharge wells. Even though the sinkhole might function satisfactorily under natural recharge conditions for some time, the accumulation of silt from the floodwater might necessitate the construction of recharge wells later to sustain an adequate rate of recharge.

HONDO RESERVOIR—SITE 3

The Rio Hondo, like other major drainages on the east slope of the Sacramento Mountains, sometimes overflows its banks in the lowland area and loses large quantities of water by evapotranspiration. Diverting some of the water from unusually large floods to the Hondo Reservoir in T. 11 S., R. 22 E., would keep the flow of Rio Hondo within its banks and prevent wasteful flooding downstream. The water diverted to the reservoir would infiltrate underground and move toward the heavily pumped area near Roswell. The reader is referred to Bean (1949) and Theis (1951) for a description of Hondo Reservoir and its recharge characteristics.

JUAN LAKE SINKHOLES—SITE 4

The Juan Lake sinkholes in T. 12 S., Rs. 22 and 23 E., could drain to the subsurface more of the flood waters in Thirteenmile Draw if diversion structures and canals were built on the draw to shunt more waer to the sinkholes. Small floods in the draw enter the principal sinkhole, Juan Lake sinkhole, but much of the water in large floods bypasses that sinkhole. The channel of Thirteenmile Draw is not continuous to the Pecos River, and floodwaters in the draw move downstream from the sinkhole and are lost by evapotranspiration when the water spreads over lands in T. 13 S., R. 25 E. The floodwaters that normally would be lost, if considered to be unappropriated water, could be used for artificial recharge in the Juan Lake sinkholes.

A more accurate estimate of the size of floods in Thirteenmile Draw would be required to know whether or not sinkholes in this group other than Juan Lake and North Juan Lake sinkholes would be needed to contain the floods. The construction of a diversion structure in the draw and a channel to Juan Lake sinkhole while discharge studies were in progress could be the first steps in a recharge program in the vicinity of the Juan Lake sinkholes. A channel cut through the low divide between Juan Lake and North Juan Lake sinkhole would facilitate the entry of water from the draw by keeping the general water surface in the sinkhole low while the sinkhole was filling. If the amount of water available for recharge exceeds the natural infiltration rate of the sinkhole, one or more recharge wells could be constructed in the sinkhole. This might be more economical than building diversion structures and channels for other sinkholes in this group. The permeability of the main aquifer is high in the general vicinity of the Juan Lake sinkholes, according to plate 5, and large-capacity recharge wells probably could be constructed in Juan Lake sinkhole.

Most of the water infiltrating the floor of Juan Lake would discharge directly to the main aquifer, but some might move eastward through the alluvial fill and be intercepted by wells in the alluvium. Water entering the main aquifer in the vicinity of Juan Lake sinkhole would move toward the Orchard Park–Hagerman area.

FELIX SINKHOLES—SITE 5

An unnamed sinkhole in secs. 19 and 30, T. 14 S., R. 26 E., one of the Felix sinkholes, has an area of about 250 acres and has a water-storage capacity of about 900 acre-feet. This sinkhole is in the alluvial lowland, and natural infiltration of water in the sinkhole floor would recharge the alluvial aquifer. Recharge wells could be constructed to put water into the main aquifer; however, that might be too costly because the wells would have to be about 1,000 feet deep. Artificial recharge injected through this sinkhole probably should be used only to recharge the alluvial aquifer.

The permeability of the alluvium in the sinkhole may be low in the first few feet below land surface. The infiltration of water under natural conditions probably would be slow, and much water would be lost by evaporation. Water in the sinkhole could be put into the alluvial aquifer through recharge wells at a rate that would minimize the evaporation loss. The recharge wells would be shallow, probably less than 150 feet deep. Morgan (1938, pl. 1) estimated that the valley fill beneath the sinkhole is between 100 and 200 feet thick. The depth to the water table was between 90 and 100 feet in 1959, or about 50 feet below the level of 1940. If silt- and bacteria-free recharge water is used, the recharge wells probably could be less than 100 feet deep, and could discharge into the alluvium above the water table; however, if the wells are finished below the water table, they could be pumped occasionally to remove silt and algae that might accumulate in the well and aquifer.

The sources of water for recharge probably would be water from floodflows in the Rio Felix and water salvaged in a saltcedar-control program in the bottom land of the Pecos River. If water from floodflows in the Rio Felix is available, a canal or pipe line about 2 miles long would deliver the water to the sinkhole. Water from the saltcedar-control area probably would be transported by the Hagerman Canal and then pumped through a pipeline to the sinkhole.

ANTELOPE SINKHOLES—SITE 6

Antelope sinkholes in T. 18 S., R. 23 E., are in the southern evaporite area (pl. 4). The sinkholes are bottomed in highly permeable evaporite rocks. The evaporite rocks are underlain by carbonate rocks of ground-water province B (pl. 5), which have low permeability in this area. The carbonate rocks are partly in the Grayburg Formation and partly in the San Andres Limestone.

The Antelope sinkholes have sufficient volume to hold several hundred acre-feet of water. The floors and walls of most of the sinkholes seem to be highly permeable, and water should infiltrate to the subsurface rapidly. Recharge wells in some sinkholes having less permeable floors would facilitate the drainage of water to the subsurface.

The source of water for artificial recharge in the Antelope sinkholes would be floodflows in Rio Penasco and Fourmile Draw. The channels of these drainages are near the sinkholes, and short canals could connect these drainages with the sinkholes. The flow in Rio Penasco might be increased by diverting flow from Eagle Creek into Rio Penasco west of Hope. Rio Penasco, Fourmile Draw, and Eagle Creek have about a 1,400-square-mile drainage area upstream from Antelope sinkholes. Little of the floodflow that passes Antelope sinkholes in these drainages reaches the Pecos River; most of the floodflow accumulates in swampy areas near the river and either evaporates or supplies water to a dense growth of saltcedar.

Additional data on stream flow, geology, and topography are required for these drainages. Streamflow data upstream from the Antelope sinkholes would be valuable for the location and design of small impoundment dams; streamflow data downstream from Antelope sinkholes would help determine the amount of water lost by evapotranspiration.

According to the general pattern of water movement in the main aquifer (pl. 4), water entering the aquifer at the Antelope sinkholes would move toward the Artesia-Lakewood area.

IMPOUNDMENT AREAS ALONG DRAINAGES

According to water laws, water may be impounded in flood water-retaining structures for 72 hours and then must be released. Proof that the water impounded would have been lost by evapotranspiration might alter the interpretation and execution of those laws. Several sites for impounding water behind dams in stream channels are shown on plate 6; the sites designated as 7, 8, 14, 15, and 16 are reaches of the channel in which dams probably could be built; the exact location of the dams are not shown because the channels were not studied in sufficient detail. Sites 9 and 10 seem to be suitable for small dams. Floodwater-retarding structures are being built at sites 11–13 by the U.S. Soil Conservation Service.

CIENEGA DEL MACHO AND SALT CREEK—SITES 7 AND 8

Near sites 7 and 8 in Cienega del Macho and Salt Creek, a series of small dams could be constructed to impound some water from floodflows over sections of the channel having numerous solution openings. The dams would serve to prolong the period that water is in contact with those highly permeable sections of the channels.

RIO HONDO AND TRIBUTARY—SITES 9 AND 10

At sites 9 and 10 the floor and sides of the channels of the Rio Hondo and its tributary are highly permeable. The damsites shown would impound water over some of the channel area that is permeable, and, in addition, water could be released from these dams slowly to allow a longer period of contact between water and channel in areas immediately downstream from the dams.

THIRTEENMILE, ZUBI, AND GREENFIELD DRAWS—SITES 11–13

In 1958 the U.S. Soil Conservation Service was constructing flood water-retarding structures at sites 11, 12, and 13 to control the floods in Thirteenmile, Zubi, and Greenfield Draws. The largest water-impoundment area of these three is that on Zubi Draw. Recharge wells might be constructed in the water-impoundment areas behind these structures to put some water into the alluvial aquifer and possibly the main aquifer.

FOURMILE DRAW AND NORTH SEVEN RIVERS—SITES 14–16

Fourmile Draw at site 14 and North Seven Rivers and its tributary at sites 15 and 16 cut deeply into carbonate rocks, and excellent damsites and large water-impoundment areas could easily be found. Some of the floodwaters impounded could be injected into the main aquifer through recharge wells in the impoundment area. Test drilling would be necessary to determine the proper depth of the recharge wells. The permeability of the main aquifer is high at these sites, and high-capacity recharge wells probably could be developed. The controlled release of water from the impoundment areas after floods probably would result in some additional recharge to the main aquifer by increasing the infiltration of water in permeable sections of the stream bed downstream from the dams.

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BASIC DATA

TABLE 4.—*Records of selected wells in the Roswell basin, New Mexico*

LOCATION: See page 6 of text for explanation.
OWNER OR NAME: The owner or name used for well at time of visit. PVACD, Pecos Valley Artesian Conservancy District observation well.
DEPTH: Reported by owner, tenant, or driller.
DIAMETER: The diameter of the casing, if cased, or the mean diameter of the hole if uncased.
WATER LEVEL: Depths expressed to nearest tenth of a foot were measured by Geological Survey; those expressed in whole feet were reported by owner, tenant, or driller.
PRINCIPAL WATER-BEARING BED: Determined by field observation, from well cuttings, or by interpretation from maps.
STRATIGRAPHIC UNIT: Py, Yeso Formation; Psh, Hondo Sandstone Member of the San Andres Limestone; Ps, San Andres Limestone; Pg, Grayburg Formation; and Pa, Artesia Formation.
METHOD OF LIFT: N, none; P, plunger or cylinder pump, wind driven; Pe, plunger or cylinder pump, electrically driven; Pg, plunger or cylinder pump, gasoline driven; Te, turbine pump, electrically driven; Tg, turbine pump, gasoline driven.
USE OF WATER: D, domestic; Irr, irrigation; N, none; O, observation; Ps, public supply; S, stock.
REMARKS: All wells are drilled; gpm, gallons per minute; Temp., temperature of water in degrees Fahrenheit.
CHARACTER OF MATERIAL: Siltst, siltstone; ss, sandstone; carb rk, carbonate rock; sh, shale; gyp, gypsum; dolo, dolomite; ls, limestone.

Location	Owner or name	Driller	Year completed	Depth of well below land surface (feet)	Diameter of well (inches)	Altitude above mean sea level (feet)	Water level: Depth below land surface (feet)	Water level: Date	Principal water-bearing bed: Character of material	Principal water-bearing bed: Stratigraphic unit	Method of lift and power source	Use of water	Remarks
7.20.2.340	R. L. Corn			604		4,600	540	1940	Blue sandy sh.		P	S	Pumped 5 gpm.
6,410	D. Corn			700		4,946	600	4-3-50			P	S	
16.333	PVACD 1	K. G. Miller	1955	750	7-5½	4,694	452	12-31-57	Ss, gyp, and carb. rk.	Py and Psh.		O	Cased with 7-in pipe from 0 to 20 ft and with 5½-in pipe from 475 to 657 ft.
36.220	W. J. Ball			467		4,376	430	3- -50	Gray sh and carb rk.		P	D, S	Reportedly yields water of good quality. Two wells about 60 ft apart; west well not used.
7.21.12.420	Ronald Corn	George Perry		740		4,313	650		Ls	Ps(?)	P	D, S	Pumped 10 gpm. Reportedly yields water of good quality.
29.333	W. J. Ball	W. E. Doolin	1950	755	8	4,531	700	4-3-50			P	S	
7.22.19.130	Ronald Corn	Oscar Noscar		720	8	4,313	680		Ls	Ps(?)	P	S	Cased to 20 ft. Pumped 10 gpm. Reportedly yields water of good quality.

7.23.8.220						3,924	360	6- 1-50			P	D, S	
23.242	Jess Corn			426	14	3,814	239.8	5-26-51	Ls and gyp.	Ps and Pa(?)	Tg	Irr	
8.20.23.410	W. B. Jones	A. Cole	1943	450	8	4,443	438				P		Pumped 5 gpm. Reportedly yields water of good quality. Sucks dry sometimes, may have caved.
33.230	C. Marley					4,408	360	4- 3-50			P	D, S	
8.21.30.300	W. B. Jones			470		4,260	454				P	D, S	
34.240	Charles Douthitt			465		4,125	437.3	4- 4-58			P	D, S	Reportedly yields potable water.
8.22.10.214	Tom and Richard Corn.			580		4,138	545		Ss	Psh	P	S	Pumped 10 gpm.
8.23.22.211	J. Corn		1940	410	8	3,918	365	1940	Carb rk.	Ps	P	S	Pumped 15 gpm.
8.24.16.333	PVACD 10	A. H. Lewis	1957	435	8¼-7	3,622	78.9	12-26-57	Dolo, SS, and gyp.	Ps and Pa.		O	Cased with 8¼-in pipe from 0 to 155 ft and with 7-in pipe from 0 to 395 ft.
9.19.35.333	S. C. Marley		1940	280		4,747	222.2	5-16-57	Siltst(?)	Psh	P	S	
9.20.21.410	do	A. Cole	1939	550		4,490	440	1955		Psh(?)	P	S	
9.21.18.110						4,330	426.9	4-18-50			P	S	
31.133	Marley and Whitney.			425		4,305	365	5-18-50			P	S	
9.20.20.444	Alton Corn	H. R. Davis		725		4,228	675		White and yellow ss.	Psh	P	S	
35.323	Dick Alexander	do	1956	575	8	4,100	525	1956	Ss and carb rk.	Psh	P	D	Reportedly yields water of good quality.
9.23.25.324	Elmer Sons	W. E. Doolin	1948	775	10	3,675	109	1949	Ls	Ps	Tg	Irr	Cased to 297 ft. Pumped 2,000 gpm.
10.20.8.134	S. C. Marley			486	5	4,596	426	5-18-50		Psh(?)	P	S	
16.444	PVACD 2	K. G. Miller	1956	503	6	4,504	422.6	12-31-57	Ss and carb rk.	Psh		O	Cased to 503 ft.
10.21.16.222	3	do	1956	672	10-7	4,190	590.4	12-31-57	Ss and carb rk.	Psh		O	Cased with 10-in. pipe from 0 to 40 ft and with 7-in. pipe from 0 to 670 ft.
24.322a	Marley and Whitney.	do	1958	603	8	4,088	530	1958	Siltst	Psh	P	S	
10.23.12.212	Juan Sena	Ray Taylor		167	6	3,670	110	7- -56	Siltst and carb rk.	Ps		Irr	Cased to 137 ft. Deepened from 137 to 167 ft in 1956.
15.131	J. D. and R. O. Pyeatt.		1948	700	13	3,728	174.6	1-22-57	Ls	Ps	Te	Irr	

TABLE 4.—*Records of selected wells in the Roswell basin, New Mexico*—Continued

Location	Owner or name	Driller	Year completed	Depth of well below land surface (feet)	Diameter of well (inches)	Altitude above mean sea level (feet)	Water level: Depth below land surface (feet)	Water level: Date	Principal water-bearing bed: Character of material	Principal water-bearing bed: Stratigraphic unit	Method of lift and power source	Use of water	Remarks
10.23.27.234	E. M. Haley	A. H. Lewis	1949	425	16	3,725	160.9	2- 3-54	Ls	Ps	Te	Irr	Cased to 168 ft. Pumped 1,200 gpm. Yields water of good quality.
33.433	C. O. Morrow	do	1953	303	7	3,840	273		Ls	Ps	Pe	D	Cased to 51 ft.
11.20.20.442	R. C. Nunez	Bill Marschbanks.	1955	561	8	4,699	520	4- -55	Ss and carb rk.	Psh(?)	P	S	Cased to 207 ft.
11.21.9.333	J. P. White	Smith and Gibson.	1944	687		4,312	620	1956		Psh	P	S	Pumped 10 gpm.
18.333	PVACD 8	A. H. Lewis	1957	524	7	4,283	399.0	12-31-57	Ss and carb rk.	Psh		O	Cased to 524 ft.
28.144	J. P. White	L. L. Pate and L. A. Hanson.	1946	675	6	4,278	593	1946		Psh	P	S	Cased to 658 ft.
32.111	Tom White	H. R. Davis or C. Keyes.	1954	600	6	4,302	570	1956			P	S	Cased to 438 ft. Pumped 12 gpm.
11.22.2.131	H. L. Woods	A. Cole		326		3,888	312.8	5- 6-47		Ps	P	D, S	
4.221	Marley and Whitney			433		3,965	412	6-15-57	Carb rk	Ps	P	S	
18.211	H. L. Woods (State land).	Cole Bros	1947	515	6	4,066	484.1	7-14-47	Carb rk	Ps	P	S	Cased to 18 ft.
22.111	J. P. White			410		3,943	362.8	5- 5-47	Carb rk	Ps	P	S	
25.331	J. B. Patterson		1949	430	8	3,895	318.5	5- 5-47	Carb rk	Ps	Pg	S	
11.23.34.143	B. L. Brown	Case Drilling Co	1949	500	16	3,751	184.5	1-27-52	Ls	Ps	Te	Irr	
12.20.1.131	Lee B. and Harold Corn.	H. R. Davis	1945	550	8	4,559	475			Psh(?)	P	S	
8.243	J. P. White	H. R. Davis	1943	870	6	5,045	810			Py(?)	P	S	
11.341	Lee Corn		1916	600		4,680	550				P	S	
12.21.16.220	S. P. Johnson, Jr	S. P. Johnson, Jr	1948	800	6	4,436	600	6-18-59			P	S	Yields water of good quality.
27.121	Tom White	Keyes Drilling Co	1953	712	8	4,463	600	1956		Psh(?)	P	S	Temp 70° F.
12.22.12.144	Mrs. J. E. Bloom					3,874	293.7	5- 5-47	Ls	Ps	P	S	
15.344	J. B. Patterson			357		3,929	347.5	5-21-57				N	
12.23.10.331	B. L. Brown	H. R. Davis	1956	260	7	3,776	220	1956		Ps			Cased to 165 ft.
13.20.13.222	PVACD 4	K. G. Miller	1955	386	7	4,524	260.3	12-31-57	Ss	Psh		O	Cased to 386 ft.
13.21.30.120	S. P. Johnson, Jr	W. A. Melson	1950	665	6	4,786	630	6-18-59	Ls	Ps	P	S	Cased to 20 ft. Yields water of good quality.
13.22.28.232	Mrs. A. M. Threlkeld.	A. F. Smith	1952	560	8	4,046	500	1952	Ls	Ps	P	D, S	

32.211	Iva Chesser			560±		4,075	550	7- 7-58			P	S	Reportedly yields water of good quality.
13.23.6.312	State of New Mexico.	W. A. Melson	1955	424		3,945	394	7- 1-58	Ls	Ps	P	S	Pumped 9 gpm for 3 hours without any significant change in discharge. Yields water of good quality.
19.321	Mrs. Savino			500+		3,926	364.5	10-17-58	Ls	Ps	P	S	Has large drawdown. Yields impotable water.
31.444	do				10	3,917	364.8	10-25-58	Ls	Ps	P	S	Yields water of good quality.
35.333	do	Kincaid		300+	10	3,834	301.6	10-25-58	Ls	Ps	P	S	Pumped 10 gpm. Yields water of good quality.
13.24.3.411	Glaze Sacra			225	5½	3,689	165	4-24-58	Ls	Ps	P	S	Pumped 11-12 gpm. Yields water of good quality.
17.222	do					3,710	148	4-23-58	Ls	Ps	P	S	
13.24.21.224	Glaze Sacra			225	5	3,715	160	4-24-58	Ls	Ps	P	S	Pumped 11-12 gpm.
14.22.13.444	Jack Price	A. Fiddler	1934	380		3,929	368	7- 3-58	Ls	Ps	P	D, S	Pumped 3-5 gpm. Reportedly yields water of good quality.
14.23.22.214	Elvin Crow			240		3,780	220	7- 7-58	Ls	Ps	P	S	Do.
24.444	M. D. Kincaid				6	3,725	152.1	7-13-51	Ls	Ps	P	S	
33.210	Elvin Crow			400		3,910	360	7- 7-58	Ls	Ps	P	D	Pumped 3-5 gpm. Reportedly yields water of good quality.
15.20.5.130	W. F. Waller	Tom James and Ed Bryant.	1914	440		4,800	400	7- 2-58	Ls	Ps	Pg	D, S	Pumped 15 gpm. Reportedly yields water of good quality.
30.230	C. Hendricks	H. Everett	1951	525		4,777	522	7- 9-58	Ss and siltst	Psh	P	S	Pumped 3 gpm. Sands up. Yields water of good quality.
15.21.13.330	W. F. Waller	H. R. Davis	1946	660	6	4,192	600	7- 2-58	Ss and siltst	Psh	Pg	S	Pumped 5-8 gpm. Reportedly yields water of good quality.
36.220	E. J. Treat	W. A. Melson	1947	670		4,192	630	7-31-58	Ls	Ps	P	S	Do.
15.22.1.121	Elvin Crow	Leonard George	1950	395		3,970	380	7- 7-58			P	S	Pumped 3-5 gpm. Reportedly yields water of good quality.
15.23.4.311	do	Kincaid	1948	400		3,919	355.2	10-23-58	Ls	Ps	P	S	Do.
6.222	do		1920	443		3,950	403	5- 5-58	Ls	Ps	P	S	Pumped 12 gpm. Yields water of good quality.
16.20.6.210	Lloyd Treat	W. A. Melson	1944	620		4,500	58	7- 9-58	Ss and siltst	Psh	P	S	Pumped 3-5 gpm. Reportedly yields water of good quality.
10.110	do		1917	700		4,422	670	7- 9-58	Ss and siltst	Psh	P	S	Do.
16.210	R. J. Parks		1947	830		4,534	810	7-24-58	Ls	Ps	P	S	Pumped 4 gpm. Reportedly yields water of good quality. Temp. 68°F.
18.333	PVACD 5	K. G. Miller	1956	767	6⅝	4,489.0	580.1	12-31-56	Ss and carb rk	Psh and Ps		O	Cased to 610 ft.
16.21.6.330	R. J. Parks	Ray Hill	1947	660		4,300	625	7-24-58	Ls	Ps	P	S	Pumped 3-4 gpm. Yields water of good quality.

TABLE 4.—*Records of selected wells in the Roswell basin, New Mexico*—Continued

Location	Owner or name	Driller	Year completed	Depth of well below land surface (feet)	Diameter of well (inches)	Altitude above mean sea level (feet)	Water level: Depth below land surface (feet)	Water level: Date	Principal water-bearing bed: Character of material	Principal water-bearing bed: Stratigraphic unit	Method of lift and power source	Use of water	Remarks
16.21.19.220	R. J. Parks	Glenn Stevenson.	1938	760		4,377	710	7-24-58	Ls	Ps	P	S	Pumped 4-5 gpm. Reportedly yields water of good quality.
33.140	do	Ray Hill	1948	670		4,220	625	1957	Ls	Ps	P	D, S	Pumped 8 gpm. Yields water of good quality. Deepened to 670 feet in 1957.
16.23.20.233	Lyle Hunter	Haskell Harris	1951	440(?)	8	3,969	400	1951	Ls	Ps	P	S	Pumped 14 gpm. Yields water of good quality. Temp 68° F.
27.120				200	6	3,775	195.3	1-13-50	Ls	Ps(?)	P	S	
16.24.6.444	C. and M. Ranch				6	3,659	95.4	1-10-55	Ls	Ps	P	S, O	
7.214	Everhart				4	3,667	99.7	1-10-55	Ls	Ps	P	D, S	
9.343	F. T. Boyce			180	6	3,653	117.1	1-10-55	Ls	Ps		N	
10.123	do			250	6	3,595	82.3	1-10-55	Ls	Ps	P	D, S, O.	
20.130	Henry Coffin	L. A. Summers	1946	315	8	3,666	160	7-21-58	Ls	Ps	P	S	Cased to 33 ft. Yields water of good quality.
17.20.5.420	Scharbauer Cattle Co.	H. R. Davis	1938	760		4,703	710(?)	7- 8-58	Ls(?)	Ps(?)	P	S	Pumped 8 gpm. Yields hard water. Temp 62° F.
10.320	Felix Cauhape	Haskell Harris	1948	833		4,593	790	7- 8-58	Ls	Ps	P	D, S	Pumped 3-4 gpm. Yields water of good quality. Deepened to 833 feet in 1955.
18.434	PVACD 7	A. H. Lewis	1957	801	7	4,512	463	7- -57	Carb rk	Ps		O	Cased to 801 ft.
34.340	George Teel and Felix Cauhape.	H. R. Davis	1939	900		4,700	850	7- 8-58	Ls	Ps	P	S	Pumped 3-4 gpm. Yields water of good quality.
17.21.15.340	Sam Hunter	C. E. Geiser		700	8	4,215	620	1948	Ls	Ps	P, Pe	D, S	Pumped 12 gpm. Yields water of good quality. Deepened to 700 ft in May 1959.
17.410	E. F. Harris	Paul Stevenson.	1948	750	7	4,260	660	1-11-49	Ls	Ps	P, Pe	D, S	Cased to 130 ft. Pumped 10 gpm. Yields water of good quality. Temp 63° F.
17.23.9.120	R. H. McAshan	H. Everett	1948	515	8	4,000	475	6-30-58	Ls	Ps	P	S	Cased to 40 ft. Reportedly yields water of good quality.

27.132	J. C. Ward	Haskell Harris	1950	515	7	4,000	445	7-21-58	Ls	Ps	P	S	Cased to 515 ft. Pumped 3-5 gpm. Yields sulfurous water of poor quality.
30.111	Hope Cooperative Corp.	Leonard George	1954	600	14	4,100	508.9	3-17-54	Ls	Ps	Te	Ps	Cased to 558 ft. Yields water of good quality.
34.420	J. J. Steele	Haskell Harris	1947	520		3,950	500	7-21-58	Ls	Ps	P, Pe	D, S	Pumped 3-5 gpm. Yields water of good quality.
17.24.3.422	Paul Jones				6	3,713	268.0	1- 7-55	Ls	Ps	P	S, O	
11.342	do				6	3,711	261.9	1- 7-55	Ls	Ps	P	D, S	
13.334					6	3,694	238.3	1- 7-55	Ls	Ps	P	S	
25.244	Paul Jones				6	3,667	198.1	1- 6-55	Ls	Ps	P	S	
18.20.22.440	Jack Casabonne	H. R. Davis	1913	888		4,378	800	1952		Py(?)	Pe	D, S	Cased to 60 ft. Pumped gpm. Reportedly yields water of good quality.
28.120	do	do	1944	940		4,498	875	8-16-57		Py(?)	P, Pe	S	Pumped 6 gpm. Reportedly yields water of good quality.
18.21.3.420	Henry Crockett	Haskell Harris	1955	669	8	4,200	640	7-15-58			Pg	S	Pumped 18 gpm. Reportedly yields water of fair quality.
8.120	Elna Teel	Paul Stevenson	1939	888	8	4,239	630	1939	Ls	Ps	Pe	S	Cased to 20 ft. Pumped 6-8 gpm. Reportedly yields water of good quality. Temp 66° F.
18.23.8.141	O. L. Anderson	Reeves Drilling Co.	1949	460	8	3,950	400.9	7-16-51	Ls	Ps		D, S	Yields water of good quality.
8.240	R. W. Newbill	do	1949	460		3,950	420	1949	Ls	Ps	Pe	D, S	Do.
12.111	J. J. Steele	Haskell Harris	1947	620	6	3,885	463.9	1- 6-55	Ls	Ps	P	S	Cased to 300 ft. Pumped 3-5 gpm. Yields high sulfurous water of poor quality. Deepened from 540 to 620 ft. in 1956.
18.23.15.113	Paul Jones				6	3,933	441.1	1- 6-55	Ls	Ps	P	S	
15.130	Mrs. Edgar Williams.			540		3,950	475	7-21-58	Ls	Ps	P	S	Pumped 3-5 gpm. Reportedly yields water of good quality. Deepened from 480 to 540 ft in 1956.
20.410	W. M. Tulk	Black		500		4,025	460	1957	Ls	Ps	P	S	Yields water of fair quality.
18.24.11.222	Paul Jones				8	3,680	222.0	1- 5-55	Ls	Ps	P	S	
19.20.3.310	Jack Casabonne	H. R. Davis	1938	1,157	8	4,600	1,050	1938		Py	P	S	Cased to 20 ft. Pumped 5 gpm. Reportedly yields water of good quality.
16.111	PVACD 6	K. G. Miller	1956	1,120	10¼-9-7	4,591	993.2	12- -56	Ss and carb rk.	Psh		O	Cased with 10¼-in. pipe to 40 ft, with 9-in. pipe to 180 ft, and with 7-in. pipe to 1,120 ft.
19.21.5.230	Elna Teel	Paul Stevenson	1947	850	10	4,375	820	1956	Ls	Ps(?)	Pe	D, S	Pumped 6-8 gpm. Reportedly yields water of good quality. Deepened from 815 to 850 ft in 1956.

TABLE 4.—*Records of selected wells in the Roswell basin, New Mexico*—Continued

Location	Owner or name	Driller	Year completed	Depth of well below land surface (feet)	Diameter of well (inches)	Altitude above mean sea level (feet)	Water level		Principal water-bearing bed		Method of lift and power source	Use of water	Remarks
							Depth below land surface (feet)	Date	Character of material	Stratigraphic unit			
19.23. 4.222	Frank Runyan		1955	400	5	3,950	370	8-28-58	Ls	Ps	P	S	Cased to 200 ft. Reportedly yields sulfurous water of fair quality.
6.333	do		1934	585	6	4,025	502	8-28-58	Ls	Ps	P	D, S	Pumped 3-5 gpm. Reportedly yields water of good quality.
20.20.19.330	W. M. Tulk, Jr.			1,050	8	5,000	970	7-24-58		Py or Psh	P	S	Cased to 40 ft. Pumped 6-8 gpm. Yields water of good quality. Deepened to 1,050 ft in 1947.
20.23.26.131	Frank Runyan		1925	485	6	3,950	455	8-28-58	Ls	Ps	P	S	Cased to 485 ft. Pumped 3-5 gpm. Yields sulfurous water of fair quality.
21.20.35.240	Armstrong and Armstrong.		1952	1,200		5,250	1,000	10-22-58		Py or Psh	P	S	Cased to 20 ft. Pumped 4-6 gpm. Yields water of excellent quality.
21.21. 7.430	do		1924	1,300		4,760	1,100	10-22-58		Ps or Psh	P	D, S	Cased to 140 ft. Pumped 4-6 gpm. Yields water of good quality.
36.213	C. F. McWilliams	T. Hillyer	1941	962	6	4,550	942	1948	Ls	Ps	P	S	

TABLE 5.—*Logs of selected shallow test holes*

[See figs. 3 and 4 for particle-size distribution of material in selected intervals in these test holes]

	Thickness (feet)	Depth (feet)
Test hole 2—Marley sinkhole—sec. 20, T. 10 S., R. 22 E.		
Alluvium:		
Clay, slightly silty, calcareous, dark-brown, cohesive, compact; high plasticity; very high dry-breaking strength; contains much organic material	5	5
Clay; similar to 0–5 but has less organic material	8	13
Clay, slightly silty, calcareous, light-yellowish-brown, cohesive, compact; high plasticity; high dry-breaking strength	15	28
Clay, silty, calcareous, light-brownish-yellow, cohesive, compact; high plasticity; medium dry-breaking strength	5	33
Clay, silty, calcareous, yellowish-brown, cohesive; medium plasticity; medium dry-breaking strength	15	48
Test hole 3—Marley sinkhole—sec. 20, T. 10 S., R. 22 E.		
Alluvium:		
Silt, calcareous, slightly sandy, yellowish-tan, coarse-grained, well-sorted; low plasticity; contains a scattering of granule to small pebble-sized gravel partly coated with calcium carbonate	6. 5	6. 5
Clay, silty; similar to 0–6.5, but contains more gravel	1	7. 5
Silt, calcareous, slightly sandy, yellowish-tan, well-sorted; contains a scattering of granule to medium pebble-sized gravel partly coated with calcium carbonate	1	8. 5
Silt, gravelly, sandy, coarse-grained, well sorted; low plasticity; contains well-sorted very fine and coarse sand to angular medium pebble-sized gravel	4. 5	13
Gravel, calcareous, sandy and silty, granule- to medium-pebble-sized, subangular to subrounded, poorly sorted; matrix is predominantly very fine sand	3	16
Test hole 10—North Marley sinkhole—sec. 7, T. 10 S., R. 22 E.		
Alluvium:		
Silt, slightly sandy, calcareous, coarse-grained, well-sorted; low plasticity, low dry-breaking strength	3	3
Silt, sandy, calcareous, coarse-grained, poorly sorted; contains some sand and granule-sized gravel	4	7
Gravel, mostly limestone, angular to well-rounded; as much as 1 inch in diameter	6	13
Test hole 12—Juan Lake sinkhole—sec. 31, T. 12 S., R. 23 E.		
Alluvium:		
Clay, calcareous, dark-brown to black, cohesive, compact; high dry-breaking strength	4	4
Clay, silty, yellowish-tan, cohesive; medium plasticity; high dry-breaking strength	9	13

TABLE 5.—*Logs of selected shallow test holes*—Continued

	Thickness (feet)	Depth (feet)
Test hole 15—Blackdom terrace—SW¼ sec. 31, T. 12 S., R. 23 E.		
Clay, silty, yellowish-tan; high plasticity; contains a few silty lenses and calcareous nodules	8	8
Silt, clayey, sandy, calcareous, yellowish-tan, poorly sorted; contains subangular to subrounded granule-sized gravel	5	13
Gravel, limestone, sandy, granule- to large pebble-sized, subangular to subrounded; contains some coarse sand	4	17
Test hole 16—Orchard Park terrace—SW¼SW¼SW¼ sec. 24, T. 12 S., R. 25 E.		
Sand, quartzose, brown, medium-grained, subrounded to well-rounded, well-sorted	0. 8	0. 8
Sand, very silty and clayey, poorly sorted	. 2	1. 0
Silt and sand, reddish-brown, moderately well sorted, wet; contains coarse-grained silt and very fine sand; some caliche	1. 5	2. 5
Silt, clayey, very dark-brown; has white spots, low plasticity, friable; scattered sand grains; impregnated with white caliche	1. 5	4. 0
Silt, very sandy, slightly clayey, yellowish-brown, coarse-grained, moderately sorted; low to medium plasticity; some very fine to fine sand; scattered caliche, amount decreases between depths of 4.0–6.0 feet	2. 5	6. 5
Sand, siliceous, slightly silty, brown, very fine- to medium-grained, subangular to well-rounded, moderately well sorted	1. 5	8. 0

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