United States

Department of the Interior

Geological Survey

Geology and ground-water resources of the Verde River Valley near Fort McDowell, Arizona

by

Harris R. McDonald and Harold D. Padgett, Jr.

Prepared in cooperation with the city of Phoenix

45-109

Tucson, Arizona

November 1, 1945

CONTENTS

TABLES

Illustrations

Water resources of the Verde River Valley near Fort McDowell, Arizona

by

H. R. McDonald and H. D. Padgett

ABSTRACT

The Verde River is a perennial stream that rises about 20 miles north of Prescott, Arizona, and flows southeast and then south to its junction with the Salt River about 20 miles northeast of Phoenix, Arizona. The area considered in this report is the lower part of the Verde Valley, below Bartlett Dam. In this area the Verde Valley is cut in valley-fill deposits that occupy a basin formed by downfaulting in ancient crystalline rocks. The Salt River approximates the southern boundary, the eastern boundary is a line through Stewart Mountain, the Rio Verde Ranger Station and Sheep Mesa, and the McDowell Mountains form the western boundary. About five miles below Bartlett Dam, Camp Creek, an intermittent stream, enters the Verde River from the northwest. Opposite the community of Fort McDowell, Sycamore Creek, also an intermittent stream, joins the Verde from the east.

The flood plain of the Verde River ranges in width from one to three-quarters of a mile, and the main channel is from 1,000 to 1,500 feet wide. At the surface of the flood plain on either side of the main channel is either gravel and sand, or sandy silt overlying coarser material. The river gravels, which underlie the flood plain to a maximum depth of about 90 feet, occupy a wide and irregular trough carved by the river in the older valley-fill deposits. The river channel swings from one side of the flood plain to the other in its course from Bartlett Dam to its junction with the Salt River, forming isolated areas of flood plain. These flood-plain segments are rather stable, and the well fields of the City of Phoenix have been developed on two of them at the west side of the river. Water is supplied to the wells by the underlying saturated gravels, through which water is transmitted directly from the river.

Prior to 1922 the city obtained its water supply from wells in the Salt River valley. In that year an infiltration gallery was constructed on the flood plain of the Verde River. The water thus obtained reached the city by gravity through a pipe-line and two tunnels. The quality of the water was far superior to that of the water from the city's original wells, and from deeper wells drilled more recently in the Salt River valley. About 1927 the need for additional water led to the drilling of four wells in the area now known as the upper well field. Later, several wells were drilled about three miles south of the first ones, and this area is now called the lower well field.

Bartlett Dam, which is on the Verde River about 15 miles upstream from the city's present gallery and wells, was built primarily to store flood waters for release to the Salt River Valley Water Users Association for irrigation. Each year, when the reservoir is emptied, the silt deposits in the reservoir are exposed to erosion by the river. During the period of low flow a part of the silt is removed from the reservoir and redeposited in the channel downstream. These deposits are highly effective in sealing up the pore spaces in the river gravels that supply water to the Verde wells. When the flow of the river is increased sufficiently to produce scouring action in the channel, the silt is carried away and favorable recharge conditions are restored.

The principal source of water for the city's Verde wells is recharge from the surface flow and underflow of the Verde River, although some water is received from the older valley-fill deposits bordering the valley. The recharge area for the river gravels that supply the wells lies between the city's present brush diversion dam, near the mouth of Sycamore Creek, and a point about 1,000 feet southeast of the detritor, at the southern part of the lower well field. The maximum rate of infiltration from the river, as determined from tests made under favorable conditions, is two feet a day over the wetted area. The maximum effects of silting occur during periods of low flow in the river. Seepage measurements made under different conditions of silting indicated that, with the same flow in the river, the recharge is more than twice as great under conditions of minimum silting as when the effect of silting is at a maximum.

Mutual interference among wells in the lower well field is too small to be of any practical importance. Interference among wells in the upper well field during periods unfavorable for recharge is so great that only two of the six wells should be operated. Also, at such times, the interference of these wells with the infiltration gallery is serious. In 1944 the yield of the gallery declined from more than 5 million gallons a day to less than half a million gallons a day during the period of maximum silting of the river gravels.

It is estimated that if the water table were lowered 10 feet over the 2,960 acres comprising the upper and lower well fields, 152 million gallons of water would be released from storage, which can be removed by the existing wells at a maximum rate of only 7 or 8 million gallons a day. This stored water represents a reserve supply which is largely unused except during the relatively short periods unfavorable for recharge. Even at such times all water pumped from the existing wells in excess of about 8 million gallons a day must be derived from recharge.

Large quantities of water are stored in the river gravels and the older fill from the upper end of the valley to the Sycamore staff gage, near the mouth of Sycamore Creek. For each foot that the water table is lowered in this area about 236 million gallons of water is yielded from storage. It is believed that about 10 feet is the greatest amount that the water table could be lowered in this stretch by means of any feasible system of wells. Tests made on the effects of silting indicate that complete sealing will never occur, and therefore that some recharge from the river will always occur to supplement the storage.

Geophysical probes made with the Gish-Rooney electrical-resistivity apparatus indicate that productive water-bearing sands and gravels underlie two areas in the Verde Valley upstream from the present well fields, and that additional public-supply wells could be drilled in these areas. Test wells must be drilled and pumped before the yield of well fields in these areas can be estimated.

Artificial methods of recharge are practiced in the present well fields, by diverting water from the river to channels dug near the wells. These practices should be continued in the present well fields and should be undertaken in any new well fields that may be developed. Present practice could be improved by careful operation of the diversion gates to prevent silt-laden water from entering the artificial recharge channels.

It is believed that the city could develop a permanent supply of at least 56 million gallons a day from wells properly spaced along the Verde River from Bartlett Dam to its junction with the Salt River. Additional quantities may be developed by increasing the minimum flow in the river and by artificial recharge in channels kept free of silt-laden water.

INTRODUCTION

Cooperation

A cooperative agreement between the City of Phoenix and the United States Geological Survey was signed in May 1944, calling for an intensive investigation of the ground-water resources of a part of the Verde River valley near Fort McDowell, Arizona. Geologic and hydrologic field work was started immediately and was substantially completed by July 1945. Owing to difficulty in obtaining a well driller, the exploratory test wells have not all been completed. Results of the test drilling will be reported as soon as possible.

The work was under the general direction of O. E. Meinzer, geologist in charge of the Division of Ground Water in the Geological Survey, and under the immediate direction of S. F. Turner, district engineer of the Division of Ground Water in Arizona. Mr. Benjamin E. Jones of the Geological Survey began the geophysical explorations at the start of the project. Mrs. Theda P. Shelley assisted with the pumping tests and in checking computations. Miss Mary Scott assisted with the preparation of the manuscript, and Miss Geraldine Morris prepared the illustrations. Messrs. S. F. Turner, T. W. Robinson, J. F. Hostetter, and J. Z. Thompson took part in the field work.

Acknowledgements

The writers are grateful for the valuable assistance given by the Honorable J. R. Fleming, Mayor of Phoenix, Mr. J. Roy Heyne, city manager, and Mr. Richard Bennett, city engineer. Mr. John Smith, pump foreman, cooperated in every way to facilitate the work. An expression of gratitude is also due the several ranchers in the surrounding area, the Tribal

Council of the Mohave-Apache Indians, officials of the Indian Service and of the Salt River Valley Water Users Association, and others for their helpful cooperation.

Previous investigations

The only previous ground-water investigation of this area known to the writers was conducted by the consulting-engineering firm of Black and Veatch, Kansas City, Missouri, in 1928. It included a study of the Verde infiltration gallery, wells, and pipe-line. Several test wells were drilled on the Verde in search of locations for additional wells to supply the City of Phoenix, and studies were made of water levels and quality of water in the Indian Bend country of the reentrant zone in the Paradise Valley. Several independent problems, primarily concerned with increasing the amount of water discharged by the Verde infiltration gallery, were investigated by the City Engineering Department. It was found that by diverting part of the flow of the Verde River to the west bank of the channel, recharge to the aquifers supplying the wells was increased. This practice has been maintained to the present time.

Purpose and scope of present investigation

The primary purpose of the present investigation was to determine the permanence and adequacy of the water supply of the Verde River gravels for municipal supply for the City of Phoenix. The following problems were investigated:

1. The source, rate of movement, and direction of flow of the ground water in the Verde River valley below Bartlett Dam.

2. The rate of recharge to and the quantity of underground storage in the present well fields and in the valley, and the effect of silting on the recharge from the Verde River.

3. The interference between the existing wells and the best spacing for new wells.

4. The sites for new wells that may be drilled to furnish adequate water.

5. Utilization of the ground-water supply of Paradise Valley.

BIBLIOGRAPHY

Barnes, W. C., Arizona place names: Univ. of Ariz. Gen. Bull. 2, vol. 6, No. 1, p. 258, Jan. 1, 1935.

Black and Veatch, Unpublished report on the water works system, Phoenix, Arizona, p. 63, 1928.

Eckis, Rollin, Geology and ground-water storage capacity of valley fill, South Coastal Basin investigation: California Division of Water Resources, Bull. 45, pp. 85-94, 1934.

Eve, A. S., and Keys, D. A., Applied geophysics in the research of minerals: Cambridge Univ. Press, pp. 63-131, 1938.

Gatewood, J. S., Robinson, T. W., Colby, B. R., and Hem, J. P., Use of water by river-bottom vegetation in lower Safford Valley, Arizona, U. S. Geol. Survey unpublished report, p. 81, Jan. 1945.

Grover, N. C., and others, Surface water supply of the United States, Part 9, Colorado River Basin: Geol. Survey Water-Supply papers as follows: No. 704, p. 111, 1930; No. 719, p. 116, 1931; No. 734, p. 127, 1932; No. 749, p. 109, 1933; No. 764, p. 143, 1934; No. 789, p. 166, 1935; No. 809, p. 176, 1936; No. 829, p. 187, 1937; No. 859, p. 268, 1938.

Guyton, W. F., Depleted wells at Louisville recharged with city water: Water Works Engineering, vol. 98, No. 1, p. 18-20; Jan. 10, 1945.

Heiland, C. A., Geophysical exploration, Prentice Hall, Inc., pp. 619-819, 1940.

Jakosky, J. J., Exploration geophysics: Times-Mirror Press, pp. 249-380, 1940.

Lee, Willis T., Underground waters of the Salt River Valley, Arizona: U. S. Geol. Survey Water-Supply Paper 136, pp. 99-100, 1905.

Meinzer, O. E., Plants as indicators of ground water: U. S. Geol. Survey Water-Supply Paper 577, p. 1, 1927.

Meinzer, O. E., and Wenzel, L. K., Hydrology, Physics of the Earth Series, vol. 9, McGraw Hill Book Co., Inc., p. 453, 1942.

Paulsen, C. G., and others, Surface water supply of the United States, Part 9, Colorado River Basin: U. S. Geol. Survey Water-Supply Paper 879, p. 302, 1939.

Smith, H. V., and Smith, M. C., Mottled enamel in Arizona and its correlation with the concentrations of fluorides in water supplies: Univ. of Ariz., College of Ag. Tech. Bull. 43, p. 284, 1932.

BIBLIOGRAPHY Cont.

Theis, C. V., The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., pp. 519-524, 1935.

Tolman, C. F., Ground water, McGraw Hill Book Co., Inc., p. 467, 1937.

Turner, S. F., and others, Water resources of Safford and Duncan-Virden Valleys, Arizona and New Mexico: U. S. Geol. Survey (mimeographed), p. 27 and table 22, Oct. 13, 1941.

Turner, S. F., and others, Geology and ground-water resources of Safford Valley, Arizona: U. S. Geol. Survey water-supply paper, in preparation.

Turner, S. F., and Robinson, T. W., A laboratory method for determining the physical properties of unconsolidated material, with special reference to specific yield: U. S. Geol. Survey, in preparation.

Wenzel, L. K., Methods for determining permeability of water-bearing material, with special reference to discharging well methods: U. S. Geol. Survey Water-Supply Paper 887, pp. 50-97, 1942.

GEOGRAPHY

Location

The area considered in this report is the Verde River valley below Bartlett Dam. The valley is in Maricopa County, Arizona, and is a part of the Mexican Highland section of the Basin and Range province. The Verde River flows southward through a broad intermontane trough and enters the Salt River, which flows westward across the lower end of the valley. The valley is bounded on the north by Bartlett Dam and the rugged, hard-rock country northwest and southeast from it, at approximately 33°50' N. Lat.; the Salt River approximates the southern boundary at about 33°33' N. Lat.; the McDowell Mountains form the western boundary at about 111°50' W. Long.; and the eastern boundary is a line through Stewart Mountain, the Rio Verde Ranger Station, and Sheep Mesa, at approximately 111° 35' W. Long. (pl. 2).

The Verde River is a perennial stream rising in T. 17 N., R. 2 E., about 20 miles north of Prescott, Arizona. The first half of its course is in a southeasterly direction and the remainder in a southerly direction. The mean daily discharge of the Verde River below Bartlett Dam, where the drainage area is 6,168 square miles, for the period 1903-44, inclusive, was 780 second-feet. The minimum natural flow during the above period was 32 second-feet.[1] The channel is characterized by a series of pools

[1] Surface water supply of the United States, Part 9, Colorado River Basin, U. S. Geol. Survey water-supply papers listed in bibliography.

separated by rapids, and averages about 150 to 200 feet wide with a discharge of 600 second-feet. Since 1939 the flow through the valley has been controlled by Bartlett Dam, which was constructed for and is operated by the

Salt River Valley Water Users Association for the purpose of impounding flood waters for irrigation use. About 20 miles upstream from Bartlett Dam the Horseshoe Dam is now under construction by the Defense Plant Corporation to provide additional storage for flood waters to be used by the Salt River Valley Water Users Association in exchange for water taken from the Gila River near Morenci, Arizona, by the Phelps-Dodge Corporation.

The Verde River leaves Bartlett Dam at an elevation of 1,600 feet above mean sea level and enters the Salt River at an elevation of 1,320 feet. The distance along the stream between these points is 22 miles, which gives the Verde a gradient of about 13 feet to the mile in this area.

Five miles below Bartlett Dam, Camp Creek, an intermittent stream, joins the Verde River from the northwest. Its gradient is about 100 feet per mile. Opposite the community of Fort McDowell another intermittent stream, Sycamore Creek, enters the Verde from the east. Sycamore Creek originates at the foot of the west slope of Mount Ord and flows in a southerly direction to the Ranger Station, where it turns and flows south of west to enter the Verde. The gradient is about 50 feet per mile in the lower reach.

Fort McDowell, approximately in the center of the area, is 22 miles east and 13 miles north of Phoenix, Arizona, and 9 miles east and 16 miles north of Mesa, Arizona.

The Camp McDowell Indian Reservation is a strip of land 4 miles wide, about 2 miles on each side of the Verde River, extending about 10 miles northward from Mt. McDowell, with an area of 25,688 acres. Adjoining the reservation on the south is the Salt River Indian Reservation, and on the north and east is the Tonto National Forest. The land bordering the Camp McDowell Indian Reservation to the west is privately leased range land.

Maps and surveys

The area is covered by topographic maps issued by the Geological Survey, United States Department of Interior, as follows:

The main part of the valley is shown on the Fort McDowell quadrangle, but the extreme western part is shown on the Camelsback quadrangle, which adjoins the Fort McDowell quadrangle on the west. Both of these are mapped on a scale of 1:62,500 and with a contour interval of 50 feet, and were surveyed in 1904. The northern part of the area is in the Cave Creek quadrangle which was mapped on a scale of 1:125,000 and with a contour interval of 100 feet, and was surveyed in 1930. These maps were used in mapping the geology.

The Office of Indian Affairs, United States Department of Interior, has made two large-scale topographic maps of the irrigable portions of the reservation, and these have been used to compile a base map showing the wells, geophysical probes, and other features within the reservation.

The Forest Service, United States Department of Agriculture, has compiled a small-scale map of the Tonto National Forest and surrounding areas which includes the lower Verde River Valley and shows section lines, roads, drainage, settlements, and other cultural features.

The City of Phoenix has detailed maps of its present well fields and pipe-lines, and has also made aerial photographs of the flood plain of a part of the lower Verde River valley on a scale of 1:2,400.

The Salt River Valley Water Users Association has aerial photographs of the entire flood plain of the Verde River to the scale of 1:190,000.

The State Highway Commission has issued a map of Maricopa County to the scale of 1:63,360, which shows section and township lines, drainage, cultural features and, to some extent, the topography.

Routes of travel

The lower Verde River valley is accessible by two routes. The principal route is a graded road that enters the southern end of the valley through the Salt River Indian Reservation and the McDowell Mountains. The other route is a graded road that enters the northern end of the valley from Paradise Valley, around the northern end of the McDowell Mountains. A little-used road runs the length of the valley and connects the two roads mentioned above.

Bartlett and Horseshoe Dams on the Verde River are reached by graded roads from Phoenix, by way of the settlement of Cave Creek.

The area is skirted on the east by the Bush Highway, a graded road that leaves U. S. Highway 70 eight miles east of Mesa, Arizona, running north to Granite Reef and Stewart Mountain Dams and thence to Sunflower and Payson. Several other roads used by ranchers enter the lower Verde River ~~River~~ Valley from the Bush Highway.

Climate

The climate is desert, with low humidity and little precipitation. There are two periods of rainfall during the year. One is in January and February and the other, characterized by thundershowers, is in July and August. In general it is cool and dry in winter and very hot and dry in summer.

A summary of the climatological records at the Granite Reef Dam appears in table 1 below and can be considered to apply to the lower Verde River valley. A station has been maintained for five years at Bartlett Dam, but the short period of the record limits its present value. However, there is a similarity to the Granite Reef record.

Vegetation

On the flood plain and low terrace along the Verde River the vegetation consists mostly of mesquite, cottonwood, and willow trees, baccharis brush, and some annual grasses. Along the dry washes in the area mesquite, palo verde, and ironwood are most abundant. On the rocky slopes and high terraces mesquite, creosote bush, cholla cactus and saguaro or giant cactus, and ocotillo are abundant, with annual and some perennial grasses.

Agriculture

Within the reservation about 250 acres of the Verde River flood plain and low terrace is cultivated, the chief crops being wheat, barley, corn, pumpkins, and melons; some maize and a little hay are also grown. The rest of the reservation is range land, which in normal years supports about 700 head of cattle; in dry years this number is greatly diminished.

The valley outside the reservation is practically all range land, of which less than 50 acres is under cultivation.

Settlements and population

Fort McDowell, the only settlement in the area, consists of a church, school, Indian Service Agency, and several residences. About 200 Indians of the Mohave-Apache tribe live on the Camp McDowell Indian Reservation, chiefly on the flood plain west side of the river in the stretch from about two miles below Fort McDowell to four miles above.

Outside the reservation about five ranchers and their families, less than 30 people altogether, comprise the balance of the population.

Table 1. Summary of climatological data for station at Granite Reef Dam through 1940.
(From records of U. S. Weather Bureau)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ann.
Mean max. temp.	66	69.6	75.9	84.1	92.5	101.8	104.5	102.0	97.9	87.9	75.9	67.0	85.4
Mean min. temp.	37.7	40.8	44.5	49.7	57.1	64.3	75.0	74.1	67.5	55.5	44.9	38.5	54.1
Mean temp.	51.2	54.8	60.2	67.3	75.6	84.7	92.0	90.1	84.3	72.8	60.1	52.4	70.5
Extreme max. temp.	90	91	97	105	116	119	121	118	115	108	100	89	121
Extreme min. temp.	10	17	22	22	31	41	55	46	39	20	16	15	10
Mean precipitation	1.05	1.19	0.82	0.43	0.15	0.12	1.18	1.27	0.83	0.48	0.82	1.36	9.70
Greatest monthly precipitation	5.65	4.81	3.47	3.20	1.17	1.00	9.16	7.17	4.11	2.94	3.22	5.70	9.16
Year of occurrence	1916	1891	1884	1878	1917	1876	1872	1872	1887	1911	1905	1867	1872

GEOMORPHOLOGY

Prior to the series of events that produced the present structure and land forms (see pl. 2) the area was underlain by crystalline rocks, principally granite and schists. The surface was of moderate relief, and it seems likely that sedimentary deposits accumulated only in local areas; probably deflation proceeded at about the same rate as weathering and disintegration, except in the deeper depressions.

In Late Tertiary time a considerable thickness of volcanic material was deposited on this surface. The first deposit was volcanic ash, but the material consists predominantly of lava flows. All the area was covered by these flows, with the possible exception of the higher parts of the McDowell Mountains.

A period of deformation involving considerable displacement followed, probably in pre-Miocene time. The block of crystalline rocks whose axis trends approximately southeast from Bartlett Dam, parallel to the axis of the McDowell Mountains, was tilted downward along its western edge, where the displacement is probably at least 2,000 feet. Although this tilted block moved broadly as a unit, it was composed of a group of smaller fault blocks which were displaced in different amounts and tilted in slightly different directions, to establish the general trend of the composite block. Step faulting and faulting across the general trend were the dominant processes in forming the structural trough that underlies the valley. The displacement was progressively greater toward the west and is presumed to have reached a maximum somewhere east of the McDowell Mountains.

The deformation resulted in an enclosed basin, in which stream and lake sediments were deposited. The fluviatile detritus consists of fanglomerate at the edge of the valley, grading into finer material toward the center of the valley, where it interfingers with the playa deposits occupying the central part of the valley. The valley fill culminated in a playa surface at least 500 feet above the present river level at Fort McDowell.

Through drainage was established during the Pleistocene epoch, and its advent ended the accumulation of valley fill. The present valley was carved out of the largely unconsolidated valley-fill deposits. The process of downcutting was retarded for long periods of time at three different levels, and remnants of the three resulting terraces are clearly defined in many places. The lowest terrace is separated from the present flood plain by an escarpment that averages 25 feet in height and is capped by water-worn gravel, sand, and boulders with a considerable range in thickness and degree of cementation. The middle terrace is separated from the lowest by a definite escarpment in some places and a gentle slope elsewhere, the difference in elevation averaging 30 feet. The surface of the middle terrace is underlain by a conglomerate of differing thickness and degree of cementation, composed of well-rounded particles. The surface grades into the upland slope that reaches back to hard rock, except where this slope is broken by the group of hills that lie along the western boundary of the reservation. Capping these hills are remnants of the upper terrace, underlain by a well-cemented conglomerate that has an average thickness of 25 feet and lies 250 feet above the present river channel. No remnants of this terrace were observed elsewhere in the valley.

West of the river the upland slope between Camp Creek and the southern boundary of Tonto National Forest is an unusually smooth piedmont alluvial plain. This surface is underlain by a partly cemented caliche conglomerate that thins gradually toward the center of the valley. South of this area comparable pediments appear to have developed on both sides of the river, but owing to the proximity of the Salt River and Sycamore Creek and to the narrowing of the Verde Valley, they have been thoroughly dissected.

The valley-fill sediments at one time covered the hard rocks at the edges of the valley to a higher elevation than they do now. The drainage system was developed on the unconsolidated sedimentary material, and as downcutting of the main valley progressed the tributary streams held their previously established courses across hard rock barriers that normally would have resisted erosion. This may be seen in several of the washes that enter the Verde River from the east.

The present flood plain of the Verde River below Bartlett Dam ranges in width from one- to three-quarters of a mile and the relatively narrow stream channel swings from one side to the other. At the surface in the flood plain is fine material, largely silt, which overlies gravels and sands laid down in former channels of the river. The river has not showed much tendency to cut into and destroy the areas of the flood plain lying outside the present channel; consequently these areas have been developed for human use. Much of the farming is done in these areas and the entire water supply for the City of Phoenix has been developed in them.

GEOLOGY

Structure

The lower Verde River valley is a structural depression caused by step faulting, the total displacement increasing progressively toward the west side of the valley. No faults were actually observed, but the indirect evidence appears to be conclusive. The principal evidence is the occurrence of numerous tuff-and lava-capped knolls and mesas with dips of 5 to 30 degrees toward the west.

The valley-fill material dips toward the center of the valley at angles of 1 to 5 degrees. The higher angles are found in the fanglomerate around the edge of the valley. The dips decrease toward the center of the valley, and become too small to measure some distance before the lacustrine material is reached. The exposed section is conformable throughout, and has not been disturbed since it was deposited. The sediments overlap the hard rocks in a depositional contact. In the central part of the valley, the bedrock has never been reached in drilling. In the vicinity of city well 8 a geophysical probe (No. 3) indicated material thought to be bedrock at a depth of about 350 feet. Another probe (No. 17) further upstream failed to indicate bedrock to a depth of more than 700 feet.

Crystalline rocks

Crystalline rocks enclose the valley continuously except at the southeast edge, where they are covered - but probably not deeply - by alluvium. Except for the southern three-quarters of the McDowell Mountains, which is made up of metamorphic rocks, chiefly gneiss, the crystalline rocks in the area around the valley are granite. In the geologic mapping the crystalline rocks were not differentiated. The granite is almost everywhere coarse-textured. The feldspar crystals commonly are half an inch in diameter and sometimes an inch and a half. Veins and pipes of massive quartz are numerous.

The pre-volcanic surface of the crystalline rocks is preserved beneath the volcanic cover at many places; however, good exposures of the crystalline-volcanic contact occur at only a few places. From these limited exposures it appears that prior to vulcanism and deformation the surface was a peneplain. From Bartlett Dam to the volcanics at Brown's ranch a considerable thickness of detrital material, at least 100 feet, accumulated prior to the volcanic activity. It appears to have disintegrated in place. This is the only area where an appreciable amount of detritus is known to have been preserved at the crystalline-volcanic contact.

One granite knoll occurs well within the valley, a quarter of a mile east of the Verde River and half a mile north of the Indian reservation. Others probably will be shown to lie beneath the surface when further geophysical exploration is done on the east side of the river. One well, (No. 8. pl. 1) is reported to obtain water from a joint in the granite that was encountered at a depth of 113 feet.

Volcanic rocks

Lying upon the crystalline rocks at many places around the valley is a series of volcanic rocks. The basal unit is an even-bedded to massive felsite tuff, ranging from 10 to 100 feet in thickness. It is tan in fresh exposures and weathers to a buff color. In some places the tuff contains beds of coarser pyroclastic material. The greatest thickness of tuff was noted at Brown's ranch, T. 5 N., R. 5 E., where it is about 100 feet thick. It has a 30-degree dip to the northwest, is evenly thick-bedded, and is capped by several successive flows of vesicular lava aggregating 75 feet in thickness. Elsewhere in the valley the tuff is thinner, averaging about 30 feet in thickness.

At Brown's ranch a well 204 feet deep penetrated fill and tuff to within a few feet of the bottom, where water was encountered under pressure in a fissure in lava and rose within 75 feet of the surface. The massive tuff at the ranch was once quarried for building stone and is reported to have yielded fossil footprints.

Overlying the tuff are successive lava flows of differing composition, aggregating 25 to 350 feet in thickness in the vicinity of the Verde Valley.

Tertiary sandstones

Mount McDowell, near the southern end of the Verde River valley, is comprised of more than 1,000 feet of sandstones, siltstones, shales, and interbedded tuffs and lavas, the sandstones largely predominating. The color of fresh exposures is buff to tan and weathered surfaces are brick red. Sorting is poor to fair, and the beds are distinct and range from 2 or 3 to 40 feet in thickness. The rocks strike north 15 degrees west and have a dip of about 10 degrees to the west. The formation rests upon coarse granite. In addition to this large exposure there are scattered smaller outcrops as much as a mile to the northeast and 3 miles to the west and northwest, too small and discontinuous to map. The formation occurs in several other places in the Salt River Valley, where it was mapped and described by W. T. Lee, [1] who states that at some time in the Tertiary it

[1] Lee, W. T., Underground waters of the Salt River Valley, Arizona: Geol. Survey Water-Supply Paper 136, pp. 99-100, 1905.

had a wide and continuous distribution. It seems likely that at one time the formation was present in at least a part of the lower Verde River valley, but no deposits are known to remain and the relation to the fill in the Verde Valley is not clear. Both the sandstones and the fill are barren of fossils.

Gila formation

The lower Verde River valley is filled with detritus of fluviatile and lacustrine origin, comprising the Gila formation described by Morrison[1]

[1] Turner, S. F., and others, Geology and ground-water resources of Safford Valley, Arizona: U. S. Geol. Survey water-supply paper, in preparation.

in a report on the Safford Valley. The three phases recognized and described by Morrison in the Safford Valley occur in the lower Verde River valley in a similar fashion. There is a peripheral phase of rudely-stratified fanglomerate, coarse and poorly sorted, derived from the bordering hard rocks upon which it overlaps. This phase differs in composition according to the bordering hard rock, ~~material~~ so that it may consist of volcanic, granitic, or metamorphic material. The fanglomerate phase grades into finer material that is better sorted and stratified, and ultimately reaches an intermediate phase in which beds of fine sand, silt, and clay alternate or interfinger. As the distance from the hard rock increases, the sands and sandstones become thinner and fewer. Only a few beds of sand occur among the thin- to thick-bedded clays and silts of the central or playa phase.

The conditions of deposition of the Gila formation have been well stated by Morrison[1] in connection with the Safford Valley, and as the

[1] Turner, S. F. and others, op. cit.

conditions are quite similar in the lower Verde River valley, part of his description is quoted:

> ". . . torrential floods, resulting from the rapid runoff of occasional down-pours, played a large part in the transportation and deposition of the Gila sediments. As these floods, heavily loaded with debris, left the steep and narrow mountain canyons and emerged on the alluvial slopes of the basin, they quickly dropped the coarser portion of their load. This resulted in the deposition of a steep fan of coarse debris at the mouth of each canyon. Stream channels, radiating from the canyon out over this fan, shifted their courses with each large flood, as their channels became choked with debris.
>
> "Farther down the alluvial slopes, as the gradient decreased, the stream channels became less well-defined, and the water tended to spread out in sheet-flood fashion and deposited the fine sand and silt of the transitional facies. In this zone the sides of individual fans joined to form a concave piedmont plain sloping toward the interior of the basin. In the narrower portions of the basin the piedmont plain on one side of the basin met that of the other along the axis of the basin; in the broader portions of the basin, however, the piedmont slopes flattened toward the interior of the basin until they merged with an almost level interior plain bordering the central playa. Silty sediments were deposited by sheet-floods on the outer margins of this plain, and the clays were finally dropped in the playa. The playa also received the dissolved salts, which were deposited as salines, such as salt and gypsum, during stages when the lake was almost dry."

The width of the fanglomerate phase ranges from one to three miles. The intermediate phase is much narrower, averaging between a quarter to half a mile in width.

The most extensive exposure of fanglomerate occurs at the north end of the valley. Here it is well cemented with caliche and forms steep-walled canyons and bluffs. The thickest sandstone outcropping in the valley is an exposure of 50 feet of cross-bedded, evenly fine-grained friable tan sandstone which occurs for a mile along the river in the vicinity of the granite knoll just above the north boundary of the Indian Reservation. From this outcrop the sandstone becomes coarse to the east and grades into fanglomerate that overlaps on the bedrock. Downstream, at an increasing distance from the bedrock, the sandstone interfingers with beds of clay and silt that pass into massive beds of clay and silt.

Although a total of about 500 feet of lacustrine clay is exposed in the valley, the exposures are discontinuous and scattered. Several thin beds of tuff and several thin layers of sandstone with ripple marks were noted, but no fossils were found in the valley. The bulk of the lake or playa beds seems to be an impervious, buff-colored clay that contains an appreciable amount of silt and is thin-bedded to massive.

It is likely that coarse water-bearing material underlies nearly all the valley in the form of basal conglomerate or buried fanglomerate. Above this are probably lenticular beds of sand and gravel. At least two wells have penetrated considerable thicknesses of clay to find water-bearing conglomerates beneath (see logs of wells 4 and 114, p.   ). Other wells, nearer the edge of the valley, have penetrated deep into fanglomerate and found only the lower part saturated (see records of wells 6, 7, and 12 and pl. 2). With one exception, all the wells located far out on the lake beds toward the center of the valley have failed to reach an aquifer, but they have not reached the base of the valley fill. The one exception is particularly interesting because it is an artesian well reported to be 540 feet deep (well 26, pl. 1), and at one time had sufficient pressure to flow at the surface. This well proves that artesian conditions exist in the central part of the valley.

The only spring in the valley at present is in the SW$\frac{1}{4}$ sec. 17, T. 5 N., R. 7 E., in the bank of a wash that has cut about 20 feet into alternating coarse and fine beds of the intermediate phase of the valley fill. The spring has been made to produce approximately 5 gallons a minute by trenching into the permeable layer of fine sand that transmits the water.

Although it is barren of fossils, the conditions of deposition and other characteristics of the valley fill so closely resemble those of the Gila formation found elsewhere in Arizona that the Lower Verde River valley fill is assigned to this formation.

Recent alluvium

The flood plain of the Verde River ranges in width from one- to three-quarters of a mile, and the main channel is from 1,000 to 1,500 feet wide. The flood-plain surface on either side of the main channel is underlain either by gravel and sand or by sandy silt that overlies coarser material. The river gravels that underlie the flood plain occupy a wide trough carved by the river in the valley-fill deposits. That the surface of the fill upon which the river gravels rest is highly irregular has been demonstrated by test wells and geophysical probes. The river swings from one side of its channel to the other in its course from Bartlett Dam to its junction with the Salt River, so that isolated areas of flood plain alternate with the main channel. These flood-plain segments are relatively stable. The two well fields of the City of Phoenix have been developed on two of them, on the west side of the river, and water is produced from the saturated gravels through which water is transmitted from the river.

The gravels that underlie the flood plain were laid down in former times under conditions similar to those which prevail today, and therefore consist of buried channels having far greater longitudinal than lateral persistence. As a result, water moving toward the wells from the river does not follow a normal at right angle to the river but enters the buried channel at some point upstream from the wells, where the former channel intercepts the present channel. This is indicated by wide differences in the capacities of closely-spaced city wells, by test drilling, and by closely-spaced shallow geophysical probes made on the flood plain on the west side of the river.

Several test wells were drilled east of the Verde River in the vicinity of McDowell Mountain to obtain a profile of the bedrock when this locality was being considered for a damsite[1]. The profile shows a maximum of 90 feet

[1] Lee, W. T., op. cit., p. 101.

of river fill. Inasmuch as the river was able to cut 90 feet below its present channel at this point, into granite, it is probable that it cut that far below its present channel throughout its course over unconsolidated sediments, and that on any cross-section of the flood plain there will be some point where the older valley fill lies about 90 feet below the present stream channel. At any given section, however, the point of maximum depth is as likely to be east of the river or beneath the river as to be on the west side. Only on the flood-plain segment west of the river in sec. 20, T. 4 N., R. 7 E., was the maximum thickness of river alluvium indicated by geophysical probes to be present and here the deeply-buried channel seems to be lying on a sandstone or conglomerate bed of considerable extent.

Four test wells described by Black and Veatch[1], 250 feet apart in a line

---

[1] Black and Veatch, Unpublished report on the water works system, Phoenix, Arizona, 1928, p. 63.

---

running across the river channel eastward from municipal well 4, show that there is some possibility of finding a deep channel buried under the wide, silt-covered flood plain of the river. No geophysical probes have been made to date east of the river, but such probes should be made to determine whether a deep channel exists.

GROUND WATER

History of use of ground water in the Lower Verde Valley

Fort McDowell was established by the U. S. Army on September 7, 1865[1],

---

[1] Barnes, Will C., Arizona place names: Univ. of Ariz. Gen. Bull. 2, vol. 6, No. 1, p. 258, Jan. 1, 1935.

---

for protection of travelers and settlers against the roving tribes of Apache Indians. The post was named after General Irvin McDowell, who then commanded United States troops in California and Arizona. The army troops consisted of five companies of California volunteers. On April 10, 1890, the fort was abandoned. On March 2, 1891, the area was established as a reservation for the Mohave-Apache Indian tribe. At some time during the occupation of the fort a well was drilled on the bank of the river to an artesian aquifer. According to different reports the depth of the well was between 280 and 570 feet and was abandoned because a string of tools, lost in the well, shut off the flow. The well is still in existence, but the flow is negligible. The disintegrated casing has been replaced by a 3/4-inch pipe extending several feet beneath the surface and secured at the surface by masonry. A centrifugal pump installed on the well during the summer of 1944 produced only two or three gallons a minute. When this well was abandoned another well of unknown depth was drilled a few feet south of the fort, but was abandoned and filled when it failed to supply sufficient water. In recent years another well was drilled in the gravels near the river and this well is now used by residents of Fort McDowell for domestic supply.

Several wells have been drilled in the river gravels upstream from the fort, and others have been drilled on the terraces that border the valley, to furnish water for stock. These are discussed elsewhere in this report.

Development by the City of Phoenix

The municipal water supply of the City of Phoenix was originally obtained from wells in the Salt River valley. In 1915 the city filed an application with the U. S. Commissioner of Indian Lands for an appropriation of 1,100 miner's inches of water from the underflow of the Verde River. Subsequently the construction of an infiltration gallery was undertaken. It consisted of 3,627 feet of reinforced concrete open-joint pipe, 60 inches in diameter, and 7,863 feet of closed-joint pipe, laid level in a trench a few feet beneath the water table. The pipe was then buried throughout its length. In February 1922 water from the Verde infiltration gallery was first turned into the city mains. The quality of the water was much better than that of the water from the original wells and from deeper wells drilled more recently in the Salt River valley.

During the summer of 1922, when the water table declined as a result of a decline in river stage, it became evident that the gallery as installed would not supply enough water. Later in the same year an additional 576 feet of pipe, 60 inches in diameter, was laid. Apparently the supply was still inadequate, for in 1924 an additional 145 feet of 36-inch pipe was added to the upper end of the gallery and extended toward the west bank of the Verde River. This met only a part of the need for more water, and a further effort to increase the supply was made by diverting a portion of the flow of the river against the west bank. This afforded a greater recharge area, nearer the gallery, and infiltration was materially increased. However, the system still had a decreased and inadequate discharge during the summer months, and additional recharge was sought by pumping water from the river into a shallow surface basin dug adjacent to the gallery. Moss and algae were so effective in sealing up the sand and gravel on the bottom and sides of the basin that the idea was abandoned.

About 1927 the need for additional water led to the drilling of four wells, south of the lower end of the open-joint section of the infiltration gallery in the area now known as the upper well field. These wells were good producers. They discharged into the closed section of the 60-inch pipe. The back pressure on the gallery, thus produced, necessitated the construction of a sump and the installation of a booster pump to raise the water at the lower end of the open-joint section. This arrangement is still in use today. About 1930 additional wells were drilled two and a half to three miles south of the four drilled in 1927, in the area now known as the lower well field. These wells did not have capacities as large as the original four, but they added materially to the production of the Verde installations. About 1940 two additional wells were drilled on the flood plain of the Verde River east and north of the four original wells. One of these (city well 5) penetrated a fairly thick section of saturated gravel and is a good producer. The other (city well 6) was not so productive, but was sufficiently productive to warrant the installation of a pump. At about the same time city wells 12 and 13 were drilled in the lower well field, and although not particularly good producers they helped to relieve the load during the summer months. Several test wells, all unsuccessful, were drilled downstream from the present lower well field. This was the last development work up to the present time. Table 2 shows the logs of some of the wells drilled by the City of Phoenix.

Reinforced concrete pipe extends from the infiltration gallery and the two well fields to the detritor. The detritor, as its name implies, was built to remove materials carried in suspension in the well water. It consists principally of a settling basin that may be emptied periodically. The seven 6-foot sharp-crested rectangular weirs form a convenient means of measuring the combined flow of water from the Verde installations. A water-level recorder is now maintained in the settlement basin and gives a continuous record of discharge. Flow from the detritor to the city's reservoirs, which have a combined capacity of 35 million gallons, is by gravity through a pipe-line and two tunnels. Chlorination and ammoniation are controlled automatically by apparatus housed at municipal well 1.

Power is furnished to the electric motors on the pumps by the Salt River Valley Water Users Association through a high-voltage transmission line.

Construction of Bartlett Dam and its effect on the regimen of the Verde River

Bartlett Dam, completed in 1939, is on the Verde River about 15 miles upstream from the Phoenix gallery and wells. The dam was built primarily to store flood waters for release to the Salt River Valley Water Users Association for irrigation. Release of water from the reservoir is synchronized with the needs of the Association and with the amount of water being released on the Salt River system for both power production and irrigation. Consequently there is little uniformity in the rate of dis-

Table 2. Well logs, Lower Verde River Valley, Maricopa County, Arizona

	Thickness (feet)	Depth (feet)
Log of well 12		
Dick Robbins, owner. NE¼ sec. 29, T. 4 N., R. 6 E.		
Wash material ------	10	10
Conglomerate, probably caliche ----	186	196
Log of well 52		
City of Phoenix well 5, SW¼ sec. 7, T. 3 N., R. 7 E.		
Loose gravel, boulders- -	7	7
Fine sand ---------	3	10
Large boulders -----	2	12
Large boulders -----	40	52
Clay ----------	1	53
Coarse gravel ------	1	54
Sandy brown clay ----	18	72
Log of well 55		
City of Phoenix well 4, SW¼ sec. 7, T. 3 N., R. 7 E.		
Sandy silt- --------	18	18
Coarse gravel, boulders	47	65
Clay, dry --------	178	243
Log of well 57		
City of Phoenix well 3, SW¼ sec. 7, T. 3 N., R. 7 E.		
Sandy silt -------	15	15
Coarse gravel, boulders -	41	56
Clay ----------	10	66
Log of well 58		
City of Phoenix well 2, SW¼ sec. 7, T. 3 N., R. 7 E.		
Sandy silt -------	9	9
Boulders --------	6	15
Boulders and coarse gravel	25	40
Clay ----------	9	49
Log of well 59		
City of Phoenix well 6, SE¼ sec. 7, T. 3 N., R. 7 E.		
Sand, gravel, and boulders	28	28
Clay ----------	687	715
Log of well 62		
City of Phoenix well 1, NW¼ sec. 18, T. 3 N., R. 7 E.		
Sandy silt -------	9	9
Fine sand, silt ----	6	15
Coarse gravel, boulders-	22	37
Coarse gravel -----	10	47
Clay ----------	61	108
Log of well 77		
City of Phoenix well 7, NE¼ sec. 19, T. 3 N., R. 7 E.		
Silt ----------	12	12
Clay ----------	4	16
Coarse gravel, boulders	29	45
Clay ----------	17	62
Log of well 84		
City of Phoenix well 8, SW¼ sec. 19, T. 3 N., R. 7 E.		
Sand, gravel ------	12	12
Gravel, boulders ----	36	48
Clay ----------	14	62
Log of well 85		
City of Phoenix well 13, SE¼ sec. 19, T. 3 N., R. 7 E.		
Silt, sand, and gravel -	8	8
Gravel and boulders, slightly cemented ---	23	31
Dry clay --------	24	55
Log of well 96		
City of Phoenix well 12, NE¼ sec. 30, T. 3 N., R. 7 E.		
Sand and silt ------	3	3
Coarse gravel, boulders -	27	30
Fine grained clay, dry -	53	83
Log of well 103		
City of Phoenix Detritor test well, NE¼ sec. 30, T. 3 N., R. 7 E.		
Boulders and gravel ---	9	9
Large boulders and gravel	20	29
Clay, red with white streaks ---------	32	61

Table 2. Well logs, Lower Verde River Valley, Maricopa County, Arizona - Cont.

	Thickness (feet)	Depth (feet)
Log of well 105 City of Phoenix well 9, NW$\frac{1}{4}$ sec. 30, T. 3 N., R. 7 E.		
Sandy wash material - - - -	15	15
Fine sand - - - - - - - - -	1	16
Coarse gravel, boulders - -	31	47
Clay - - - - - - - - - - - -	18	65
Log of well 106 City of Phoenix well 11, NW$\frac{1}{4}$ sec. 30, T. 3 N., R. 7 E.		
Silt and clay - - - - - - - -	14	14
Gravel and boulders - - - - -	26	40
Clay - - - - - - - - - - - - -	25	65
Log of well 114 Dick Robbins, owner, SW$\frac{1}{4}$ sec. 10, T. 3 N., R. 6 E.		
Wash material - - - - - - -	27	27
Clay, streaks of dry sand -	303	330
Cemented boulders, water bearing - - - - - - - - -	55	385

charge from Bartlett Reservoir (see fig. 1), but it is usually emptied sometime between July 1 and September 15. When the reservoir is emptied, the silt deposits in it are exposed to erosion by the river. Occasionally the operating officials, in order to prevent the flood gates from being buried, have sluiced out the silt by playing a jet of water on the deposits from a barge equipped with pumps. Thus, each year large quantities of silt are removed from the reservoir during the period of low flow (see fig. 2), and because of the low velocity of the water this silt is deposited in the channel downstream from the dam (see pl. 5). These silt deposits, as shown later, are highly effective in sealing up the pore spaces in the river gravels. In the reach of the Verde from Bartlett Dam to the junction with the Salt River the channel is characterized during low flow by a series of pools and rapids. The rapids are relatively short when compared with the pools. The pools range in length from 200 feet to more than a quarter of a mile. Although the average gradient of the river in the vicinity of the well fields is about 15 feet per mile, deposits of silt up to eight inches in thickness were observed during September and October 1944 (see pl. 3). The thickest deposits were, of course, in the pools and the thinnest were in the rapids (see pl. 4). Because the surface flow is regulated, the low flows with high suspended silt loads may last for several weeks each year. Under natural conditions, before the erection of the dam, the silt load, though high during floods, was not as constant and the high velocities of the flood waters impeded silt deposition in the channel.

Plate 3. View of the city's diversion channel showing silt deposits more than eight inches in thickness, November 11, 1944.

Plate 4. View of the Verde River looking upstream, showing character of channel at rapids about two miles below mouth of Camp Creek.

Plate 5. View of the Verde River channel near the upper well field of the City of Phoenix, showing silt deposits near the banks of the stream.

Silting of the channel may be decreased a few years hence if Horseshoe Dam, now being constructed a few miles upstream, reduces silt deposition in Bartlett Reservoir. The effect will be delayed, however, owing to the large amount of silt now stored in Bartlett Reservoir.

Except for the silt problem, the regulatory effects of the two reservoirs on the Verde River would be beneficial as far as recharge of the river gravels is concerned. Even under favorable recharge conditions, as shown later, the natural flow of the Verde River would be insufficient during low flows to recharge the river gravels at a rate equal to the discharge of the city wells. If, however, flood waters stored in the reservoirs were released during the period of low flow, recharge to the river gravels would be increased.

Recharge and discharge of ground water

Source and movement within the valley.-The Verde River from Camp Creek to the junction with the Salt River is usually an effluent or gaining stream, except in the immediate vicinity of the Phoenix well fields. In other words, the Verde River receives a part of the water which falls as rain or snow on the terraces and mountain areas east and west of the river. This contribution of water consists of underflow from some of the larger washes and water that percolates through the crevices of rocks and porous sands and gravels to the saturated zone near the river in the stretches between the washes. The effluent condition of the river is shown in figure 4, which indicates the position of the water-table contours on November 11, 1944, after a period of very low flow in the Verde River.

Within the cone of depression of the well fields the river is influent, that is, it contributes water to the river gravels. During favorable recharge conditions when silting is at a minimum, the cone of depression is relatively small and the water table is, for the most part, in contact with the river. When the silt is of maximum thickness and extent the cone of depression is relatively large and the water in the river is perched with respect to the water table. Infiltration from the river then produces a ground-water ridge. This condition is illustrated in figure 5.

The ground-water inventory.-In defining the term "ground-water inventory" Tolman[1] states:

[1] Tolman, C. F., Ground water, McGraw Hill Book Co., Inc., p. 467, 1937.

> "The ultimate goal of quantitative hydrologic measurements is to determine additions of water to the ground-water reservoir of the area under investigation from all sources (ground water increment) and discharge of every kind from the ground water body, (ground water decrement). The balancing of one against the other is called the ground water inventory."

Inasmuch as measurements indicate that the various factors of the ground-water inventory fluctuate from year to year and month to month, it is advisable that trial balances for a short period be used. Only short-period trial balances could be obtained on account of the large and irregular releases of water from Bartlett Reservoir, the principal source of recharge to the Verde River gravels. Only the part of the valley from Sycamore staff gage to the Detritor staff gage (see pl. 1) was used because all recharge to aquifers supplying the municipal wells occurs in this area.

Two unknown quantities in the pumpage inventory - evapo-transpiration and water contributed by the mountain areas - affect the ground-water reservoir. However, their effects would be relatively small and in opposite directions, and hence would not materially affect the values of the inventory. The difference in channel storage at the beginning and end of each period was small and was also neglected.

Surface flows in rivers or streams cannot be measured, even under excellent conditions, with an accuracy greater than 3 percent. Thus with a flow of 1,000 cubic feet per second it was not possible to measure the losses by seepage with an accuracy greater than 30 cubic feet per second, which is approximately the maximum estimated rate of recharge to the Verde River gravels. Reliable measurements of recharge, therefore, could be made only during periods of low flow. Fortunately, two periods of low, regulated flow occurred during the investigation. The first period of low flow was in July 1944 and covered a period of four days. The second was in November 1944 and lasted 14 days. Seepage measurements were made during these two periods and are discussed in detail in later paragraphs.

Because the cross-sectional areas and gradients are about the same, the underflow passing Sycamore staff gage is estimated to be equal to that passing Detritor staff gage, and the water equation for the reach between the two staff gages may then be written: recharge (from surface flow of the Verde River) equals water pumped, plus or minus the change in storage. The change in storage equals the volume of material unwatered or saturated multiplied by the average specific yield of the material.

For the period July 28 to 31, 1944, inclusive:

Surface flow passing Sycamore staff gage	329.5 acre-feet
Surface flow passing Detritor staff gage	131.5 acre-feet
Difference, or amount available for recharge to river gravels	198.0 acre-feet
Pumped from upper and lower well fields	287.1 acre-feet
Difference, or amount derived from storage	89.1 acre-feet

The city wells had been pumped continuously for several weeks before the beginning of both the 4-day and the 14-day tests, so that the cone of depression was well established (see fig. 3). Measurements made on wells within the cone during each of these periods indicated the amount of material unwatered between the two cones, the original one, and the new (larger) one formed during the tests. From these measurements it was noted that during the 4-day test the new cone was deeper than the original one by a layer 0.54 foot thick, that is, it deepened at the rate of 0.135 foot per day. Projecting the area between the cones to a horizontal plane, it was estimated that the change in water level covered an area approximately 5,600 feet long and 4,350 feet wide. Computing this area in acres and multiplying by the total change in water level, the average specific yield of the material was computed as follows: Area unwatered (1,116 acres) times average change in water level (0.54 foot) equals 603 acre-feet of material unwatered.

$$\frac{\text{89.1 acre-feet of water drawn from storage}}{\text{603 acre-feet of material unwatered}} = \text{14.8 percent, average specific yield of material unwatered.}$$

This figure is comparable to the specific yields obtained by tank tests described later in this report and with results obtained in other areas[1].

---

[1] Turner, S. F., and others, Water resources of Safford and Duncan-Virden Valleys, Arizona and New Mexico: U. S. Geol. Survey (mimeographed), p. 27 and table 22, Oct. 13, 1941.

Turner, S. F., and Robinson, T. W., A laboratory method for determining the physical properties of unconsolidated material, with special reference to specific yield; U. S. Geol. Survey, report in preparation.

Eckis, Rollin, Geology and ground-water storage capacity of valley fill, South Coastal Basin investigation: California Division of Water Resources, Bull. 45, pp. 85-94, 1934.

A second and longer period of small and relatively constant flow in the Verde River afforded an opportunity for another determination. For the period October 31 to November 13, 1944, inclusive:

Surface flow passing Sycamore staff gage	362.1 acre-feet
Surface flow passing Detritor staff gage	147.5 acre-feet
Difference, or amount available to recharge river gravels	214.6 acre-feet
Pumped from upper and lower well fields	578.9 acre-feet
Difference, or amount derived from storage	364.3 acre-feet

Measurements of water level in observation wells indicated an average decline of 0.065 foot per day or a total of 0.91 foot during this period. The area affected was approximately 4,350 feet wide and 26,400 feet long, plus an area estimated as 320 acres near the junction of Sycamore Creek with the Verde River, or a total of 2,960 acres. Multiplying this by the total change in water level, the average specific yield of the materials was computed as follows: 2,960 x 0.91 = 2,700 acre-feet material unwatered.

$$\frac{454.3 \text{ acre-feet of water drawn from storage}}{2{,}700 \text{ acre-feet of material unwatered}} = 13.5 \text{ per cent specific yield}$$

This is a reasonable check on the result during the first period.

Underflow.-The coefficient of permeability (Pm), as used in the hydrologic work of the Geological Survey, is expressed as the rate of flow of water at 60^{o}F., in gallons a day, through a cross section of one square foot under unit hydraulic gradient. For field use the coefficient of permeability (Pf) is expressed as the rate of flow in gallons a day, through each foot of thickness of water-bearing material in a width of one mile, for each foot per mile of hydraulic gradient. In a section of the Verde River, above the upper well field at Sycamore staff gage, underflow of the shallow aquifers may be computed as follows:

$Q = Pf \times S \times A$ (by definition)

$Pf = 7{,}500$ gallons per day per square foot (determined by pumping tests described later in this report)

$Q =$ discharge, gallons per day

$S =$ hydraulic gradient, in feet per mile $= 15$

$A =$ cross-sectional area (average thickness of 25 feet x average width of 0.825 mile, based on geophysical probes and well logs)

$Q = 7{,}500 \times 15 \times 25 \times 0.825 = 2{,}320{,}000$ gallons per day, or 3.6 second-feet. Similarly, the underflow of the Verde River at Mount McDowell, near the Richens staff gage, may be computed. Borings reported by Willis T. Lee[/] show a maximum depth to bedrock of about 90 feet below the stream bed. The width is about 0.25 mile, the average thickness of saturated material is estimated to be 60 feet, the hydraulic gradient is about 15 feet per mile, and the coefficient of permeability is 6,400 gallons per day per square foot, as determined by pumping tests described later. From the above the underflow leaving the valley is computed as 2.2 cubic feet a second. These computations

[/] Lee, Willis T., op. cit., p. 101.

indicate that the capacity of the lower section at the existing gradient is 1.4 cubic feet per second less than that of the upper section. It is believed that the cross-sectional area of the river gravels remains nearly the same from the Sycamore staff gage to the Detritor staff gage, but the channel narrows below the latter. This constriction in cross-sectional area forces a part of the underflow to the surface between the Detritor and Richens staff gages. The average increase in surface flow from the Detritor staff gage to the Richens staff gage, determined by 15 measurements, was 1.0 cubic foot per second. This checks as closely as could be expected with the computations of the underflow.

Recharge to the valley alluvium from mountainous areas and terraces bordering the valley.-That water occurs in the interstices of the sand and gravel deposits lying along the base of the McDowell and Mazatzal Ranges is evidenced by several wells that supply water for livestock. The surface runoff from the mountainous areas is rapid, owing to the relatively steep slopes and the large areas of barren rock exposed. However, a part of this runoff and some of the rainfall finds its way into the coarse stream-laid deposits near the mountains and in the beds of the larger washes and percolates downward until it reaches impermeable beds of rock or clay. Thence, it percolates toward the river with a gradient less than that of the land surface, so that the depth to water in wells near the river is less than that in wells near the mountains. In some areas water becomes perched above an impervious stratum and travels along the stratum until it is able to move downward to the main water table or issues at the surface as a seep or spring, like the Williams Spring near the river. Undoubtedly a part of this percolating water recharges the river gravels, and forms a part of the underflow of the Verde River. However, such recharge is not believed to constitute an important source of water for the aquifers tapped by the present city wells.

Seepage measurements.-During this investigation only two periods occurred when the river flow was constant and low enough for runs of seepage measurements to have any significance. These flows came at times of approximate maximum and minimum silt deposition, respectively. The first period was of short duration (July 28-31, 1944) and occurred when practically all the silt deposits of the preceding year had been carried downstream. The second period, coming after the peak silt discharge, showed how the silt retarded recharge to the aquifers supplying the city wells. During the runs of seepage measurement the mechanism of silt deposition and removal, and the effect on recharge, were studied in detail.

Staff gages were installed on the Verde River near the site of the old gaging station of the Geological Survey at the mouth of Camp Creek, at the mouth of Sycamore Creek, in the vicinity of the old Richens valve about 0.8 mile above the junction of the Salt and Verde Rivers, and near the detritor (pl. 1). Current-meter measurements were made at these points at various gage heights so that the relations between discharge and stage of the river could be determined. The gains or losses in surface flow in the reaches between the staff gages are shown in table 3. The measurements made in July 1944 at the old Geological Survey gaging station and the Sycamore staff gage show the depletion of bank and channel storage under natural conditions following a decrease in stage of the Verde River. This reach, approximately 11 miles in length, is outside the influence of the Phoenix well fields. On July 28, 1944, the measurements showed a gain of 12.0

Table 3. Runs of seepage measurements on the Verde River

From abandoned Geological Survey gaging station near Camp Creek to Sycamore staff gage, 11 miles

Date 1944	Flow at upper station sec.-ft.	Loss (-) or gain (+) sec.-ft.	Average temperature °F	Per cent lost corrected to 60°F
July 28	43.4	+12.0	-	-
July 29	44.8	+10.8	76	-
July 30	43.8	+10.7	76	-
July 31	48.6	- 1.3	75	2.03
Oct. 31	0.30	+15.9	-	-
Nov. 2	0.20	+14.8	-	-
Nov. 6	5.4	+ 9.2	-	-
Nov. 9 and 10	3.2	+ 7.4	-	-
Nov. 12	1.7	+ 9.2	-	-
Nov. 13	-	-	-	-
Nov. 15	-	-	-	-
Nov. 17	-	-	-	-
Nov. 18	40.4	+ 1.7	58.5	-
Nov. 22	43.5	+ 3.3	56.5	-
Nov. 25	45.8	+ 4.7	-	-
Nov. 30	-	-	-	-
Dec. 5 and 6	48.4	+ 2.9	50.0	-

From Sycamore staff gage to Detritor staff gage, 4.7 miles

Date 1944	Flow at upper station sec.-ft.	Loss (-) or gain (+) sec.-ft.	Average temperature °F	Per cent lost corrected to 60°F
July 28	55.4	-31.3	80	43.6
July 29	55.6	-	-	-
July 30	54.5	-33.2	77	48.8
July 31	47.3	-28.2	81.5	43.8
Oct. 31	16.2	- 9.7	75	49.2
Nov. 2	15.0	-10.0	73.5	56.6
Nov. 6	14.6	- 7.8	63	51.4
Nov. 9 and 10	10.6	- 6.2	63.5	55.5
Nov. 12	10.9	- 8.2	60	75
Nov. 13	11.8	- 7.5	57	66.4
Nov. 15	32.5	-20.0	60	38.5
Nov. 17	42.8	-21.3	56.5	52.3
Nov. 18	42.1	-20.5	57	53.5
Nov. 22	46.8	-20.0	58.5	43.6
Nov. 25	50.5	-14.4	49	33.6
Nov. 30	52.2	-	-	-
Dec. 5 and 6	51.3	-11.1	51	22.3

Table 3. Runs of seepage measurements on the Verde River - Cont.

From Detritor staff gage to Richens staff gage, 0.7 miles

Date 1944	Flow at upper station sec.-ft.	Loss (-) or gain (+) sec.-ft.	Average temperature °F	Per cent lost corrected to 60°F
July 28	24.1	+ 2.3	-	-
July 29	-	-	-	-
July 30	21.3	+ 1.3	87.5	-
July 31	19.1	+ 0.9	-	-
Oct. 31	6.5	- 0.5	75	6.3
Nov. 2	4.9	+ 1.2	-	-
Nov. 6	6.8	+ 1.0	-	-
Nov. 9 and 10	4.4	+ 0.8	-	-
Nov. 12	2.7	+ 0.9	-	-
Nov. 13	4.3	+ 1.2	57	-
Nov. 15	12.5	+ 1.3	60.5	-
Nov. 17	21.5	+ 0.9	55.5	-
Nov. 18	21.5	+ 3.0	57.5	-
Nov. 22	26.8	+ 0.9	59.5	-
Nov. 25	36.1	- 0.5	48.5	1.65
Nov. 30	-	-	-	-
Dec. 5 and 6	40.2	- 0.3	51.5	0.85

Note: Staff gage near abandoned Geological Survey gaging station is about one-quarter mile below mouth of Camp Creek. Sycamore staff gage is about 900 feet above City of Phoenix brush diversion dam and southeast of Fort McDowell. Detritor staff gage is 1,700 feet southeast of Detritor near point where two channels of Verde join. Richens staff gage is about 1.2 miles below Detritor.

cubic feet per second, but this decreased progressively until on July 31 the measurements showed a loss of 1.2 cubic feet per second. These measurements were made during a period of high transpiration by phreatophytes (water-loving plants) and the transpiration probably caused the loss on July 31. Measurements made from October 31 to December 6 showed a consistent gain in the same reach, transpiration being at a minimum during this time. The river is normally effluent throughout this reach of the channel, but for several hours each day during the summer it probably becomes influent to a slight extent in response to use of water by phreatophytes. After the flow of the river was completely shut off at Bartlett Dam on October 31, there was a gradual unwatering of the saturated materials in and near the river channel. Water from this source is usually called bank storage. The water from bank storage, together with the water percolating in from the sides of the valley, as discussed earlier in the report, caused surface flow below Bartlett Dam. The flow began at a point some distance below the dam, and this point moved progressively downstream as the unwatering continued. There was always a small flow at the Sycamore staff gage above the well fields.

Measurements made at the Detritor staff gage below the well fields consistently showed flows less than those at the Sycamore staff gage, the loss representing recharge to the aquifers that supply the municipal wells. The percentage lost from the total flow passing the Sycamore staff gage during seepage measurements made in July and those made in November cannot be compared, because the increase in wetted area is not in direct proportion to the increase in flow. Only during periods of equal flow at the Sycamore staff gage did the comparison of losses in flow have any significance. Fortunately there were two periods (July 28 and December 1-4, 1944), when the flows passing the Sycamore staff gage were nearly equal. During the first period the effect of the silt deposited during the previous year had practically disappeared and was considered to be at a minimum for the year; during the second period the effect of silt deposition was nearly at a maximum, as the heaviest silt loads occurred during September and October. Because the first period represents the minimum silted condition and the second period represents the maximum, they may then be compared directly. On July 28, 1944, 31.3 cubic feet per second was lost from a total flow of 55.4 cubic feet per second passing the Sycamore staff gage, or a loss of 56.5 percent. On December 1, 2, and 3, 1944, about 53 cubic feet per second passed the Sycamore staff gage, and an average of 11.4 cubic feet per second was contributed to recharge or 21.6 percent. Thus the percentage lost to recharge on July 28, with minimum silting effect, was approximately 26 percent as great as during the first three days of December with maximum silting effect. When the recharge at both times is corrected to a water temperature of 60°F., as in table 3, the difference is not so marked.

Figure 6 shows graphically, plotted against time in days, (1) flow passing Sycamore staff gage, in cubic feet per second, (2) average rate of production from the well fields, from both the wells and the infiltration gallery in cubic feet per second, and (3) the average rate of recharge from the river to the aquifers that supply the wells, in cubic feet per second. From the graphs it is evident that during about three-quarters of the period shown the rate of recharge from the river was less than the withdrawal from the well fields. Thus, even under the best recharge conditions, a flow of 55 cubic feet per second at the Sycamore staff gage will not result in sufficient recharge to supply all the present municipal wells. It was not possible, because of the manner in which the flow of the river was regulated, to determine the minimum flow necessary, under the best recharge conditions, to supply the aquifers with water as fast as the present municipal wells could withdraw it. However, it is estimated that a minimum flow of at least 100 cubic feet per second would be required.

Deposition and persistence of silt.--The mechanism of silt deposition and removal proved to be very significant. The writers observed the following conditions in the flood plain and river channel while making stream measurements, but doubted their significance until supporting evidence was obtained by plotting the data:

The flood gates at Bartlett Dam are usually opened just before the reservoir is completely empty, thus providing enough velocity to remove part of the silt. The silt load initially is extremely heavy and declines with the rate of discharge. Silt deposition begins along the entire length of the channel in the pools and near the banks of the stream where the velocity is low, and continues as the wetted perimeter becomes progressively smaller. The silt deposits are highly effective in sealing up the pore spaces of the river gravels near the surface, but there is no evidence to indicate that the silt penetrates the gravels very deeply. The growth of moss and algae in the channel also acts to retard infiltration, especially in the rapids where the silt deposits are at a minimum. Section AA' of figure 4 shows the relation between the rapids and pools and the water table.

An infiltration test made on June 27, 1944, in a 1,200-foot stretch of the city's diversion channel just above municipal wells 5 and 6, with minimum silting effect, showed an infiltration rate of 2.02 feet over the wetted area in 24 hours. Another test made in the same reach of channel on October 18, 1944, with maximum silting effect, showed no measurable loss out of a flow of 18 cubic feet per second. The channel contained no rapids and probably received somewhat more silt than did the main channel.

When the river stage is gradually increased, the dried silt is brought back into suspension. If the river stage falls again before removal of silt from the channel has been completed, redeposition occurs in the same manner as before. If the river stage continues to rise, the silt deposit will be carried downstream. However, during the fall of 1944, about three months after the peak of the silt load had passed, three to four inches of silt still remained in the shallow water near the river banks. Thus, because of the sealing action of the silt, both the actual amount of recharge and the percentage of surface flow going to recharge decreased as the river stage increased. This is shown graphically in figure 6. It shows that, at least for some time after an increase in flow, recharge is decreased, but as the silt is gradually washed downstream, recharge tends to increase. A part of the decrease in recharge noted in the latter part of November was due to the cooling of the river water.

Discharge of the Verde River below Bartlett Dam was such that it was impossible to study the persistence of silting in detail. No sealing that could be considered permanent was observed in the channel during this investigation, as the high flows during the spring of 1945 removed practically all silt deposited during the season of 1944. Some deposits were observed and photographed that, originally, exceeded eight inches in thickness (see pl. 3), but these were almost completely removed by the river before the summer of 1945.

It is believed that seepage measurements made over a period of years would show whether silting is producing permanent harmful effects on the recharge. These should be made under comparable conditions each year, after the peak silt load had passed and at the same stage of the river.

Artificial recharge.-Artificial recharge has been practiced successfully in the United States since about 1889[1]. In recent years probably the

[1] Tolman, C. F., op. cit., p. 174.

greatest development has been in California where intensive cultivation and the intermittent nature of the surface-water supply have led to large-scale use of ground-water storage. As much as 500 cubic feet per second has been diverted in the upper part of the Santa Ana River alluvial cone and successfully fed to the underground reservoir by spreading the water in open ditches cut in highly permeable material. More recently Guyton[1] has

[1] Guyton, W. F., Depleted wells at Louisville recharged with city water: Water Works Engineering, vol.____, No. ____, p.____, Jan. 10, 1945.

described the successful use of filtered and treated surface water to recharge a depleted ground-water reservoir through wells. This method, of course, is not feasible for use on the Verde system of the City of Phoenix. During periods of high silt loads in the river no method of artificial recharging could be successful. However, when the river is relatively free from silt artificial methods have been and are being used by the city. and are at least partially successful. These methods consist of diverting a portion of the river flow into an artificial channel on the west side of the flood plain near the wells. This practice not only increases the area of infiltration but shortens the distance which the water must travel after leaving the river in order to reach the wells.

The present practice could be improved by shutting off, at the diversion gates, water carrying high suspended silt loads, thus allowing only water relatively free of silt to flow through the artificial channel. The period of high silt loads is relatively short, and by careful observation of the quantity of silt carried by the stream the time to open and close the diversion gates could be determined. This would prevent any appreciable sealing of the river gravels in the diversion channel, so that during periods of clear water and low flow in the river the recharge would be considerably greater than at present. This is the time when the extra recharge is needed most. It is the low steady flows passing over the silt deposits that furnish the least recharge. At this time the velocity of the water is too small to remove the silt, and these flows should be diverted into clean artificial channels. This method should also be applied to any additional well fields that are developed.

Scarifying the diversion channel, as practiced by the City of Phoenix some years ago, probably is not beneficial in the long run although it may provide a temporary increase in recharge. The scarifying action increases the depth of penetration of the clay and silt in surface layers of the infiltration beds by mixing the fine materials with the underlying sand and gravel, and thus eventually reduces the amount of water penetrating them. The velocity required for removal of these deep deposits of silt would be several times as great as that required for removal of silt deposits on undisturbed river gravels.

Evaporation and transpiration.-Evaporation occurs from the lower part of the flood channel of the Verde River in which the capillary fringe extends to the surface, and from the water surface of the stream. This stream channel area is practically barren of vegetation. However, in most places the flood plain is covered with a dense growth of phreatophytes, which transpire large quantities of water. The principal phreatophyte in the valley is mesquite, and there are small areas of cottonwood, willow, and baccharis. Phreatophytes are defined by Meinzer_/ as:

_/ Meinzer, O. E., Plants as indicators of ground water: U. S. Geol. Survey Water-Supply Paper 577, p. 1, 1927.

> ". . . plants that habitually grow where they can send their roots down to the water table or to the capillary fringe immediately overlying the water table and are thus able to obtain a perennial and secure supply of water."

For the purpose of this discussion consumptive water use or evapo-transpiration by phreatophytes may be defined to include the sum of the moisture lost to the atmosphere by transpiration of phreatophytes, by evaporation from free water surfaces surrounding the plants and from raindrops or dew on the plants, and by evaporation from wetted soil surfaces that are within the capillary fringe of the water table in the phreatophyte area. No attempt was made to measure evapo-transpiration in the Lower Verde River valley directly by measurement of water-table fluctuations or other methods. Figures for consumptive use determined in the investigation by Turner and others_/ in the Safford Valley are assumed to apply to the

---

_/ Turner, S. F. and others, op. cit., p. 11.

Verde Valley, because the two valleys have a similar climate. The phreatophyte area of the Verde River flood plain from Bartlett Dam to the junction with the Salt River was found by measurements of aerial photographs to be approximately 18,800 acres. Because the area occupied by phreatophytes other than mesquite was quite small the entire area was considered as occupied by mesquite. The density of growth, as used in computations devised by Turner and others[1], was estimated to be about 50 percent.

---

[1] Turner, S. F., and others, op. cit.

According to the Safford Valley data, the annual consumptive use for 100 percent growth density is 2.4 feet. Adding the precipitation during the growing season, which was 0.185 foot at Fort McDowell, this gives a total of 2.585 feet for 100 percent density. Using 50 percent density the consumptive use is $\frac{2.4}{2} + .185$ feet times 18,800 or 26,000 acre-feet, or an average of about 4,500 acre-feet per month during the growing season. This accounts for a considerable part of the losses, reported by the Salt River Valley Water Users Association, from water released at Bartlett Dam before it reaches Granite Reef Dam.

Cones of depression.--When water is discharged from a well the water table (piezometric surface in an artesian area) is lowered in the vicinity of the well. This causes water to flow toward the discharging well at a rate equal to the rate of discharge. If the capacity of the aquifer to transmit water is less than the rate of discharge, the drawdown will increase and the difference in the quantity pumped and the rate of flow toward the well will be derived from storage. The line of intersection between a vertical plane passing through the axis of the well and the water table or piezometric surface is known as the drawdown curve and roughly approximates the shape of an inverted cone. Hence the name "cone of depression" is used to denote that part of the water table or piezometric surface which lies within the area of influence of the discharging well. All discharging wells derive a quantity of water from storage until the cone of depression reaches equilibrium. The ratio of the amount of water drained to the volume of material unwatered is called the specific yield, stated as a percentage of the volume. Theis[1] prefers the term "coefficient of storage" which he

[1] Theis, C. V., Personal communication, 1940.

defines as:

> "The quantity of water in cubic feet that is discharged from each vertical prism of the aquifer with basal area equal to one square foot and height equal to that of the aquifer when the water level falls one foot."

Theis further states:

> "For non-artesian aquifers this concept is closely akin to that of specific yield and ..... computations of its value seem to be in agreement with those determined for specific yield. For artesian aquifers, the concept is related to the compressibility of the aquifer and the value of the coefficient is of a smaller order of magnitude than that for non-artesian wells."

In the present investigation the extent of the cone of depression was of primary importance in determining the mutual interference of the present wells and proper spacing for any new wells. Water-level measurements on the city's well 4, (No. 55 on plate 1) indicated a drop of about 20.0 feet from September 12, 1944 to November 13, 1944. On the latter date the cone of depression of the upper well field reached a point of maximum areal extent as indicated by measurements of water level in wells and in test pits along the stream. Upstream it reached to the city's brush dam which diverts water to the west side of the channel (see pl. 1), or about 3,000 feet above the city's well 4. Downstream it extended to a point which intersected the cone produced by municipal well 7 (No. 77 on pl. 1). Likewise the cone of well 7 then intersected, in a downstream direction, the cone produced by the wells in the lower well field. The downstream extremity of the cone of the lower well field extended to test pit 94, which is due east of the detritor or almost 1,000 feet downstream from the nearest pumping well in the lower well field.

The areal extent of the cones of depression were determined by water level measurements made in many test pits and wells described in this report. These measurements indicate that the above described limits are probably a maximum and only occur in extremely unfavorable recharge conditions. Measurements made during a pumping test on municipal well 4 (No. 55 on pl. 1) in January 1945 under favorable recharge conditions and with all other wells in the upper well field shut off, indicate an area of influence of about 1,000-foot radius. The area of influence would undoubtedly have had a much greater areal extent if all wells had been pumping as they were during the November measurements.

Mutual interference of wells.-Two interference tests were attempted in the lower well field, one on June 14-16, 1944, the other on February 5-10, 1945. During the first test municipal well 9, (No. 105 on pl. 1) was operated continuously for two days, but since no uniformity was detected in the well measurements, the test was stopped. It is thought that the water table had not yet flattened out from previous pumping when the test was started. Another test was made later, under relatively favorable recharge conditions, and more uniform trends were noted. Municipal well 10 (No. 99 on pl. 1) was operated from February 5-10, 1945. Table 4, below, shows the interference with a well (No. 105) about 800 feet distant and a well (No. 102) about 400 feet distant. Measurements of the other wells indicated the same general trend as the ones shown in the table. Those farthest from the pumped well showed least effect. All of the wells had not been pumped for some time before the test was started and a uniform rise of from 0.13 foot to 0.15 foot a day was occurring over the entire well field. It is assumed that this rate of rise would have continued if pumping had not been started. Thus the total interference is the difference between the measured rate of rise or fall during pumping and the rate of rise before pumping started. It must be remembered that this is the interference of one well with two others. If all wells were pumping, the mutual interference would be cumulative and in some proportion to the drawdown in each well and almost inversely as the relative distance between the wells. Actually the mutual interference between all wells of the lower field is only from 2 to 4 feet. The probable explanation of this is the relatively low permeability of the water bearing materials as discussed under the heading of permeability and transmissibility.

These interference tests showed that all the wells are pumping from the same ground-water reservoir or, more appropriately, the same buried river channel. The aquifers are probably lenticular and relatively discontinuous, being interbedded with impervious lenses of silt and clay.

Interference tests made on wells in the upper well field from December 28, 1944 to January 10, 1945 indicate better interconnections between the aquifers supplying the wells than between those in the lower well field. The drop in water levels in city wells 1, 2, and 3 because of pumping in city well 4 was more rapid than the drop in water levels in the test on the lower well field.

Figure 7 shows the effect of drawdown in municipal wells 1, 2, and 3 (62, 58, and 57 on pl. 1) when city well 4 had pumped 13 days. Relatively good recharge conditions prevailed during this test and rate of recharge was greater than rate of pumping (approximately 3,700 gallons a minute). This was evidenced by the rise of the water table in wells not affected by city well 4. From Figure 7 it is seen that the water level in city well 1 (No. 62

Table 4. Interference tests, lower well field, February 5-10, 1945

City well 10(No. 99 on pl. 1) pumping about 900 gallons a minute

Date	Feb. 5		Feb. 6		Feb. 7		Feb. 8		Feb. 9		Ave. daily rise before test	Cumulative interference in feet
	A	B	A	B	A	B	A	B	A	B		
City well 9(105, pl. 1) about 800 feet distant	+0.05	-0.10	+0.01	-0.14	+0.04	-0.11	+0.08	-0.07	0.00	-0.15	+0.15	0.57
Well 102, about 400 feet distant	-0.48	-0.61	-0.17	-0.30	-0.05	-0.20	+0.05	-0.08	+0.04	-0.01	+0.13	1.28

A. Measured change in water level

B. Assumed effect due to pumping

on pl. 1) was lowered over 2 feet. This decline would increase the drawdown if well 1 were pumping with a consequent decrease in discharge. Mutual interference between wells in the upper well field ranges from 5 to 7 times as much as the mutual interference between wells in the lower well field. Interference in the upper well field is, from a practical standpoint, unimportant during that portion of the year when favorable recharge conditions prevail, but during unfavorable recharge conditions it is serious enough to make questionable the value of pumping more than two wells concurrently. Probably wells 4 and 5 would be the best wells to pump during unfavorable recharge.

Interference between wells and the infiltration gallery.- The infiltration gallery described earlier in this report, produces from about 7 to 9 cubic feet a second when recharge conditions are favorable, but produces only about 0.75 cubic foot a second during unfavorable conditions. The gallery would produce no water at all if the water table were to drop one-half foot below where it was during October and November 1944. The City of Phoenix must rely largely on ground water storage to supply the Verde wells during that part of the year when the river gravels are sealed by silt. This storage cannot be utilized by the infiltration gallery because pumping from the upper well field progressively unwaters the materials supplying the gallery during such periods. Furthermore, if additional wells are drilled upstream starting about 0.3 mile north of the upper end of the gallery, as recommended elsewhere in this report, it is likely that the gallery will furnish no water when they are in operation. Therefore, from the standpoint of utilizing ground water storage during periods of high consumption and low recharge, the infiltration gallery is useless.

Spacing of future wells.-Without information concerning the nature and extent of aquifers that will supply future wells, it is difficult to recommend the proper spacing. If the test drilling now contemplated is done in the most favorable areas indicated by the geophysical probes, information as to the thickness, permeability, areal extent, and interconnection of aquifers can be obtained. In any case the best spacing will be that which can utilize the greatest amount of ground-water storage during periods of low recharge. This is the best method of overcoming the silting problem, together with the artificial recharge methods described previously. From this standpoint new wells should be spaced at about half-mile intervals where the water-bearing materials are comparable to those of the upper well field. Somewhat closer spacing could be used with less permeable materials, as the yields of the wells would be less.

Fluctuations of the water table.-The water table may fluctuate in response to many factors, such as changes in barometric pressure, earth tides, earthquakes, pumping from nearby wells, and changes in stage of a nearby stream. In the lower Verde River valley the last two named have the greatest effect. Figure 8 shows the fluctuations in well 2 (Williams well) which is outside the zone of influence of the city wells. The fluctuations of the water level in this well reflect changes in stage of the Verde River.

Within the area of influence of the well fields, the water table responds to recharge from the river and to withdrawals from the wells. During periods of high recharge the water levels are higher than during periods of low recharge, but they still show the effect of discharging wells. A graph of typical water-level fluctuations within the area of influence, well 49, is shown in figure 9.

Ground-water storage

Relation to recharge and discharge.-When the rate of discharge from the well fields exceeds the rate of recharge from both underflow and surface inflow to the river gravels, the difference must be met from storage. Under favorable recharge conditions, the recharge to the present well fields is largely determined by the quantity of water pumped, because the possible rate of recharge is greater than the rate of pumping. Furthermore, when recharge is temporarily decreased for a short period, such as when the river flow is shut off, no permanent harm is done as the deficiency is soon made up when recharge again takes place. However, when the recharge is sharply decreased for a relatively long time, the draft on stored water becomes increasingly greater and the problem of the quantity of water in storage becomes of paramount importance.

Not all the water stored in water-bearing material can be removed by pumping. A film of water, which cannot be removed by draining, is retained around each particle of rock material and in the interstitial spaces. There is also a zone above the water table varying inversely in height with the size and sorting of the particles, in which water is retained by capillarity, and this water is not available for removal by pumping. The ratio of the quantity of water that can be removed by pumping to the volume of material unwatered, expressed in the same units, is called the specific yield. The average specific yield of the water-bearing materials, determined by the pumping tests described previously, was found to be about 16 percent. Table 8, shows the specific yield of water-bearing materials as determined by tank tests described later. Using the average specific yield of 16 percent determined by pumping tests, the quantity of storage per square mile for each foot of thickness of saturated material is:

640 x .16 = 102.4 acre-feet or 33.5 million gallons.

Thus if the city required 33.5 million gallons a day and it all came from storage in one square mile, the water table would decline 1 foot per day. The present wells, however, are able to produce only 7 to 8 million gallons a day from storage. Any quantity in excess of this is dependent on recharge. An assumed demand by the city of 30 million gallons a day (see fig. 10), taken entirely from storage, would require the unwatering of about 587 acre-feet of material each 24 hours, or about four times the amount of material unwatered by the present wells in that time.

Storage in the river gravels and older fill.-The amount of inflow from the older fill and the quantity of water stored in the river gravels between Bartlett Dam and Sycamore staff gage may be estimated from the total quantity of water that passed the gage and the amount of unwatering of the river gravels, as indicated by water-level measurements in wells when the river flow was shut off at Bartlett Dam. Unwatering occurred in about 4,575 acres underlain by river gravels above the Sycamore staff gage, and the decline in water levels in six wells spaced at intervals in this reach indicated that about 1,530 acre-feet of material was drained. The water yielded from storage, as measured at the Sycamore gage from October 31 to November 13, 1944, inclusive, was 408 acre-feet. As explained earlier, the pumping tests indicated the average specific yield of the river gravels to be 16 percent. On this basis the 1,530 acre-feet of material drained would produce only 245 acre-feet of water. Therefore, the remaining 163 acre-feet of water discharged at the Sycamore staff gage did not come from storage. It must be concluded, then, that this excess water was contributed from the older fill in the form of underflow from the washes, water from precipitation that percolated through the older fill, and possibly leakage from artesian aquifers in the older fill. The excess flow was about 6 cubic feet per second, or about 12 acre-feet per day, or about one-half cubic foot per second for each lineal mile in the 11-mile reach.

The quantity of water that can ultimately be developed from the city's Verde supply may be determined by the quantity of water available from sources just described. If it is assumed that new wells are correctly spaced from Sycamore staff gage to the mouth of Camp Creek, and that the maximum lowering of water levels is 10 feet, there would then be available about 7,200 acre-feet from storage in the river gravels plus about 12 acre-feet for each day that unwatering continues. Assuming complete sealing of the river bed by silt or the stopping of all flow at Bartlett Dam, so that no recharge could take place from the Verde River, an average demand of 35 million gallons a day could be taken from the sources just described for 76 days. As indicated above, this would lower the average water level in the river gravels 10 feet. It is believed that it would not be feasible to lower the water level more than 10 feet.

Tests made to determine the effect of silting indicate that complete sealing will never occur; thus there will always be some recharge from the river to supplement the water taken from storage.

Under maximum silting effects 11.4 cubic feet per second were recharged from a flow of 53 cubic feet per second in the reach from the Sycamore staff gage to the Detritor, a distance of 4.7 miles past the city well fields. If wells were extended on upstream to Camp Creek, a distance of 11 miles above the Sycamore staff gage, it is believed that the recharge would be proportional to the length of river and therefore in this reach the recharge would be about 2.3 times the 11.4 cubic feet a second or 26.2 cubic feet a second. Thus, in the entire length of the valley that can be developed, the minimum recharge with minimum surface flow conditions as above is 37.6 cubic feet a second. To this should be added the 6 cubic feet a second recharge from the older fill and side washes above the Sycamore gage and about 2.3 cubic feet a second from the same source past the present well fields. This makes a total of 46 cubic feet a second or 30 million gallons a day that could be pumped without drawing on storage. The 7,200 acre-feet or 2,370 million gallons of ground-water storage above Sycamore gage plus the 152 million gallons in the well fields available by lowering the water table 10 feet can be pumped in addition to the above. But the maximum amount of water that can be drawn from storage in the present well fields in one day is about 8 million gallons. Applying the ratio of length again, 2.3 times 8 or 18.4 million gallons can be drawn from storage above the well fields. This makes a total of 26 million gallons daily from storage and 30 million gallons from recharge and underflow, a total of 56 million gallons which can be developed under maximum silting conditions and with minimum flow in the river.

This amount may be increased both by increasing the minimum flow in the river and by artificial recharge in channels kept free of silt-laden water.

Characteristics of water-bearing materials

Pumping tests.—During the winter of 1944-45, when the water demands of the City of Phoenix did not require the use of all available pumps, pumping tests could be made. The principal object of the pumping tests was to determine the interference between wells and the permeability of the materials comprising the aquifers in the well fields. Permeability may be computed by any of several methods which are described by Wenzel[1]. The

[1] Wenzel, L. K., Methods for determining permeability of water-bearing materials, with special reference to discharging well methods: U. S. Geol. Survey Water-Supply Paper 887, pp. 50-97, 1942.

field coefficient of permeability, P_f, has already been defined. Recently Theis[1] introduced the term "coefficient of transmissibility," which he has

[1] Theis, C. V., The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., pp. 519-524, 1935.

defined as P_f multiplied by thickness, in feet, of the saturated portion of the aquifer. Meinzer and Wenzel[1] describe the relationship:

[1] Meinzer, O. E., and Wenzel, L. K., Hydrology, Physics of the Earth Series, vol. 9, McGraw Hill Publishing Co., Inc., p. 453, 1942.

> ". . . the coefficient of permeability denotes a characteristic of the water-bearing material, whereas the coefficient of transmissibility denotes the analogous characteristic of the aquifer as a whole."

Municipal well 4 (well 55 in pl. 1) was selected to be pumped in the first test because it is centrally located in the upper well field and is between two 6-inch test wells drilled in 1928, which were cleaned out and used for observation wells in the tests. Another 6-inch test well was drilled, and the three wells were equipped with water-level recorders during the tests. Well 56 is 17 feet west of the pumped well and wells 54 and 53 are 62 and 107 feet east, respectively. All pumping was stopped in the upper well field until the water levels in all the wells were rising at a uniform rate, then municipal well 4 was pumped continuously for 14 days, from December 28, 1944, to January 10, 1945, when the pump was shut off.

Measurements of the recovery in water levels were made for 5 days afterward. Permeability was computed from both drawdown and recovery and the values obtained ranged from 7,000 to 8,000 gallons per day per square foot.

Because of its central location in the city's lower well field, municipal well 10 (well 99 in pl. 1) was chosen for pumping tests there. Four observation wells were drilled, two of them west-northwest at distances of 30 and 80 feet, respectively, from well 10, and two east-southeast at distances of 31 and 81 feet, respectively. Water-level recorders were installed on these wells, and also on well 102, which was drilled at the approximate center of pumping in the well field. All pumping was stopped until the water levels in all the wells were rising at a uniform rate, then municipal well 10 was pumped from February 5 to 10, 1945, and the recovery was measured for 72 hours. Permeability was computed by the gradient formula and by the Theis recovery method, and the values obtained ranged from 5,800 to 6,800.

Assuming that the average field coefficient of permeability of the aquifer in the vicinity of municipal well 4 is 7,500 gallons per day per square foot, the coefficient of transmissibility is about 330,000 gallons per day per foot. Assuming that the average field coefficient of permeability of the aquifer near municipal well 10 is 6,400 gallons per day per square foot, the coefficient of transmissibility is about 198,000.

The specific capacity of a well is defined as the discharge per unit of drawdown, generally expressed in gallons per minute per foot of drawdown. The lower value of the coefficient of transmissibility in the lower well field accounts for the lower specific capacities of the wells there.

Below is a table of specific capacities of municipal wells as determined during August 1944, when all wells except well 2 were pumping.

Table 5. Specific capacities of Phoenix public-supply wells, August 1944.

Upper well field		Lower well field	
Well number	Specific capacity	Well number	Specific capacity
		7	67
1	77	8	63
3	134	9	51
4	322	10	77
5	228	11	29
6	70	12	13
		13	22

Under water-table conditions the coefficient of transmissibility and the specific capacity of a well vary with the rising and lowering of the water level, owing to variation in the thickness of the zone of saturation. Computations of the coefficient of transmissibility for October and November 1944, when water levels in the upper well field averaged 15 feet below those of August 1944, and those in the lower well field averaged about 3 feet below, indicate the coefficient of transmissibility to be about 187,000 gallons per day per foot near municipal well 4 in the upper well field, and about 102,000 gallons per day per foot near well 10 in the lower well field. Specific capacities during the same period also declined, in municipal well 4 from 322 to 111, and in municipal well 10 from 77 to 55.

During periods unfavorable for recharge, as shown in figure 5, the water table declines below the river bottom because the river gravels can carry the water to the wells more rapidly than it can percolate outward from the river. For this reason, and as shown by the pumping tests, it is concluded that the factor limiting production from the existing wells is not the transmissibility of the aquifers, but the recharge from surface flow at the intake area.

Laboratory tests.-Laboratory tests were made to obtain additional information about the physical characteristics of water-bearing materials in the Lower Verde River valley. Some samples were obtained by drilling test wells and others were stream-sorted materials taken from pits in the river channel. In these tests, the methods and apparatus used were those described by Turner and Robinson[1]. The apparatus is an adaptation of the

---

[1] Turner, S. F., and Robinson, T. W., op. cit.

---

variable-head permeability apparatus originally devised and used by C. V. Theis, as described by Wenzel[1]. Because some of the samples were disturbed

---

[1] Wenzel, L. K., op. cit., p. 59.

---

by the drilling operations and also because some silt and clay from the upper horizons were carried into the lower layers, most of the values for permeability determined in the laboratory were less than those shown by the pumping tests. Tables 6 and 7 show the results of laboratory tests on the water-bearing materials.

Because of the importance of determining the quantity of water available from storage in the existing well fields, which depends on the specific yield of the water-bearing material, tests were made in six tanks on selected stream-sorted materials obtained from the channel of the Verde River. These tests were made as follows:

Three tanks 14 inches in diameter and 42 inches long, and three tanks 12 inches in diameter and 84 inches long, were buried in the ground and thoroughly insulated to maintain as constant a temperature as possible. The tanks were so arranged that they could be drained of water at the bottom through a screened sand filter and valve. A pipe ½-inch in diameter, attached to the drain pipe with a tee, allowed changes in water level within the tank to be measured with a steel tape. The tanks were filled with selected material, under water kept just above the surface of the material to prevent the entrapment of air, and tamped so as to obtain compaction somewhat similar to that found in nature. Measured quantities of water were added or subtracted and the water level was measured at intervals when the barometric pressure was the same. In general, the specific yields were higher than those determined either in the laboratory or by the field pumping tests (see table 8). This may be due partly to the inability to reproduce natural conditions in compacting the material, and partly to the fact that in the pumping tests the material unwatered probably contained a considerable proportion of material of low specific yield.

Table 8. Specific yield, determined by tank tests

(See tables 6 and 7 for the physical characteristics of material used in these tanks)

Tank number	1	2	3	4	5	6
Specific yield, percent	26	11	15	29	33	31

<u>Test wells and pits</u>.-Six test wells, previously described, were drilled in the present well fields to aid in the determination of permeability, transmissibility, and interference between wells. Two others were cleaned out and deepened. Sixteen wells, consisting of pipes 1 inch in diameter equipped with 1¼-inch by 30-inch sand points, were driven a few feet below the water table by the use of a sleeve or jack hammer. Four of these wells were lost during the investigation by the sealing of the sand points, even though they were flushed periodically. In several places where observation wells were desired, boulders encountered beneath the surface prevented the driving of sand points.

Table 6. Mechanical analyses of water-bearing materials in the Lower Verde River valley. Analyses by laboratory of Arizona State Highway Department, Phoenix, Arizona.

(Results in percent by weight)

Tank or well number	Depth (feet)	Size in millimeters: More than 19.2	19.2 to 12.7	12.7 to 9.5	9.5 to 6.4	6.4 to 4.76	4.76 to 2.38	2.38 to 2.00	2.00 to 1.19	1.19 to 0.59	0.59 to 0.42	0.42 to 0.297	0.297 to 0.149	0.149 to 0.074	Less than 0.074
Tank 1	-	0	0	0.2	0.3	0.7	5.3	7.1	26.8	48.8	5.3	0.8	1.0	2.3	1.4
Tank 2	-	0	0.9	2.2	10.0	17.4	24.5	4.7	11.4	12.5	3.3	0.5	1.2	6.0	5.4
Tank 3	-	28.8	8.9	4.0	4.1	4.9	9.7	3.1	9.5	12.7	4.5	3.8	3.6	0.9	1.5
Tank 4	-	0	0	0	0	0	0	0	0	3.0	14.6	34.3	29.8	5.7	2.6
Tank 5	-	0	0	0	0	0	0	0	0	1.5	2.1	6.8	63.0	20.6	6.0
Tank 6	-	0	0	0	0	0	0	0	0.2	35.6	22.5	22.0	16.6	1.8	1.3
Well 54	10-15	0	1.3	1.3	1.4	6.1	20.4	8.7	13.9	20.3	7.9	5.2	7.2	2.8	3.5
Well 54	34	0	0.4	0.7	1.8	4.4	15.0	6.9	20.9	20.4	6.7	5.8	8.0	3.6	5.4
Well 54	38	0	0	0	0	0	10.1	6.7	24.2	23.6	9.1	6.2	9.2	3.6	7.3
Well 54	43	0	0	0	0	4.1	10.8	5.4	20.1	26.3	11.3	8.0	6.9	3.3	3.8
Well 54	58	0	0	0	0	0	0.3	0.3	1.7	6.6	12.7	19.5	44.0	11.7	3.2
Well 54	65	0	0	0	0	0	0	0	0.6	3.1	4.8	12.7	48.9	25.5	4.4
Well 101	0-12	0	1.6	1.6	5.5	8.7	17.7	5.4	14.2	18.4	6.9	5.7	7.6	2.9	3.8
Well 101	12-20	0.6	0.3	1.2	4.0	11.8	22.2	6.3	13.4	15.5	6.3	5.9	6.5	2.7	3.3
Well 101	20-29	0	0.8	1.6	5.1	9.3	18.6	6.5	19.6	15.3	5.1	3.8	5.3	2.6	6.4
Well 101	33	0	1.6	0.5	1.9	3.5	15.6	6.2	21.8	25.3	8.6	4.3	4.6	1.9	4.2
Well 97	15-20	0	0.7	3.0	10.4	16.2	20.3	5.8	12.9	12.3	4.3	3.8	5.2	2.9	2.2
Well 97	20-25	0	0	0	0	5.0	14.8	8.0	28.1	21.5	6.1	4.2	6.7	2.7	2.9
Well 97	25-30	0	0	0	0	2.8	10.7	4.1	16.8	29.0	16.3	9.8	7.5	1.5	1.5
Well 100	2-14	0	0.3	0.2	2.3	6.4	16.3	8.7	12.9	18.2	7.3	5.4	11.4	5.9	4.7
Well 100	26	3.6	3.8	2.2	6.3	7.2	13.6	5.7	15.1	16.7	5.9	4.7	6.6	3.1	5.5
Well 100	32	0.4	1.9	2.6	3.9	7.4	18.2	6.1	16.1	15.4	6.2	5.6	6.9	4.2	5.1

Table 6. Mechanical analyses of water-bearing materials in the Lower Verde River valley-Cont.

Tank or well number	Depth (feet)	Size in millimeters: More than 19.2	19.2 to 12.7	12.7 to 9.5	9.5 to 6.4	6.4 to 4.76	4.76 to 2.38	2.38 to 2.00	2.00 to 1.19	1.19 to 0.59	0.59 to 0.42	0.42 to 0.297	0.297 to 0.149	0.149 to 0.074	Less than 0.074
Well 98	21.5	0	0.3	1.2	1.8	5.7	16.2	4.8	18.4	20.7	8.3	6.1	8.3	4.1	4.1
Well 98	0-20	0	0.7	2.8	6.0	12.3	18.3	4.0	11.1	12.0	7.9	6.6	10.6	3.9	3.8
Well 98	27.7	0	0	0.4	2.3	12.4	20.9	5.6	11.7	13.7	8.4	8.1	7.2	3.4	5.9
Well 98	30	0	0	0	0.2	0.8	4.6	2.7	14.2	39.3	15.1	9.6	8.2	2.2	3.1
Well 98	33	0	0	0	0.2	0.6	2.2	1.3	5.9	15.8	16.0	20.5	26.2	6.6	4.7
	land surface	0	1.1	1.4	3.1	7.3	23.0	12.0	20.7	20.2	4.3	2.2	2.7	0.5	1.5
Well 102	20-25	0	0	0	0	7.4	10.6	2.6	6.7	15.0	12.8	11.9	20.9	7.9	4.2

Table 7. Physical characteristics of water-bearing materials in the Lower Verde River valley.

Determinations in field laboratory of the Geological Survey, Fort McDowell, Arizona.

Tank or well number	Depth (feet)	Permeability at 60°F	Specific gravity	Apparent specific gravity	Specific yield after draining 48 hours (percent)	Additional yield by drying (percent)	Porosity (percent)
Tank 1	-	5,240	2.61	1.65	30.3	6.3	36.6
Tank 2	-	378	2.69	2.11	10.8	10.6	21.4
Tank 3	-	1,775	2.71	2.07	19.0	4.7	23.7
Tank 4	-	380	2.63	1.66	4.9	31.9	36.8
Tank 5	-	38	a/	a/	a/	a/	a/
Tank 6	-	795	2.59	1.63	26.6	10.4	37.0
Well 54	10-15	579	2.82	1.20	15.8	13.3	29.1
Well 54	34	42	2.78	1.98	13.8	14.9	28.7
Well 54	38	68	2.66	1.86	12.9	17.4	30.3
Well 54	43	400	2.65	1.85	14.8	15.2	30.0
Well 54	58	279	2.53	1.54	4.1	34.9	39.0
Well 54	65	136	2.50	1.51	2.1	37.3	39.4
Well 101	0-12	450	2.65	1.98	15.6	9.5	25.1
Well 101	12-20	294	2.74	2.00	15.4	11.6	27.0
Well 101	20-29	99	2.62	1.95	12.7	12.8	25.5
Well 101	33	796	2.67	1.84	21.2	9.8	31.0
Well 97	15-20	2,260	2.71	1.97	21.7	5.3	27.0
Well 97	20-25	1,000	2.65	1.88	21.5	7.5	29.0
Well 97	25-30	1,290	2.61	1.80	25.2	6.6	31.8
Well 100	2.-14	42	2.63	1.97	3.7	21.3	25.0
Well 100	26	98	2.64	2.03	9.6	13.7	23.3
Well 100	32	33	2.64	2.02	10.4	13.3	23.7
Well 98	21.5	158	2.80	2.02	4.3	24.0	28.3
Well 98	0-20	106	2.84	2.08	8.8	18.0	26.8
Well 98	10-15	208	2.66	2.06	10.8	11.8	22.6
Well 98	27.7	455	2.79	2.01	9.9	18.1	28.0
Well 98	30	487	2.69	1.76	6.7	27.7	34.4
Well 98	33	305	2.70	1.73	4.7	31.5	36.2
	land surface	4,010 b/	2.69	1.85	24.2	7.0	31.2
Well 102	20-25	71	2.65	1.89	7.0	22.6	29.6
Well 102	25-30	67	2.70	2.05	9.2	16.4	25.6
Well 102	30-35	266	2.16	1.70	11.4	14.8	26.2
Well 102	35	394	2.89	1.67	18.1	25.7	43.8
Well 56	39	815	-	1.91	20.4	8.0	28.4
Well 56	39-44	875	2.67	1.93	21.0	6.6	27.6
Well 56	44-49	1,039	2.55	1.82	18.0	27.3	45.3
Well 56	49-54	247	2.69	1.82	18.6	13.7	32.3

a/ Material too fine for permeameter screen

b/ Sample from recharge area, east slope of McDowell Mountains

Test pits were dug at many points in the channel of the river (see pl. 1) just above the stream level, to determine at each point whether the stream was effluent or influent. They were dug during November 1944 when all the flow was shut off at Bartlett Dam. Figure 4 shows typical conditions along the river above the well fields, as shown by the test pits. The only large area where the river was influent, as determined by the pits, was in the vicinity of the two well fields. The test pits were extended both upstream and downstream beyond the area of influence of pumping of both well fields. The measurements of water level in the pits indicated that the water table was in the approximate shape of an elongated, shallow cone. The cone of the upper well field intersected downstream with that of the lower well field. Water-level measurements in the pits also indicated that the cones expanded slowly as long as the flow of the river was shut off, but the pits were flooded soon after water was released from Bartlett Dam and filling of the cones by recharge was noted in the observation wells.

Table 11 gives the location, depth, diameter, and other data concerning wells and test pits in the Lower Verde Valley.

Quality of ground water

General.-Chemical analysis of water gives an indication of its suitability for domestic, industrial, and irrigation uses. It is desirable that water used in cooking be low in certain chemical constituents. Waters containing more than 150 or 200 parts per million of calcium and magnesium bicarbonates, carbonates, or sulfates are termed "hard" waters because they produce insoluble compounds when used for cooking and industrial purposes. Calcium and magnesium ions, when in solution in the presence of soap, form a "curd". No lather can be formed until the calcium and magnesium have been removed from solution by the soap; thus the more calcium and magnesium present, the more soap required to form a lather. Waters containing predominantly the bicarbonate radical (HCO_3) possess what is called carbonate (temporary) hardness and form a scale in vessels when the water is brought to a boil, because carbon dioxide is driven off and the water becomes incapable of holding the calcium or magnesium carbonate in solution. Waters containing predominantly the chloride and sulfate ions possess non-carbonate (permanent) hardness, which cannot be removed by boiling. Certain other objectionable constituents are often found in natural waters. Among them are sodium chloride (table salt), sodium and magnesium sulfate (Glauber's salt and epsom salt, respectively), iron, and fluoride. Sodium chloride in water for drinking and cooking is objectionable because of its salty taste, sodium and magnesium sulfate because of the bitter taste, and iron because of the yellow deposit formed on anything with which it comes in contact. Certain concentrations of fluoride are objectionable because of the tendency to cause mottled enamel on the teeth of children. Usually 1.0 part per million is considered the upper limit for safe use[1].

---

[1] Smith, H. V., and Smith, M. C., Mottled enamel in Arizona and its correlation with the concentration of fluorides in water supplies: Ariz. Univ. College Agr. Tech. Bull. 43, p. 284, 1932.

Concentrations of several parts per million of nitrate in ground water usually indicate that it has come in contact with decaying animal or vegetable matter, and a bacteriological analysis should be made to determine its suitability for human consumption. The present investigation was not immediately concerned with the bacteriological analysis, and the chemical analysis of the water is no indication of its suitability from that standpoint. Water from properly-cased wells penetrating artesian aquifers is usually not as susceptible to bacteriological contamination as is that from shallow water-table wells.

Chemical analyses.-The mineralization of ground or surface waters usually reflects the solubility of the rock materials with which they have come in contact. Table 9 gives partial chemical analysis of waters from several wells and springs in the lower Verde River valley. From the table it is seen that the water obtained from the present city wells is similar to the water flowing in the Verde River. The water is characterized by low chloride, carbonate and fluoride, and relatively high bicarbonate and hardness. It does not contain enough fluoride to produce dental fluorosis, and it is relatively low in sulfate and chloride. The water is of the type usually identified as a moderately hard bicarbonate water.

Although the water level in well 1, (the Dillon well), is affected by changes in stage of the Verde River, it probably receives its water from the older fill bordering the valley. Water from this well is higher in fluoride and lower in hardness than Verde River water.

Water from well 26 (artesian well) is lower in hardness and higher in fluoride than Verde River water, which indicates that it comes from rock materials in the older fill not directly connected with the Verde River gravels and remains in contact with them for a long period of time, thereby bringing more of certain constituents into solution.

Water from well 11 (Robbins' house well) and the Williams spring is higher in fluoride and lower in hardness than Verde River water and probably represents water derived from the older fill bordering the valley.

Table 9. Partial chemical analyses of water from wells and springs in the Lower Verde River valley, Maricopa County, Arizona.

Analytical results, in parts per million, J. D. Hem, Analyst

Location and description	Date of collection	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K) (calc.)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Dissolved solids (Sum)	Total hardness as $CaCO_3$ (calc.)	Remarks
Well 1, SE¼ sec. 17, T. 5 N., R. 7 E.	Feb. 19, 1945	22	7.6	156	210	5.9	136	58	6.9	499	86	Dillon well
Well 4, SW¼ sec. 29, T. 5 N., R. 7 E.	do.	45	28	32	254	0	58	18	0.3	308	228	Moore's irrigation well
Williams Spring, SW¼ sec. 17, T. 5 N., R. 7 E.	do.	21	17	43	172	3.9	26	26	0.8	226	122	Discharge estimated 3 gallons a minute
Well 11, SW¼ sec. 22 T. 4 N., R. 6 E.	Oct. 2, 1944	3.0	1.0	87	135	-	9.5	13	8.0	-	12	Dick Robbins' house well
Well 12, NE¼ sec. 29, T. 4 N., R. 6 E.	do.	112	14	62	277	-	122	82	1.1	-	337	Dick Robbins' stock well
Well 26, NE¼ sec. 6, T. 3 N., R. 7 E.	Oct. 31, 1944	5.0	1.1	130	294	-	23	18	2.8	328	17	Artesian well, pumped about 2½ gallons a min.
Composite sample from city wells taken at the Detritor	Oct. 1943	45	34	46	278	-	80	28	-	370	251	Analysis by University of Arizona Experiment Station
Verde River below Bartlett Dam, flow 0.9 cubic foot per second	Nov. 5, 1944	48	26	33	268	-	58	13	0.2	311	227	
Verde River at north boundary Camp McDowell Reservation, flow 6.5 cubic feet per second	Nov. 3, 1944	49	26	42	266	-	67	22	0.4	338	230	

GEOPHYSICAL PROSPECTING

Electrical-resistivity methods

Electrical-resistivity methods of geophysical prospecting have been used quite extensively in recent years in locating ore deposits, oil-bearing formations, and bedrock. Recently their use has been extended to the search for water-bearing formations. The equipment used in this investigation was built from designs prepared by O. H. Gish and W. J. Rooney and is known as the Gish-Rooney apparatus. The theory of design and operation is explained in detail in several recent books[1]. The principle of operation is based on

[1] Heiland, C. A., Geophysical exploration, Prentice-Hall, Inc., 1940.
Eve, A. S., and Keyes, D. A., Applied geophysics in the research of minerals, Cambridge University Press, 1938.
Jakosky, J. J., Exploration geophysics, Times-Mirror Press, 1940.

the fact that different rock materials offer different degress of resistance to the passage of an electric current. The values are usually expressed in ohm centimeters. Clay and silt usually show lower resistivity than sand and gravel, though the amount and conductivity of the interstitial water probably affect the value and may alter this general relation.

Some of the geophysical probes were made near an exposed river bank or dug well where a few feet of surficial material could be examined. Others were made near existing drilled wells, in order to correlate the resistivity curve with the log of the well (see probe 7, fig. 11). Most of the curves were of the two- or three-layer type, but a few of the deeper curves indicated more than three layers.

The curves of typical probes are illustrated in figures 11-14, and locations of all the probes are shown on plate 1. Table 10 gives the location and results of each probe, together with the probable characteristics of the material encountered in each. The writers' judgment of the material was based on a comparison of the curve obtained by probing unknown material with that obtained by probing known material. The probable character of material penetrated by probes that extended deeper than available well logs was suggested by the geologic structure of the area. It has been found that the finest material in a stratum is the material usually indicated by the curve. For example, boulders cemented by clay and silt give the resistance of clay and silt, the boulders having little or no effect. In the column showing resistivity in table 10 the descriptive terms used are comparative and apply only to this area.

CONCLUSIONS

The conclusions given in the following paragraphs are made without benefit of the information to be obtained by exploratory test drilling, and are subject to change pending the completion of the test wells.

Source and direction of movement of the ground water

The principal source of water for the city's present Verde wells is recharge from the surface flow and underflow of the Verde River. Some inflow is received from the older fill bordering the valley.

In general the ground water in the older fill moves toward the Verde River but the movement may have a slight downstream component. Outside the cones of depression of the city well fields the ground water in the river gravels moves principally downstream but the movement has a component toward the river. Inside the cones of depression of the city wells the ground water moves toward the center of pumping in each well field. Thus, although the general movement is downstream, the direction is completely reversed at some places and the water moves upstream to the wells.

Table 10. Results of geophysical prospecting

Probe number	Location	Approximate depth (feet)	Resistivity	Probable material	Recommendations for test drilling
1	SE¼ sec. 30, T. 3 N., R. 7 E., south of Detritor, west side of Verde River	0–30 30–52+	Medium Low	Fine to medium sand Silt or clay	Unfavorable
2	SE¼ sec. 30, T. 3 N., R. 7 E. south of southern boundary of Camp McDowell Indian Reservation	0–20 20–90+	Medium Low	Fine sand Silt or clay	Unfavorable
3	SW¼ sec. 19, T. 3 N., R. 7 E. 500 feet north 60° west, of City of Phoenix well 8	0–40 40–300 300–1,050	High Low High	Sand, gravel and boulders Silt or clay Granite bedrock	Favorable but too close to existing well
4	SW¼ sec. 19, T. 3 N., R. 7 E., northwest of lower well field	0–25 25–80	Medium Low	Sand and gravel Silt and clay	Unfavorable
5	NW¼ sec. 19, T. 3 N., R. 7 E. 0.4 mile south of city well 7	0–15 15–80	Very high Low	Gravel and boulders Silt and clay	Unfavorable
6	NW¼ sec. 18, T. 3 N., R. 7 E., 30 feet northwest of city well 1	0–40 40–70 70–260	Low Medium Low	Fine sand and silt Coarse gravel Silt and clay	Favorable but too close to existing well
7	SW¼ sec. 7, T. 3 N., R. 7 E., 55 feet west of city well 4	0–60 60–200	High Low	Sand and gravel Silt and clay	Probe made to correlate with well log. Favorable but too close to existing well
8	SE¼ sec. 7, T. 3 N., R. 7 E., 50 ft. southeast of city well 6	0–25 25–100	Very high Low	Gravel Silt and clay	Unfavorable and too close to existing well
9	NE¼ sec. 7, T. 3 N., R. 7 E., north of upper well field, 75 feet west of city diversion canal	0–20 20–100	Medium Low	Sand and gravel Silt and clay	Unfavorable

Table 10. Results of geophysical prospecting - Cont.

Probe number	Location	Approximate depth (feet)	Resistivity	Probable material	Recommendations for test drilling
10	NE¼ sec. 7, T. 3 N., R. 7 E., upstream from upper well field, 270 feet east of infiltration gallery, 290 feet west of Verde River	0-20 20-75	Very high Low	Gravel Silt and clay	Unfavorable
11	NE¼ sec. 7, T. 3 N., R. 7 E., 0.5 mile south of Fort McDowell, 200 feet west of infiltration gallery	0-40 40-100	Medium Low	Sand and gravel Silt and clay	Unfavorable
12	NE¼ sec. 7, T. 3 N., R. 7 E., 0.5 mile south of Fort McDowell, 155 feet west of infiltration gallery	0-25 25-80	Medium Low	Sand and gravel Silt and clay	Unfavorable
13	NE¼ sec. 7, T. 3 N., R. 7 E., 525 feet northwest of probe 9	0-20 20-90	Medium Low	Fine sand and gravel Silt and clay	Unfavorable
14	SE¼ sec. 6, T. 3 N., R. 7 E. 1,100 feet north of probe 13	0-20 20-90	Very high Very low	Gravel Silt and clay	Unfavorable
15	SE¼ sec. 6, T. 3 N., R. 7 E. west bank of Verde River, 800 feet south of south end of brush diversion dam	0-10 10-50 50-90	Medium High Low	Fine sand Coarse gravel Silt and clay.	Favorable
16	SE¼ sec. 6, T. 3 N., R. 7 E., 900 feet west of probe 15	0-50 50-240 240-280+	High Low High	Sand and gravel Silt and clay Sandstone or conglomerate	Favorable
17	NW¼ sec. 6, T. 3 N., R. 7 E., 0.25 mile south of Fort McDowell on west side of main north-south road.	0-30 30-300 300-400 400-460 460-740	Very high Low Medium Low Alternately high and low	Sand and gravel with considerable silt and clay Silt and clay Sand or sandstone Silt and clay Sand interbedded with silt and clay	Favorable for deep test well

Table 10. Results of geophysical prospecting - Cont.

Probe number	Location	Approximate depth (feet)	Resistivity	Probable material	Recommendations for test drilling
18	NE$\frac{1}{4}$ sec. 6, T. 3 N., R. 7 E., 250 feet southeast of well 27 (see pl. 1)	0-40 40-100	Medium Low	Sand and gravel Silt and clay	Unfavorable
19	NE$\frac{1}{4}$ sec. 6, T. 3 N., R. 7 E., west bank of Verde River about 500 feet below Sycamore staff gage	0-50 50-100	High Low	Cemented sand and gravel with boulders Silt and clay	Favorable
20	NE$\frac{1}{4}$ sec. 6, T. 3 N., R. 7 E., west bank of Verde River 0.5 mile east of Fort McDowell	0-50 50-130	High Low	Sand and gravel Silt and clay	Favorable
21	NE$\frac{1}{4}$ sec. 6, T. 3 N., R. 7 E., 0.25 mile east of Fort McDowell	0-45 45-110	Medium Low	Sand and gravel Silt and clay	Favorable
22	NE$\frac{1}{4}$ sec. 6, T. 3 N., R. 7 E., 230 feet northwest of well 26, an artesian well	0-55 55-100	Medium Low	Sand and gravel Silt and clay	Favorable
23	NE$\frac{1}{4}$ sec. 6, T. 3 N., R. 7 E., near west bank of Verde River, 500 feet southeast of picnic grounds north of Fort McDowell	0-10 10-100	Low Medium	Silt and fine sand Sand and gravel	Favorable
24	SE$\frac{1}{4}$ sec. 31, T. 4 N., R. 7 E., at picnic grounds north of Fort McDowell	0-100	Low	Silt and clay	Unfavorable
25	NW$\frac{1}{4}$ sec. 31, T. 4 N., R. 7 E., north of Robbins Wash about 0.8 mile north of probe 24.	0-60 60-130	Very high Medium	Sand and gravel Sand interbedded with silt and clay	Favorable
26	SE$\frac{1}{4}$ sec. 30, T. 4 N., R. 7 E., near west bank of Verde River about 2,000 feet upstream from probe 25	0-50 50-90	Low Low	Silt and clay Sand interbedded with silt and clay	Unfavorable

Table 10. Results of geophysical prospecting - Cont.

Probe number	Location	Approximate depth (feet)	Resistivity	Probable material	Recommendations for test drilling
27	SE¼ sec. 30, T. 4 N., R. 7 E., about 250 feet west of west bank of Verde River, about 0.5 mile upstream from probe 26	0-40 40-100	Medium Low	Sand and gravel Silt and clay	Unfavorable
28	NW¼ sec. 29, T. 4 N., R. 7 E., about 400 feet west of west bank of Verde River, in trail east of Joe Joseph's house	0-35 35-90	Medium Low	Silt and sand Silt and clay	Unfavorable
29	SW¼ sec. 20, T. 4 N., R. 7 E., in lower (southern) part of area known locally as Queena Harry Flat	0-25 25-130	Low Low	Fine sand and silt Silt and clay	Unfavorable
30	SW¼ sec. 20, T. 4 N., R. 7 E., in center of Queena Harry Flat	0-20 20-150	Low Medium	Silt and clay Sand and gravel interbedded with silt and clay	Favorable
31	SW¼ sec. 20, T. 4 N., R. 7 E., in Queena Harry Flat	0-20 20-150 150-440	Low Medium Low	Silt and clay Fine sand Silt and clay	Unfavorable
32	SW¼ sec. 20, T. 4 N., R. 7 E., near west bank of Verde River on east side of Queena Harry Flat	0-20 20-100	Medium Low	Fine sand and gravel Silt and clay	Unfavorable
33	NW¼ sec. 20, T. 4 N., R. 7 E., in Queena Harry Flat	0-20 20-200	Low Medium	Fine sand and silt Sand interbedded with silt and clay	Favorable
34	NW¼ sec. 20, T. 4 N., R. 7 E., in Queena Harry Flat	0-20 20-140	Low Medium	Silt and clay Fine sand and gravel	Favorable

Table 10. Results of geophysical prospecting - Cont.

Probe number	Location	Approximate depth (feet)	Resistivity	Probable material	Recommendations for test drilling
35	NE$\frac{1}{4}$ sec. 19, T. 4 N., R. 7 E.,	0-30	High	Sand and gravel	
	about 1,600 feet west of west	30-200	Low	Silt and clay	
	edge of Queena Harry Flat	200-400	Medium	Alternate beds of sand and clay	Unfavorable
36	NW$\frac{1}{4}$ sec. 20, T. 4 N., R. 7 E.	0-10	High	Sand and gravel	
	near west bank of Verde River	10-35	Medium	Sand and silt	Unfavorable
	on east side of Queena Harry Flat	35-100	Low	Silt and clay	
37	NW$\frac{1}{4}$ sec. 20, T. 4 N., R. 7 E.,	0-45	Low	Fine sand and silt	
	at north end of Queena Harry Flat	45-70	Medium	Medium sand and gravel	Favorable
		70-130	Low	Silt and clay	
38	NE$\frac{1}{4}$ sec. 19, T. 4 N., R. 7 E.,	0-10	Low	Fine sand and silt	
	at northwest end of Queena	10-95	High	Medium sand and gravel	Favorable
	Harry Flat near Fisher's house	95-140	Low	Silt, clay and sand	
39	NE$\frac{1}{4}$ sec. 18, T. 4 N., R. 7 E.,	0-30	Medium	Sand and gravel	
	about 0.5 mile north of	30-130	Low	Silt and clay	Unfavorable
	Queena Harry Flat				

Rate of recharge to the Verde River gravels and the effects of silting

The recharge area for the water withdrawn by the city wells is between the city's present brush diversion dam, near the mouth of Sycamore Creek, and a point about 1,000 feet southeast of the Detritor. The maximum rate of recharge or infiltration from the Verde River, estimated from infiltration tests made under favorable conditions, was 2 feet a day over the wetted area. Under favorable conditions, when the sealing effect of silt is at a minimum, the rate of recharge is sufficient to supply all the present wells, pumping at full capacity, when the flow of the Verde River is 200 cubic feet per second, and possibly when it is as low as 100 cubic feet per second. If possible, therefore, the flow should be maintained at 100 cubic feet per second or more, especially during the summer and fall.

Sediments deposited by the river are highly effective in sealing up the gravels that supply the city's wells, the amount of sealing depending on the silt content of the water and the discharge of the river at the well fields. When the discharge of the Verde River is high, the fine materials are kept in suspension and are not deposited in the channel. Also, the wetted area is relatively large, so that even with a decreased infiltration rate the total recharge may be sufficient to supply the city wells. The maximum effect of silting occurs with low flows. Runs of seepage measurements made under different conditions of silting showed that the recharge with equal rates of flow in the river (about 55 cubic feet per second) was more than two and a half times as great with minimum silting effect as with maximum effect.

Interference among wells

Mutual interference among wells in the lower well field is too small to be of any practical importance. Interference among wells in the upper well field is five to seven times as great as in the lower well field but is not believed to be serious enough to warrant abandonment of any of the wells. However, during periods of unfavorable recharge the interference in the upper well field is so great that only municipal wells 4 and 5 should be operated. These wells penetrate the greatest thickness of sand and gravel and will almost completely dry up wells 1, 2, and 6 and seriously deplete well 3.

Interference between wells and the infiltration gallery

During unfavorable conditions of recharge, wells 4 and 5 seriously interfere with the yield of the infiltration gallery, which declined in 1944 from more than 5 million gallons a day to less than 0.5 million gallons a day. If, as indicated below, additional well fields are installed upstream from the gallery, it is doubtful whether it will produce any water during unfavorable conditions of recharge. Under these conditions it is probable that more effective use of the gallery could be made by sealing the joints and using it as a conduit for water obtained from wells farther upstream.

Storage in the present well fields

It is estimated that 33 million gallons of water available for withdrawal is stored in the present well fields for each square mile of saturated material one foot in thickness. Therefore, if the water table is lowered 10 feet over the area of 2,960 acres included in the upper and lower well fields, 152 million gallons would be available for pumping. This can be removed by the existing wells at the maximum rate of only 7 or 8 million gallons a day. Fortunately, this stored water forms a reserve supply which need not be used except during the relatively short periods of unfavorable conditions of recharge. Even at such times all water pumped in excess of about 8 million gallons a day must be derived from recharge.

Storage in the river gravels and older fill above the present well fields

For each foot that the water table is lowered in the river gravels from the upper end of the valley to Sycamore staff gage, about 236 million gallons of water is yielded. If the water table could be lowered 10 feet, there would be available about 2,360 million gallons from storage plus about 4 million gallons from the older fill for each day that unwatering takes place. Assuming an average demand by the city of 35 million gallons a day, the sources just described would supply the city for about 76 days. It is believed that the water table could not be lowered feasibly more than an average of about 10 feet.

The above computations were made under the assumptions that no water would be supplied by recharge during this period and that none would be supplied from the present well fields. Tests made on the effects of silting indicate that complete sealing will never occur. Thus, as long as the river is flowing, there will always be some recharge to the river gravels to supplement the storage. In order to utilize fully the storage and recharge mentioned above it would probably be necessary to drill wells in favorable locations spaced at about half-mile intervals for about 11 miles above the present well fields.

The above quantities are in storage in that part of the valley above Sycamore staff gage. To determine the total amount stored in the valley, the quantities in the present well fields must be added to those given above.

Future well sites

Geophysical probes completed thus far indicate that at least two more well fields could probably be developed upstream from the present fields. The first is near the west bank of the Verde River just south of well 26 (see pl. 1), about in the center of the E½ sec. 6, T. 3 N., R. 7 E. Although it is difficult to estimate, without test wells, the yield that might be expected from this site, the indications are that it would be comparable to that of the present lower well field.

Another possible site for a well field is the area known as the Queena Harry Flat, about 3 miles farther upstream in the W½ sec. 20, T. 4 N., R. 7 E. Indications are that this location offers greater possibilities than the present upper well field, but test wells must be drilled to obtain accurate information as to the depth and extent of the aquifer. It is possible that artesian water can be obtained from aquifers below the river gravels at both these sites. Geophysical probes indicate the presence of formations that may be water-bearing, but information is not available as to permeability, thickness, depth, and areal extent, nor as to the quality or quantity of water available from them. Geophysical probing of the remainder of the flood plain should be done as soon as information is available from the first test wells, and the test-drilling program thereafter should closely follow the geophysical work.

Spacing of future wells

From the standpoint of the most efficient utilization of ground-water storage and recharge in the Verde Valley, new wells should be spaced at about half-mile intervals where the water-bearing materials are comparable to those of the upper well field. Somewhat closer spacing could be used with less permeable materials.

Measurements and records

It would be desirable to keep records of the logs of all wells that may be drilled and records of the total discharge of the present wells at the Detritor. Also it would be advisable to install continuous water-level recorders or to make weekly tape measurements in a well in each of the two well fields. Well 49 in the upper well field and well 102 in the lower well field are suggested. These measurements would indicate the quantity of water stored in the present well fields. Observation wells should be maintained in connection with all new developments.

Artificial recharge

In view of the past experience with artificial recharge, it is believed that this practice can be expanded, not only at the present well field but at all new well locations developed. Artificial recharge conditions would be improved by the installation and careful operation of diversion gates to prevent river water containing large quantities of silt from entering the artificial recharge channels. Scarifying is detrimental over a long period of time, and the channels could be allowed to dry up periodically to retard the growth of moss and algae.

Adequacy and permanency of ground-water supply of Lower Verde Valley

Large quantities of water are in storage in the Lower Verde Valley, and when conditions are favorable the rate of recharge is high. During periods when the river gravels are sealed by silt deposits and the flow in the river is low, it is believed that ground-water storage together with that obtained by infiltration from the surface flow will provide an adequate and permanent supply of a minimum of 56 million gallons a day. This quantity may be increased both by increasing the minimum flow in the river and by artificial recharge in channels kept free of silt-laden water.

The possibilities of obtaining water supplies from Paradise Valley and Cave Creek together with the results of test drilling and further geophysical work, will be submitted as an addendum to this report.

Table 11
Records of wells in the Lower Verde River valley, Maricopa County, Arizona
(All wells are dug unless otherwise noted in "Remarks" column.)

No.	Location	Owner	Date completed	Altitude above sea level (feet)	Depth of well (feet)	Diameter of well (in.)
	T. 5 N., R. 7 E.					
1	SE¼ sec. 17	- Dillon	-	-	25	6
2	NW¼ sec. 20	W. M. Williams	-	-	26	1½
3	SW¼ sec. 29	Moore Bros.	-	-	-	4
4	Do.	do.	1918	-	78	12
	T. 5 N., R. 5 E.F					
5	NW¼ sec. 15	- Brown	-	-	204	48
6	NE¼ sec. 36	Moore Bros.	-	-	256	-
7	Do.	do.	-	-	289	-
	T. 4 N., R. 5 E.					
8	SW¼ sec. 14	do.	-	-	113	-
	T. 4 N., R. 6 E.					
9	NW¼ sec. 2	do.	-	-	600	-
10	SW¼ sec. 8	Dick Robbins	-	-	-	-
11	Do.	do.	1915	-	260	8
12	NE¼ sec. 29	do.	1944	-	196	8
	T. 4 N., R. 7 E.					
13	NE¼ sec. 13	Queena Harry	-	-	23	36
14	NW¼ sec. 26	Vernon Hughes	-	-	-	8
15	NW¼ sec. 34	do.	-	-	-	6
	T. 4 N., R. 8 E.					
16	NE¼ sec. 30	do.	-	-	-	8

a/ T, turbine; C, cylinder; G, gasoline; W, windmill; B, bucket; H, hand.
b/ D, domestic; S, stock; P, public supply; I, irrigation; N, none.

No.	Water level: Depth below surface (feet)	Water level: Date of measurement 1944	Pump and power a/	Use of water b/	Remarks
1	15.82	June 7	C,G	D,S	
2	19.29	do.	none	N	Driven well
3	-	-	C,W	D	Drilled well
4	43.20	May 25	T,G	I	Do.
5	-	-	C,G	D,S	Reported to penetrate fill and volcanic tuff to 204 feet, where lava was encountered. Water reported from fissure in lava.
6	-	-	C,G	S	Drilled well
7	-	-	C,G	S	Do.
8	-	-	C,G	S	Drilled, reported to yield 20 gallons a minute by pumping
9	-	-	-	-	Dry hole. 0-85 feet clayey gravel, 85-600 feet clay
10	23.74	May 22	C,G	S	Drilled well
11	75.50	do.	C,G	D,S	Drilled well, shut down 2 hours before measurement
12	66.15	July 20	C,G	S	Drilled well
13	17.74	June 27	B,H	D	-
14	23.30	June 9	C,W	S	Drilled well
15	10.07	July 21	C,W	S	Do.
16	42.59	June 9	C,W	S	Do.

Table 11. Records of wells in the Lower Verde River valley, Maricopa County, Arizona - Cont.

No.	Location	Owner	Date completed	Altitude above sea level (feet)	Depth of well (feet)	Diameter of well (in.)
	T. 3 N., R. 7 E.					
17	NE¼ sec. 5	-	July 1944	1,442.34	22	1
18	NW¼ sec. 5	-	July 1944	1,417.64	16	1
19	Do.	-	Nov. 1944	1,399.61	1.5	24
20	SW¼ sec. 5	-	July 1944	1,406.72	16	1
21	Do.	-	Nov. 1944	1,393.89	1.1	24
22	Do.	-	Nov. 1944	1,392.97	1.0	24
23	Do.	-	Nov. 1944	1,392.80	1.0	24
24	NE¼ sec. 6	-	Nov. 1944	1,400.08	1.5	18
25	Do.	-	Nov. 1944	1,397.60	1.0	18
26	Do.	U.S. Indian Service	-	-	540	1
27	Do.	Mike Nelson	-	1,420.16	21.0	48
28	SW¼ sec. 6	George Norton	-	1,414.27	30	36
29	SE¼ sec. 6	James Kill	-	1,420.85	22.3	48
30	Do.	-	Nov. 1944	1,394.92	2.5	24
31	Do.	-	Nov. 1944	1,393.40	2.0	24
32	Do.	-	do.	1,393.77	2.5	24
33	Do.	-	do.	1,392.77	2.5	24
34	Do.	-	July 1944	1,382.72	24	1
35	Do.	-	July 1944	1,401.74	26.6	1
36	Do.	-	Nov. 1944	1,390.36	2.0	24
37	NE¼ sec. 7	-	Nov. 1944	1,388.91	1.0	18

No.	Water level: Depth below surface (feet)	Water level: Date of measurement 1944	Pump and power a/	Use of water b/	Remarks
17	7.61	July 24	-	N	Driven sand point well
18	14.77	do.	-	N	Do.
19	1.28	Nov. 7	-	N	Test pit
20	10.85	Aug. 9	-	N	Driven sand point well
21	0.84	Nov. 1	-	N	-
22	0.33	do.	-	-	Test pit
23	0.34	Nov. 2	-	-	Do.
24	1.25	Nov. 7	-	-	Do.
25	0.50	do.	-	-	Do.
26	-	-	-	N	Reported depth. Flow less than one gallon a minute.
27	20.03	June 27	-	-	-
28	29.14	do.	-	-	-
29	21.88	do.	-	-	-
30	2.22	Nov. 1	-	-	Test pit
31	1.53	do.	-	-	Do.
32	2.25	do.	-	-	Do.
33	2.28	do.	-	-	Do.
34	24.0	Aug. 24	-	-	Driven sand-point observation well.
35	19.95	Aug. 23	-	-	Do.
36	1.36	Nov. 1	-	-	Test pit
37	0.48	Nov. 4	-	-	Do.

Table 11. Records of wells in the Lower Verde River valley, Maricopa County, Arizona - Cont.

No.	Location	Owner	Date completed	Altitude above sea level (feet)	Depth of well (feet)	Diameter of well (in.)
38	NE¼ sec. 7	-	Nov. 1944	1,388.98	2.0	18
39	Do.	-	Nov. 1944	1,387.39	1.5	18
40	Do.	-	Nov. 1944	1,386.59	1.5	18
41	Do.	-	Nov. 1944	1,385.63	2.2	18
42	Do.	-	Nov. 1944	1,385.15	2.0	18
43	Do.	-	Nov. 1944	1,384.71	1.9	18
44	Do.	-	Nov. 1944	1,383.98	1.2	12
45	Do.	-	Aug. 1944	1,398.89	19	1
46	Do.	-	Aug. 1944	1,400.02	27	1
47	Do.	-	Aug. 1944	1,400.36	27	1
48	Do.	-	Aug. 1944	-	22	1
49	Do.	City of Phoenix	1928	1,400.50	27	2.5
50	SW¼ sec. 7	do.	1928	1,398.31	38.5	2.5
51	Do.	do.	1928	1,399.29	27	2.5
52	Do.	do.	1940	1,395.04	72	20
53	Do.	do.	1928	1,396.21	63.8	6
54	Do.	do.	1944	1,398.40	65	6
55	Do.	do.	1927	1,398.45	243	20
56	Do.	do.	1944	1,400.22	59	6
57	Do.	do.	1927	1,394.80	66	20
58	Do.	do.	1927	1,389.42	49	20
59	SE¼ sec. 7	do.	1940	1,394.15	710	20

No.	Water level: Depth below surface (feet)	Water level: Date of measurement 1944	Pump and power a/	Use of water b/	Remarks
38	1.34	Nov. 4	-	-	Test pit
39	0.99	do.	-	-	Do.
40	1.20	do.	-	-	Do.
41	1.41	do.	-	-	Do.
42	1.50	do.	-	-	Do.
43	1.60	do.	-	-	Do.
44	0.94	do.	-	-	Do.
45	14.54	Aug. 8	-	-	Driven sand-point observation well
46	19.40	Aug. 26	-	-	Do.
47	19.50	Aug. 25	-	-	Do.
48	16.99	Aug. 9	-	-	Do.
49	20.48	May 23	-	-	Do.
50	18.8	do.	-	-	Do.
51	20.98	do.	-	-	Do.
52	10.76	do.	T,E	D,P	City of Phoenix well 5
53	21.66	Sept. 13	-	N	Drilled in 1928, deepened in 1944.
54	23.42	do.	-	N.	-
55	21.13	do.	T,E	D,P	City of Phoenix well 4
56	24.65	Sept. 15	-	N	Drilled in 1928, deepened in 1944.
57	18.74	May 22	T,E	D,P	City of Phoenix well 3
58	13.54	do.	T,E	D,P	City of Phoenix well 2
59	12.50	do.	T,E	D,P	City of Phoenix well 6

Table 11. Records of wells in the Lower Verde River valley, Maricopa County, Arizona - Cont.

No.	Location	Owner	Date Completed	Altitude above sea level (feet)	Depth of well (feet)	Diameter of well (in.)
60	SE¼ sec. 7	-	1944	1,384.95	1.0	12
61	Do.	-	1944	1,386.52	2.3	18
62	NW¼ sec. 18	City of Phoenix	1927	1,391.06	108	20
63	Do.	John Smith	-	-	29	48
64	Do.	City of Phoenix	1927	-	-	60
65	Do.	-	-	1,376.22	10	60
66	Do.	-	1944	1,375.39	6.0	1
67	Do.	-	1944	1,374.30	5.0	1
68	Do.	-	1944	1,373.67	5.0	1
69	Do.	-	1944	1,370.37	2.7	24
70	SW¼ sec.18	-	-	1,374.58	8.0	60
71	Do.	-	1944	1,369.49	2.0	18
72	Do.	-	1944	1,369.06	2.0	18
73	Do.	-	1944	1,367.87	2.0	18
74	Do.	-	1944	1,367.92	2.5	18
75	Do.	-	1944	1,366.40	2.7	24
76	Do.	-	1944	1,366.41	2.2	24
77	NE¼ sec. 19	City of Phoenix	1930	1,379.68	62	20
78	Do.	-	1944	1,363.74	2.8	24
79	Do.	-	1944	1,363.59	1.7	15
80	Do.	-	1944	1,367.21	6.6	1
81	Do.	-	1944	1,363.00	1.5	15

No.	Water level: Depth below surface (feet)	Water level: Date of measurement 1944	Pump and power a/	Use of water b/	Remarks
60	0.40	Nov. 4	-	-	Test pit
61	-	-	-	-	Do.
62	17.93	May 22	T,E	D,P	City of Phoenix well 1.
63	23.57	June 27	-	N	-
64	-	-	T,E	D,P	City of Phoenix well 14, horizontal well.
65	6.40	Dec. 9	-	-	Test pit
66	5.61	Nov. 24	-	-	Driven observation well
67	3.94	Dec. 9	-	-	Do.
68	2.00	Dec. 7	-	-	Do.
69	-	-	-	-	Test pit
70	6.27	Dec. 9	-	-	Do.
71	1.55	Nov. 7	-	-	Do.
72	1.79	Nov. 1	-	-	Do.
73	1.55	do.	-	-	Do.
74	1.62	do.	-	-	Do.
75	1.44	do.	-	-	Do.
76	1.59	do.	-	-	Do.
77	12.0	Aug. 29	T,E	D,P	City of Phoenix well 7.
78	-	-	-	-	Test pit
79	1.17	Nov. 11	-	-	Do.
80	4.82	Nov. 23	-	-	Do.
81	1.28	Nov. 11	-	-	Do.

Table 11. Records of wells in the Lower Verde River valley, Maricopa County, Arizona - Cont.

No.	Location	Owner	Date completed	Altitude above sea level (feet)	Depth of well (feet)	Diameter of well (in.)
82	NE¼ sec. 19	-	1944	1,362.91	1.5	15
83	Do.	-	1944	1,362.57	1.2	12
84	SW¼ sec. 19	City of Phoenix	1930	1,370.47	62	20
85	SE¼ sec. 19	do.	1940	1,368.63	55	20
86	Do.	-	1944	1,361.61	1.4	15
87	Do.	-	1944	1,360.41	0.8	12
88	Do.	-	1944	1,359.46	0.6	12
89	Do.	-	1944	1,360.05	5.0	1
90	NE¼ sec. 30	-	1944	1,355.77	1.0	12
91	Do.	-	1944	1,353.61	1.0	12
92	Do.	-	1944	1,351.77	1.0	12
93	Do.	-	1944	1,349.51	1.0	12
94	Do.	-	1944	1,349.53	5.0	1
95	Do.	-	1944	1,348.33	1.0	12
96	Do.	City of Phoenix	1940	1,365.67	83	20
97	Do.	do.	1944	1,356.44	31	6
98	Do.	do.	1944	1,357.00	33	6
99	Do.	do.	1930	1,363.20	65	20
100	Do.	do.	1944	1,358.00	33.5	6
101	Do.	do.	1944	1,362.18	33	6
102	Do.	do.	1944	1,367.70	40	6
103	Do.	do.	1936	1,372.38	61	20

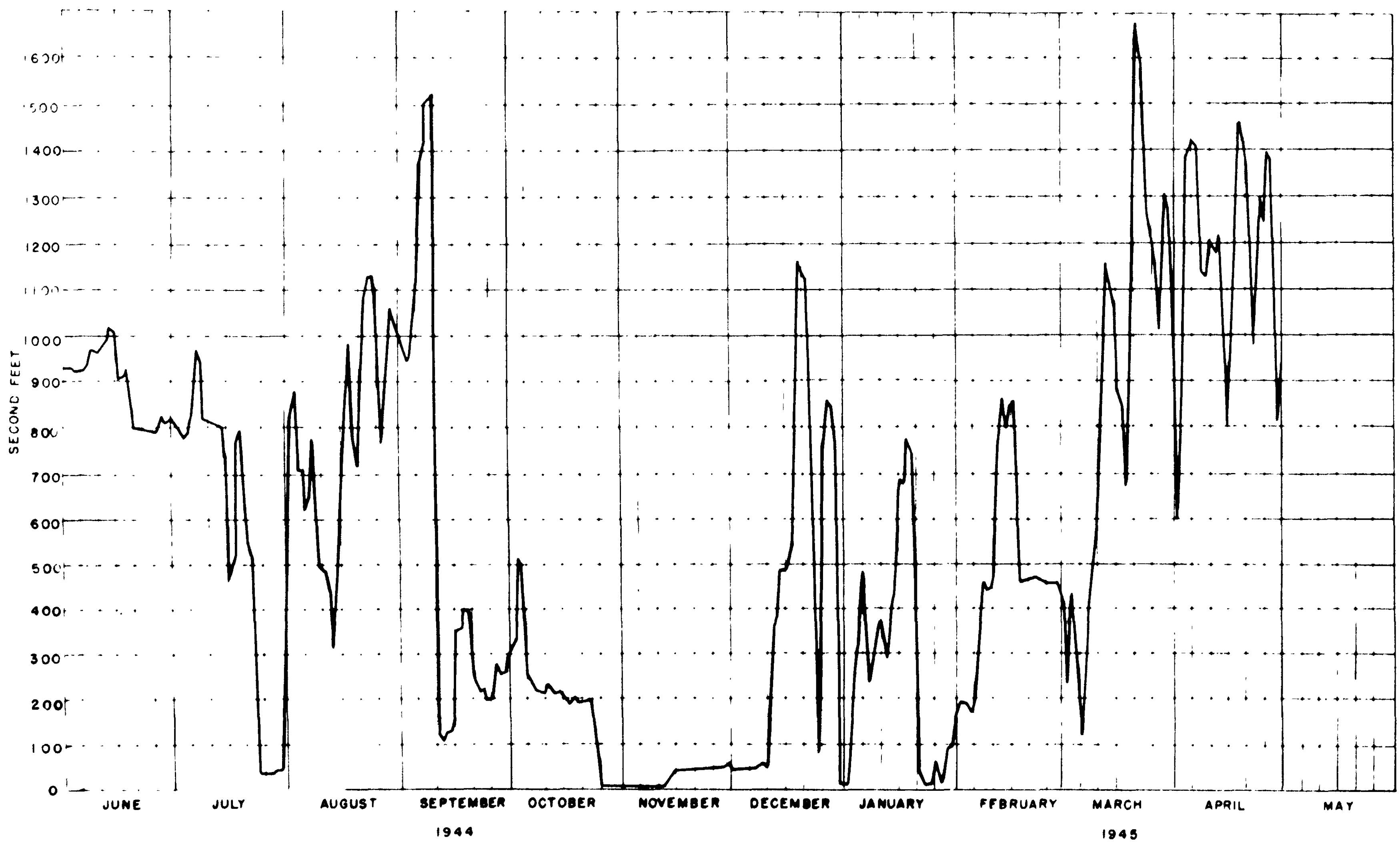
No.	Water level: Depth below surface (feet)	Water level: Date of measurement 1944	Pump and power a/	Use of water b/	Remarks
82	1.30	Nov. 11	-	-	Test pit
83	0.99	do.	-	-	Do.
84	18.05	May 23	T,E	D,P	City of Phoenix well 8
85	12.00	May 22	T,E	D,P	City of Phoenix well 13
86	1.12	Nov. 11	-	-	Test pit
87	0.69	do.	-	-	Do.
88	0.60	do.	-	-	Do.
89	2.30	Nov. 21	-	-	Driven observation well
90	0.72	Nov. 11	-	-	Test pit
91	0.79	Nov. 13	-	-	Do.
92	0.81	do.	-	-	Do.
93	0.62	do.	-	-	Do.
94	4.42	Nov. 24	-	-	Driven observation well
95	0.56	Nov. 13	-	-	Test pit
96	13.95	May 22	T,E	D,P	City of Phoenix well 12
97	13.80	Sept.21	-	-	Drilled test well
98	13.30	Sept.20	-	-	Do.
99	11.89	May 22	T,E	D,P	City of Phoenix well 10
100	14.90	Sept.18	-	-	Drilled test well
101	13.65	do.	-	-	Do.
102	18.57	Sept.21	-	-	Do.
103	22.72	May 22	-	-	Do.

Table 11. Records of wells in the Lower Verde River valley, Maricopa County, Arizona - Cont.

No.	Location	Owner	Date completed	Altitude above sea level (feet)	Depth of well (feet)	Diameter of well (in.)
104	NE¼ sec. 30	-	1944	1,347.06	1.0	12
105	NW¼ sec. 30	City of Phoenix	1930	1,370.30	65	20
106	Do.	do.	1932	1,363.09	65	20
107	SE¼ sec. 30	-	1944	1,346.37	1.0	12
108	Do.	-	1944	1,345.26	2.0	18
109	Do.	-	1944	1,346.55	5	1
110	Do.	-	1944	1,341.14	1.6	12
111	NE¼ sec. 31	-	-	1,361.31	-	20
	T. 3 N., R. 6 E.					
112	SE¼ sec. 2	Dick Robbins	-	-	211	6
113	Do.	do.	-	-	209.5	6
114	SW¼ sec. 10	do.	1945	1,340.0	385	6

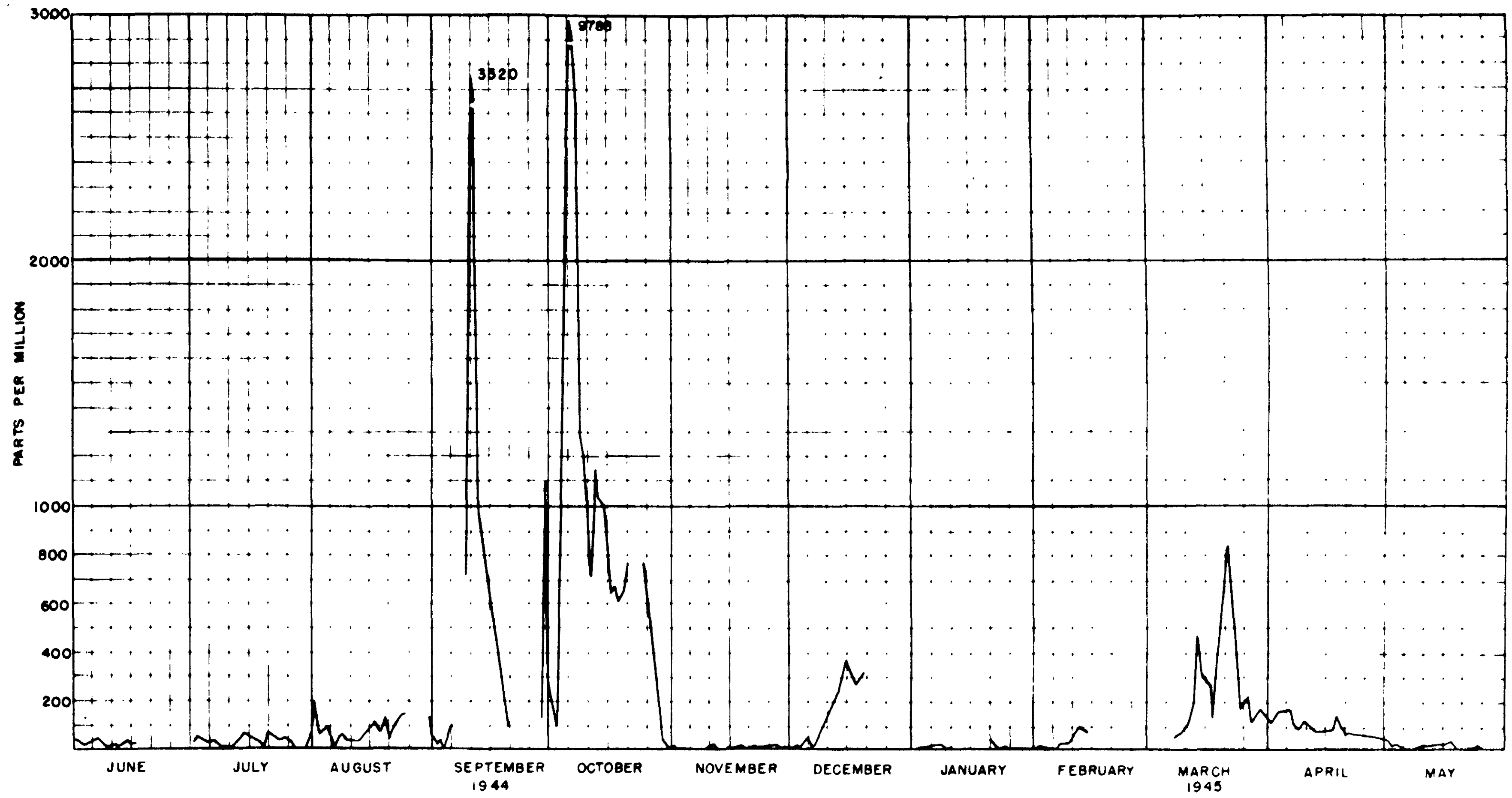
a/ T, turbine; C, cylinder; G, gasoline; W, windmill; B, bucket; H, hand.
b/ D, domestic; S, stock; P, public supply; I, irrigation; N, none.

No.	Water level Depth below surface (feet)	Date of measurement 1944	Pump and power a/	Use of water b/	Remarks
104	0.69	Nov. 1	-	-	Test pit
105	23.70	do.	T,E	D,P	City of Phoenix well 9
106	15.30	May 22	T,E	D,P	City of Phoenix well 11
107	0.54	Nov. 1	-	-	Test pit
108	1.62	do.	-	-	Do.
109	3.11	Nov. 24	-	-	Driven observation well
110	1.49	Nov. 1	-	-	Test pit
111	14.04	June 14	-	-	Drilled test well
112	194.90	Aug. 16	-	N	Drilled well
113	203.50	do.	-	N	Do.
114	350.0	Jan. 17 1945	C,G	S	Do.



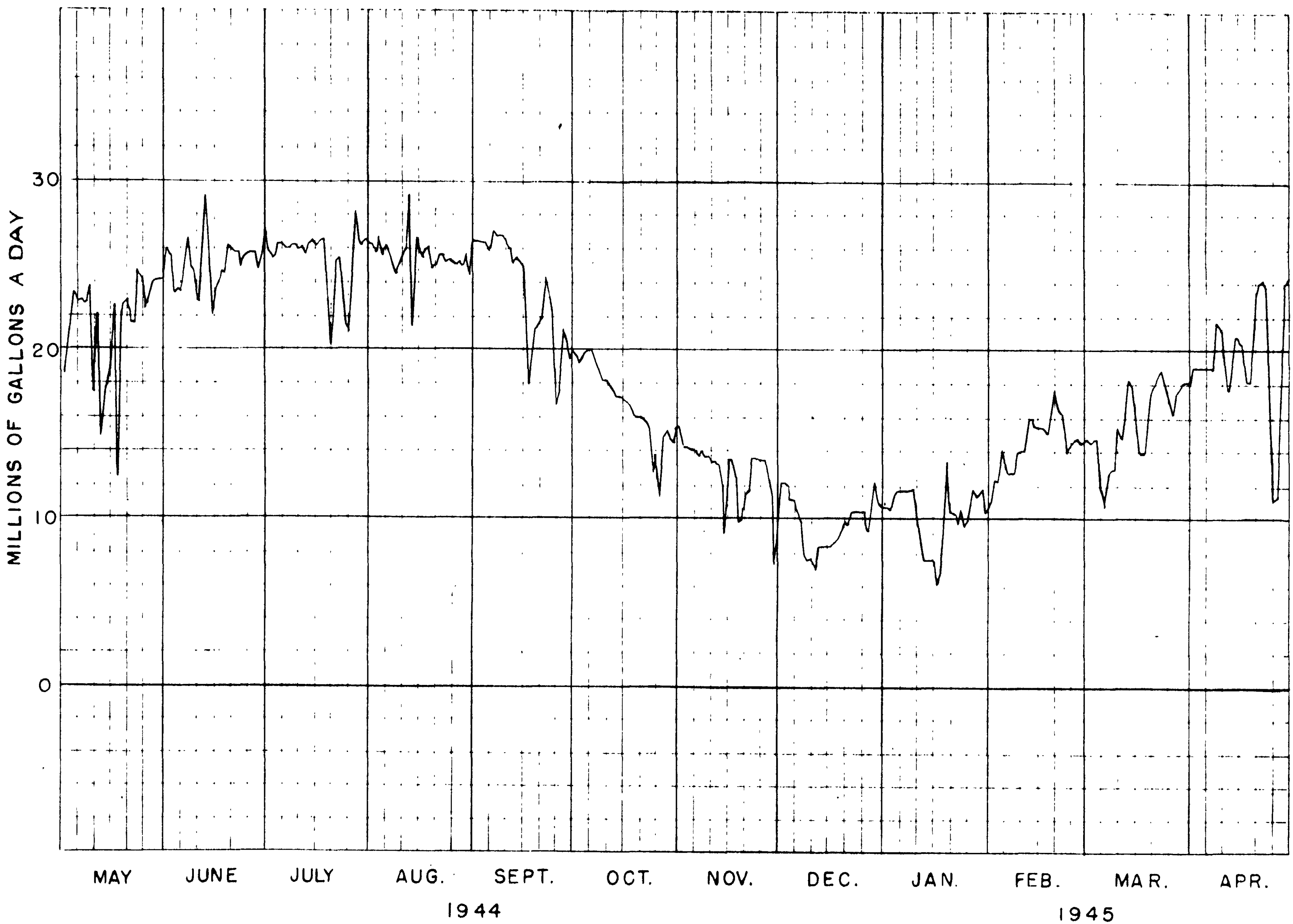
DAILY DISCHARGE OF THE VERDE RIVER BELOW BARTLETT DAM

FIGURE 1



SUSPENDED SILT LOAD IN THE VERDE RIVER NEAR FORT McDOWELL

FIGURE 2



DAILY PRODUCTION FROM THE VERDE SYSTEM MAY 1944 TO MAY 1945

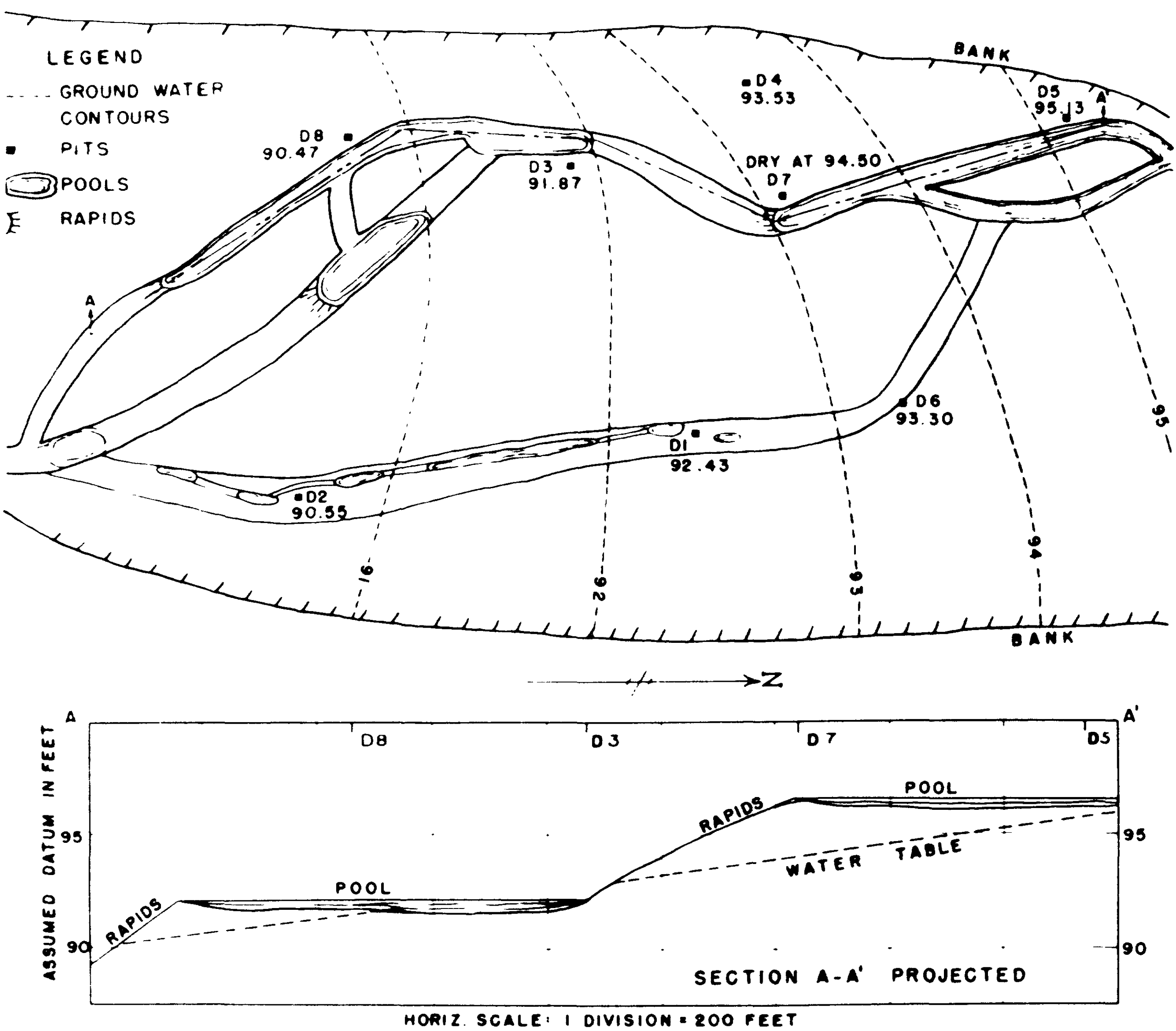
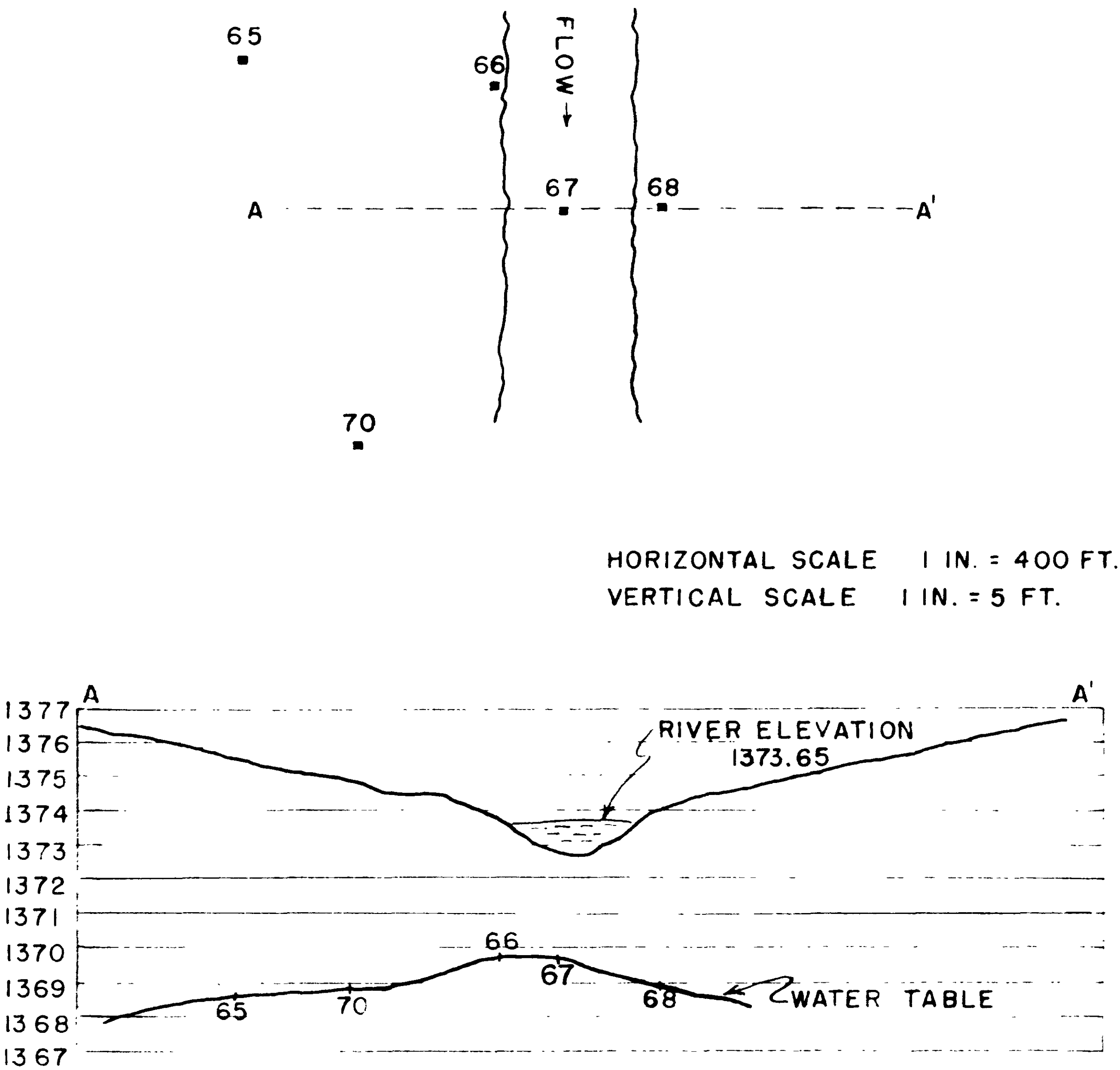
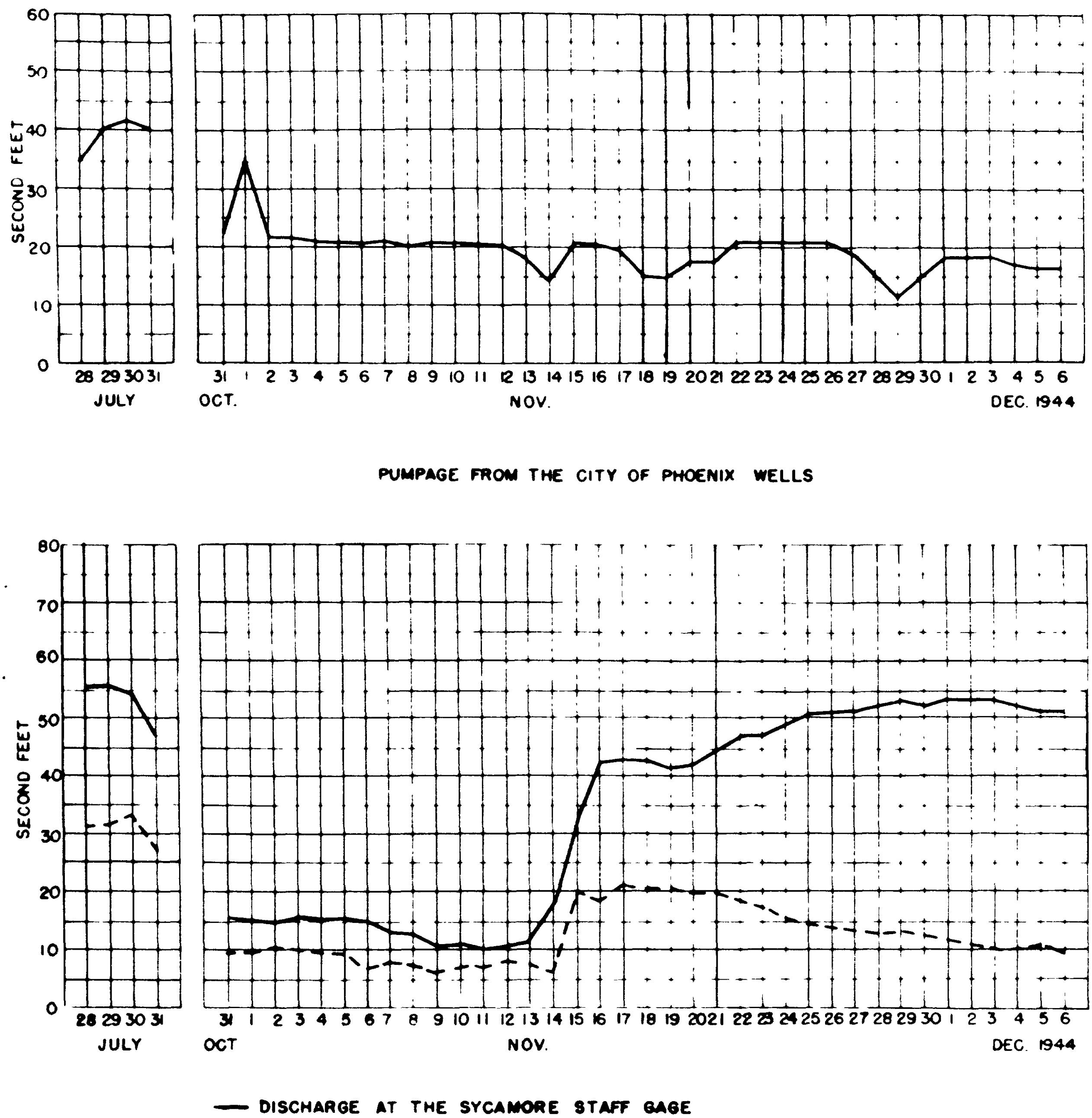


FIGURE 4 SKETCH OF A PART OF THE VERDE RIVER CHANNEL NEAR THE CANAL HEADING, SHOWING EFFECT OF RAPIDS AND POOLS ON THE WATER TABLE AND THE EFFLUENT NATURE OF THE STREAM, NOVEMBER 11, 1944.



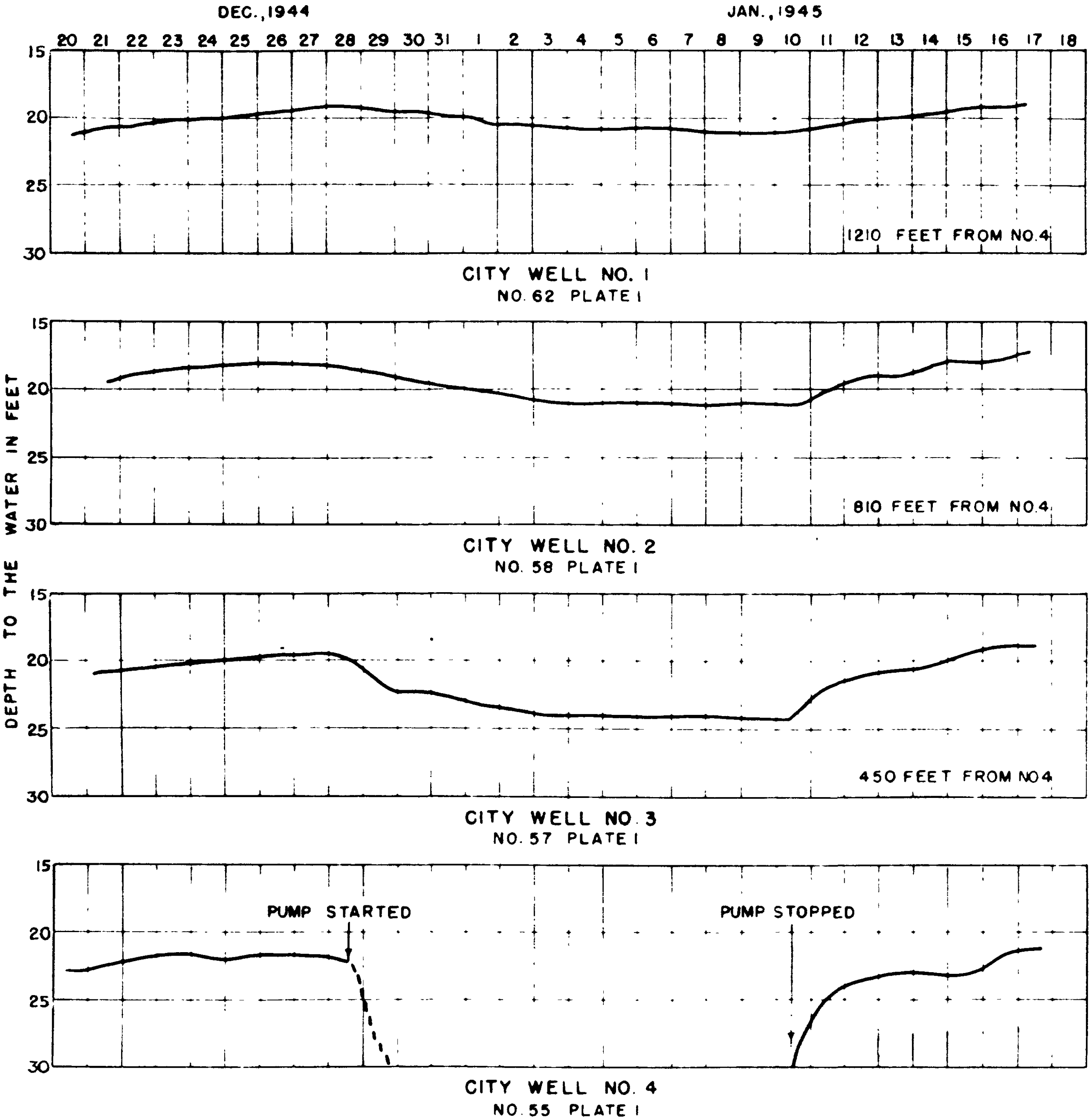
SKETCH SHOWING GROUND WATER RIDGE AND INFLUENT CONDITIONS OF THE VERDE RIVER NEAR WELL 64 (CITY NO. 14) DURING UNFAVORABLE RECHARGING PERIOD

FIGURE 5



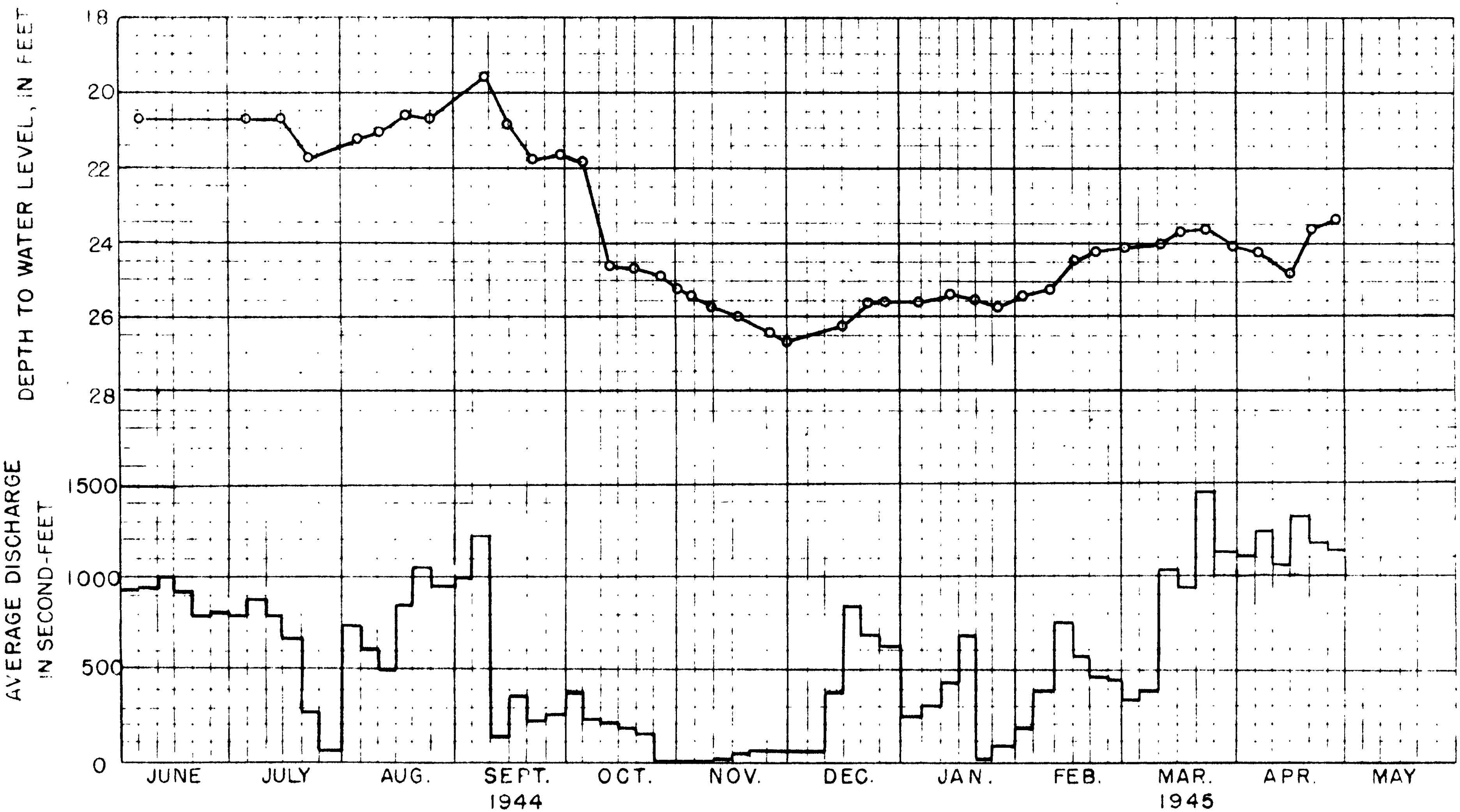
GRAPHS SHOWING RELATIONS AMONG DISCHARGE OF THE VERDE RIVER, RECHARGE TO THE RIVER GRAVELS, AND PUMPAGE FROM WELLS

FIGURE 6



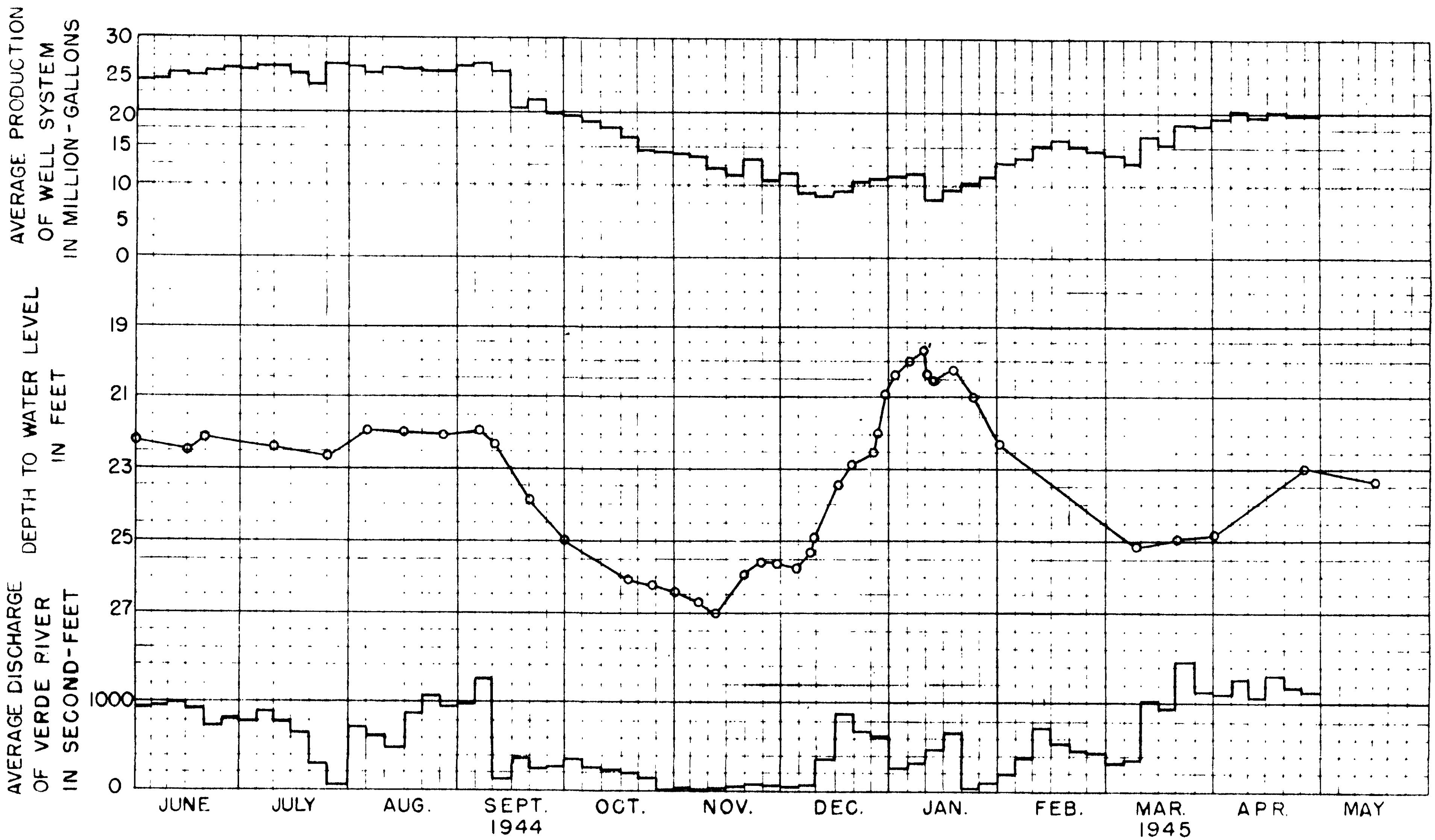
GRAPH SHOWING INFLUENCE OF DISCHARGE FROM CITY WELL NO 4
ON THE WATER LEVEL AT CITY WELLS 1, 2, AND 3

FIGURE 7



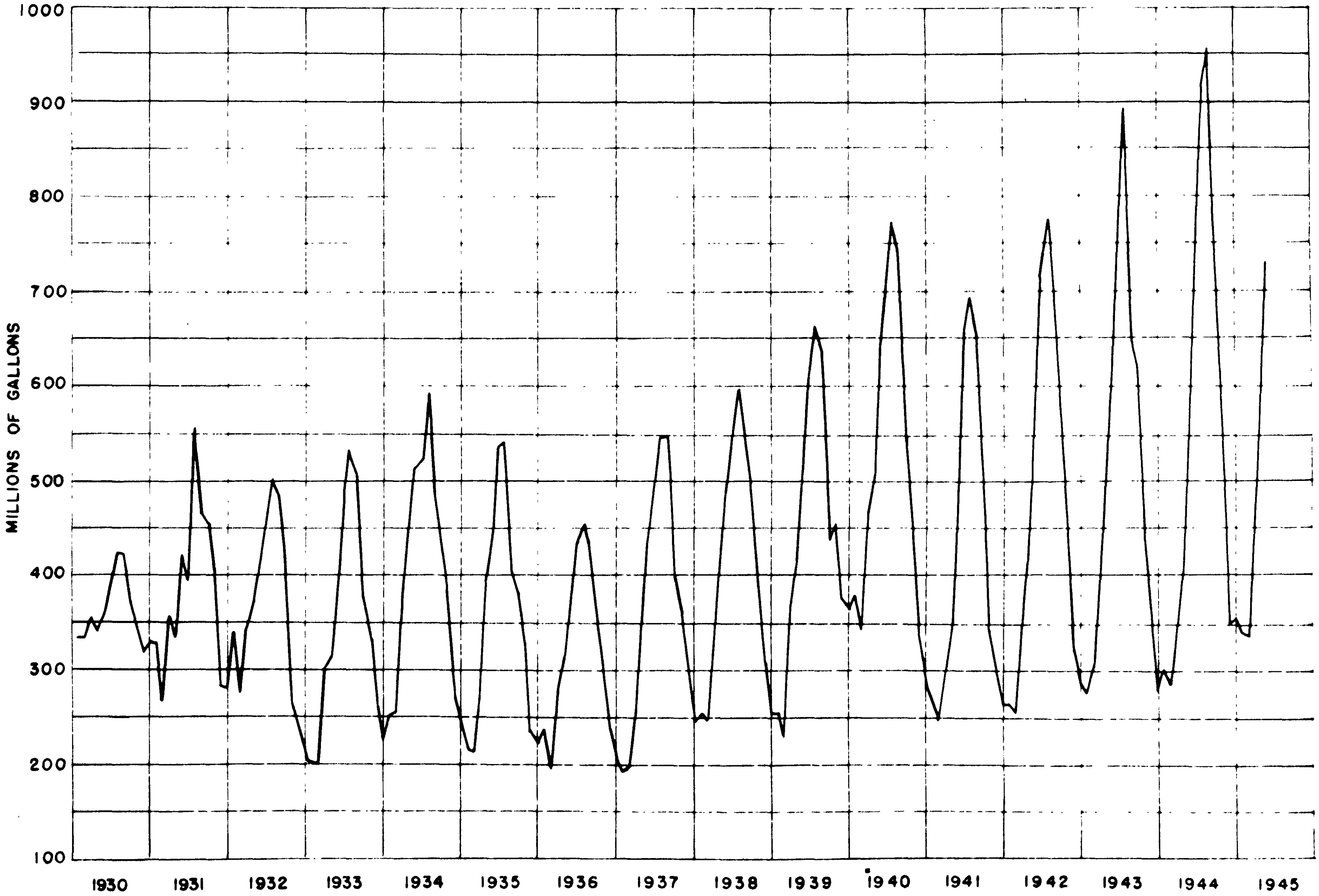
GRAPH SHOWING FLUCTUATIONS OF THE WATER LEVEL IN WELL 2
AND AVERAGE DISCHARGE, BY FIVE DAY PERIODS, OF THE VERDE RIVER BELOW BARTLETT DAM

FIGURE 8



GRAPH SHOWING FLUCTUATIONS OF THE WATER LEVEL IN WELL 49, AVERAGE DISCHARGE, BY FIVE DAY PERIODS, OF THE VERDE RIVER BELOW BARTLETT DAM AND AVERAGE PRODUCTION, BY FIVE DAY PERIODS, OF THE VERDE WELL SYSTEM

FIGURE 9



TOTAL MONTHLY WATER CONSUMPTION OF CITY OF PHOENIX

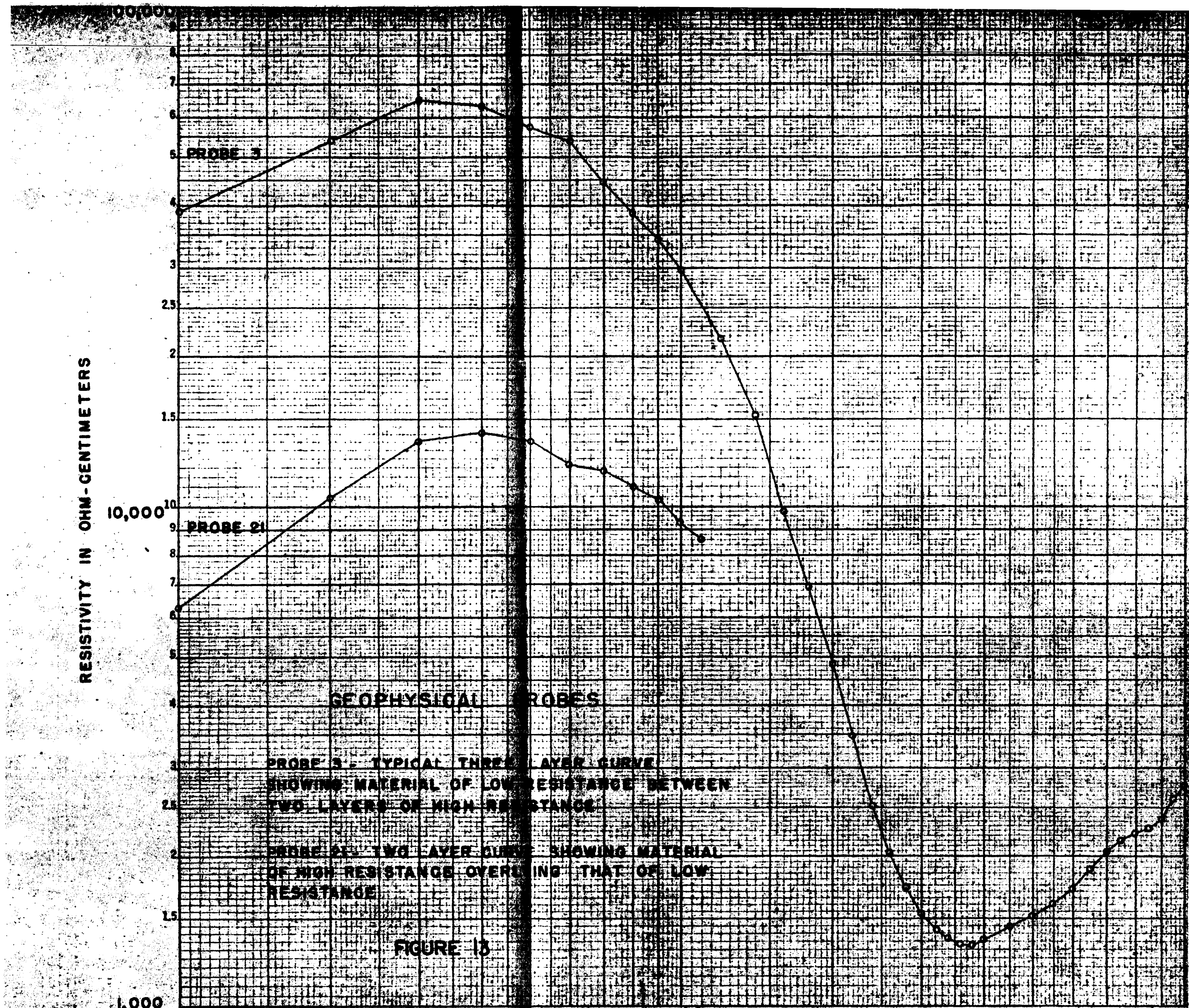
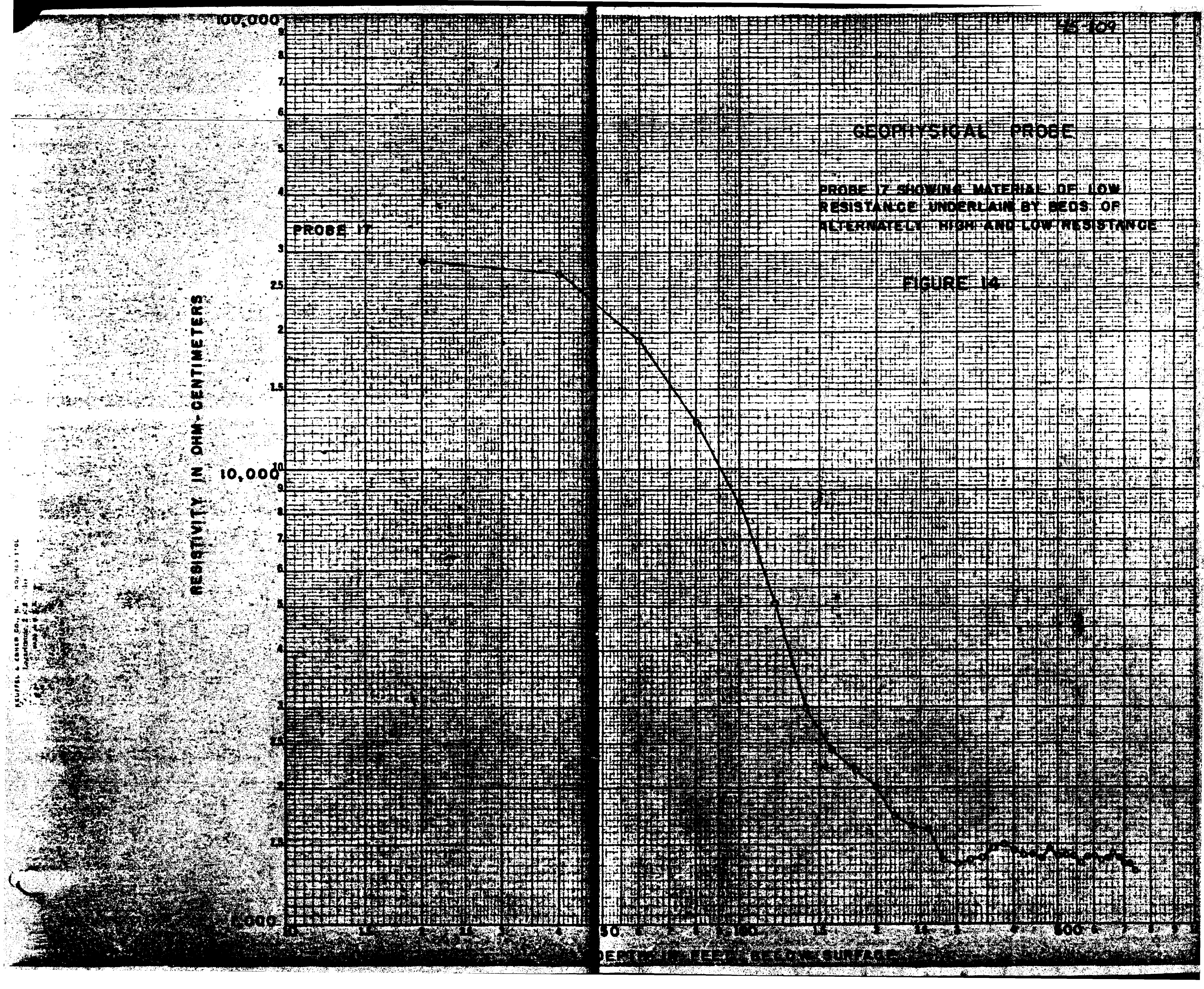

RESISTIVITY IN OHM-CENTIMETERS
100,000
10,000
1,000
PROBE 3
PROBE 21
GEOPHYSICAL PROBES
PROBE 3 - TYPICAL THRE LAYER CURVE
SHOWING MATERIAL OF LOW ESISTANCE BETWEEN
TWO LAYERS OF HIGH RE STANCE
PROBE 21 - TWO LAYER CUR SHOWING MATERIAL
OF HIGH RESISTANCE OVERL ING THAT OF LOW
RESISTANCE
100
500

FIGURE 13



GS 109
GEOPHYSICAL PROBE
PROBE 17 SHOWING MATERIAL OF LOW RESISTANCE UNDERLAIN BY BEDS OF ALTERNATELY HIGH AND LOW RESISTANCE
FIGURE 14
PROBE 17
RESISTIVITY IN OHM-CENTIMETERS
100,000
10,000
1,000
DEPTH IN FEET BELOW SURFACE
50
100
500

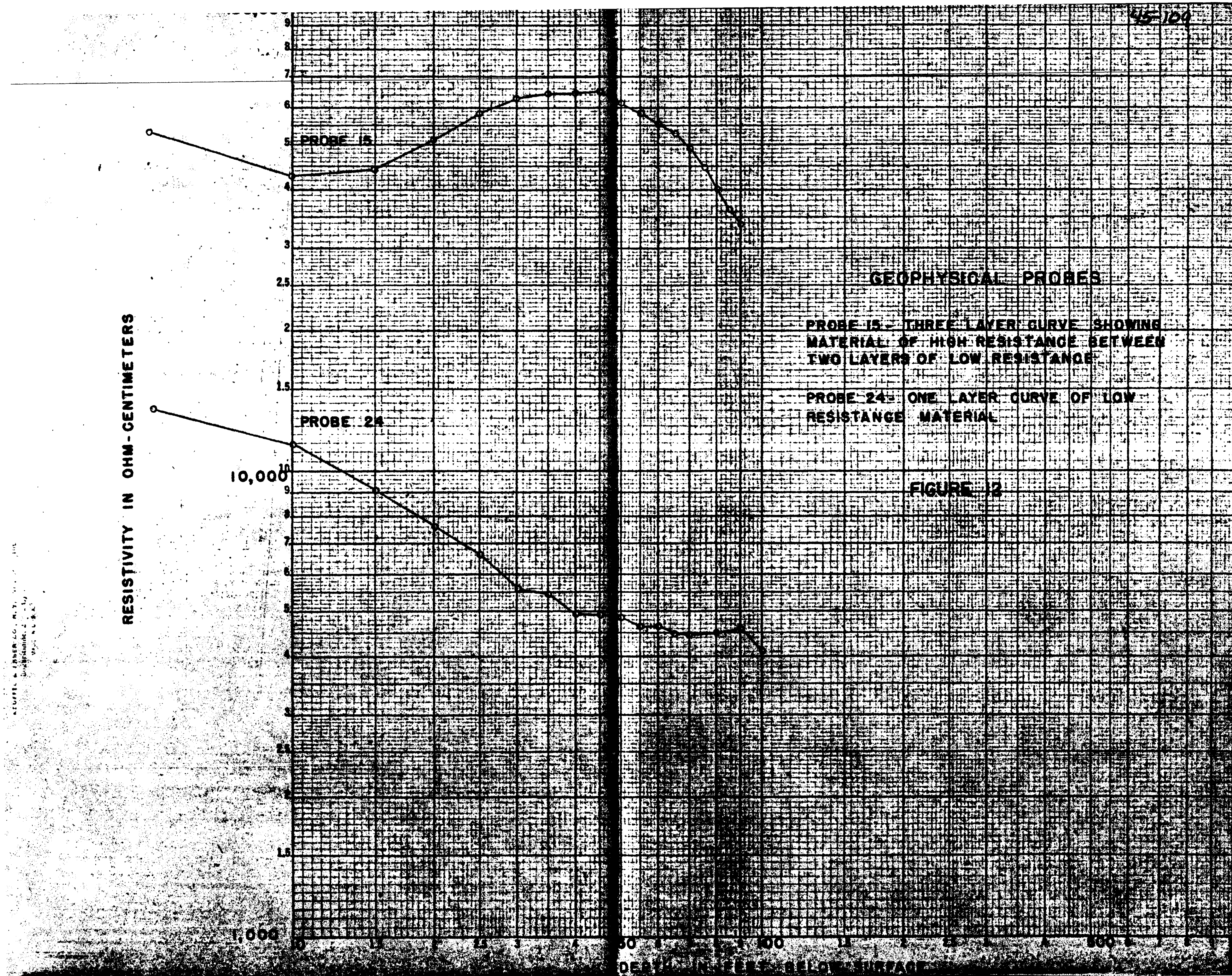

45-109
GEOPHYSICAL PROBES
PROBE 15 - THREE LAYER CURVE SHOWING MATERIAL OF HIGH RESISTANCE BETWEEN TWO LAYERS OF LOW RESISTANCE
PROBE 24 - ONE LAYER CURVE OF LOW RESISTANCE MATERIAL
PROBE 15
PROBE 24
RESISTIVITY IN OHM-CENTIMETERS
10,000
1,000
DEPTH IN FEET BELOW SURFACE

FIGURE 12

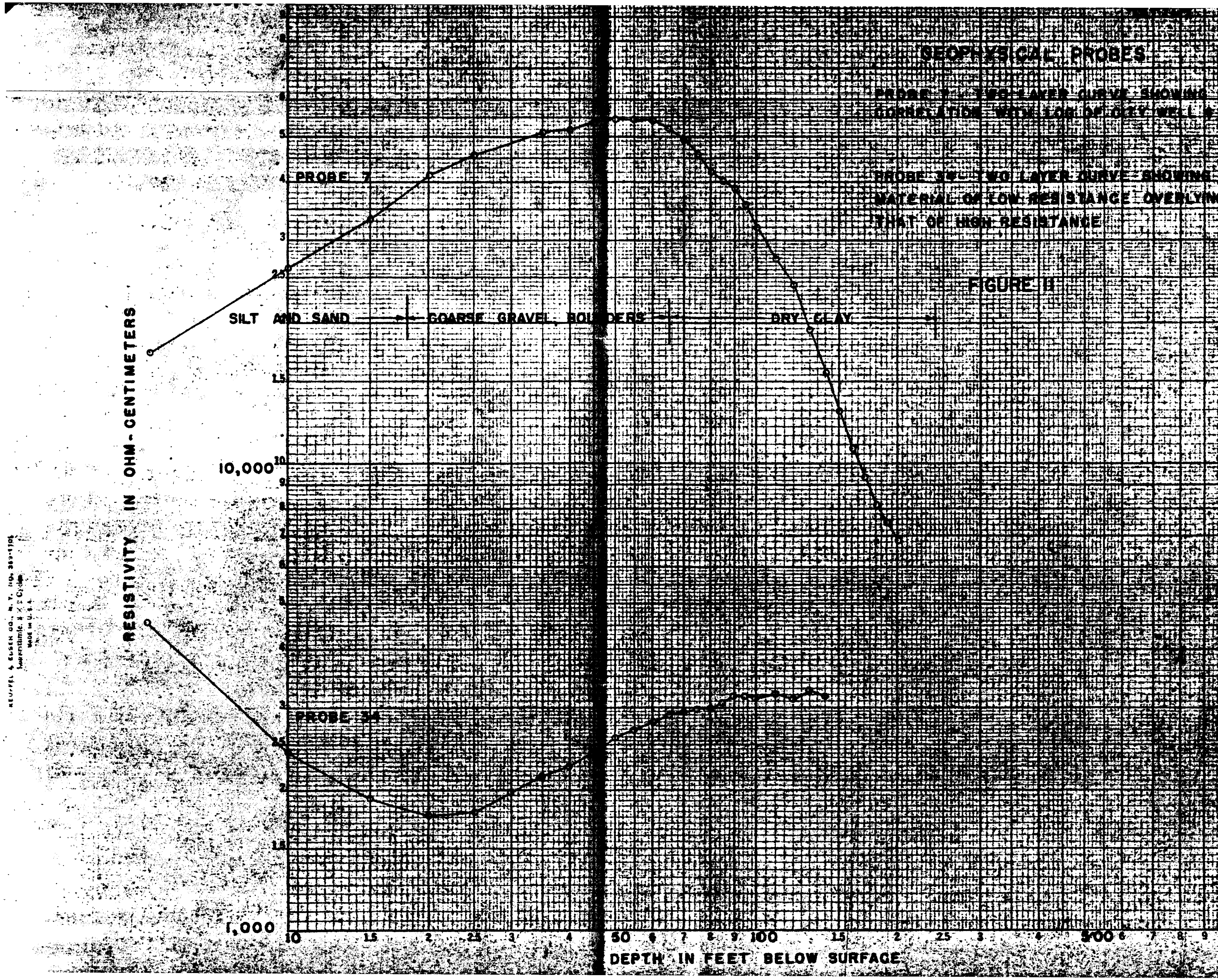

GEOPHYSICAL PROBES
PROBE 7 - TWO LAYER CURVE SHOWING CORRELATION WITH LOG OF CITY WELL 8
PROBE 34 - TWO LAYER CURVE SHOWING MATERIAL OF LOW RESISTANCE OVERLYING THAT OF HIGH RESISTANCE
PROBE 7
PROBE 34
SILT AND SAND
COARSE GRAVEL, BOULDERS
DRY CLAY
RESISTIVITY IN OHM-CENTIMETERS
10,000
1,000
DEPTH IN FEET BELOW SURFACE
10
50
100
500

FIGURE 11