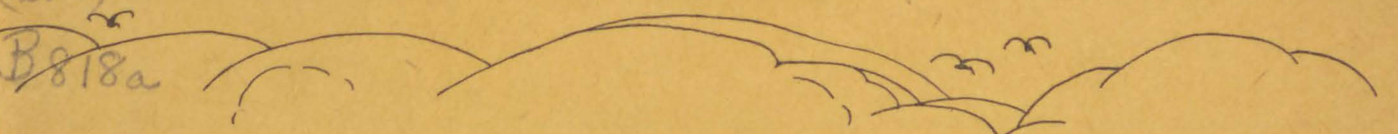


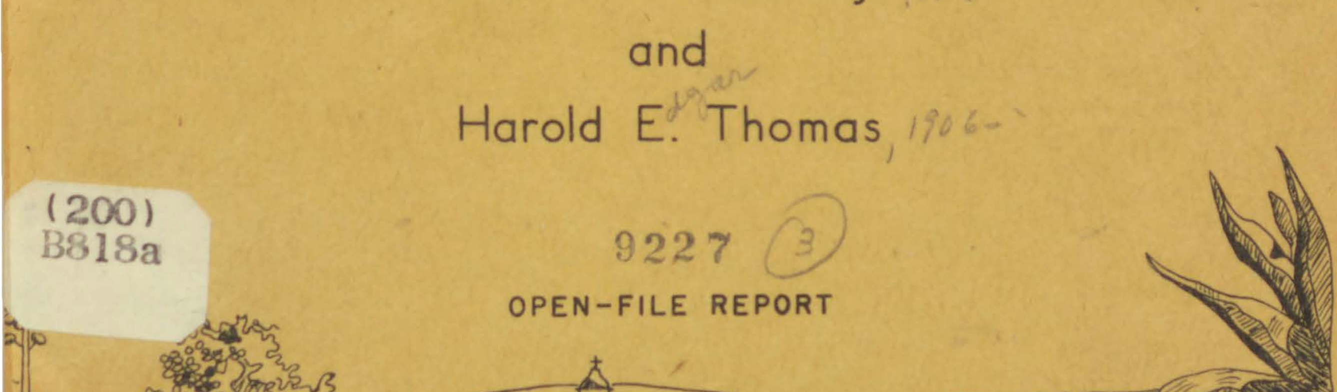
UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

ANALYSIS OF BASIC DATA CONCERNING GROUND WATER IN THE YUMA AREA, ARIZONA

By

Russell H. Brown,
John W. Harshbarger,
and
Harold E. Thomas

OPEN-FILE REPORT



United States
Department of the Interior
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Analysis of basic data concerning ground water in the Yuma area, Arizona

By

R. H. Brown, J. W. Harshbarger, and H. E. Thomas

Tucson, Arizona
April 20, 1956

CONTENTS

ILLUSTRATIONS

Page

Page

TABLES

APPENDIX

ANALYSIS OF BASIC DATA CONCERNING GROUND WATER IN THE YUMA AREA, ARIZONA

By

R. H. Brown, J. W. Harshbarger, and H. E. Thomas

INTRODUCTION

A letter dated September 9, 1955, addressed to the Secretary of the Interior by the Assistant Commissioner of Reclamation, includes the following statement: "It is recommended that the Department . . . request the Geological Survey, initially, to review the nature of the data that have been collected, and the analyses which have been made of them, to ascertain the scope of the study and the additional information needed, if any, to determine the adequacy of the conclusions drawn by the Bureau of Reclamation as to the effect of the irrigation of the Yuma Mesa on the drainage of the Valley Division of the Yuma Project." After some preliminary discussion concerning program, personnel, and financing, the investigation upon which this report is based was made by the Geological Survey in response to that request.

The Yuma area lies in the southwestern corner of Arizona (fig. 1). It is bordered on the west by the Colorado River, which constitutes the boundary between the United States and Mexico for about 17 miles, and which farther upstream forms the boundary between Arizona and California. It is bounded on the north by the Gila River, on the east by the so-called Upper Terrace flanking the Gila Mountains, and on the south by the Arizona-Mexico border. The Yuma area is one of the driest and hottest in the United States, and its agricultural economy is completely dependent upon the availability of water for irrigation.

Irrigated lands in that part of the Yuma area given special attention in this report are in the Yuma Valley and the Yuma Mesa, both of which have been developed by the Bureau of Reclamation, and both of which utilize water diverted from the Colorado River. The Valley Division of the Yuma Project was authorized by the Congress in 1904, and is thus one of the first irrigation projects of the Bureau of Reclamation. The Yuma Mesa Auxiliary Project was authorized in 1917, and the irrigated area on the Mesa was expanded by the Mesa Division of the Gila Project, authorized in 1937. The history of development and operation of these projects is summarized subsequently; here it is sufficient to note that these projects depend entirely upon surface-water diversions, and ground water has entered into them only as an intruder and a problem.

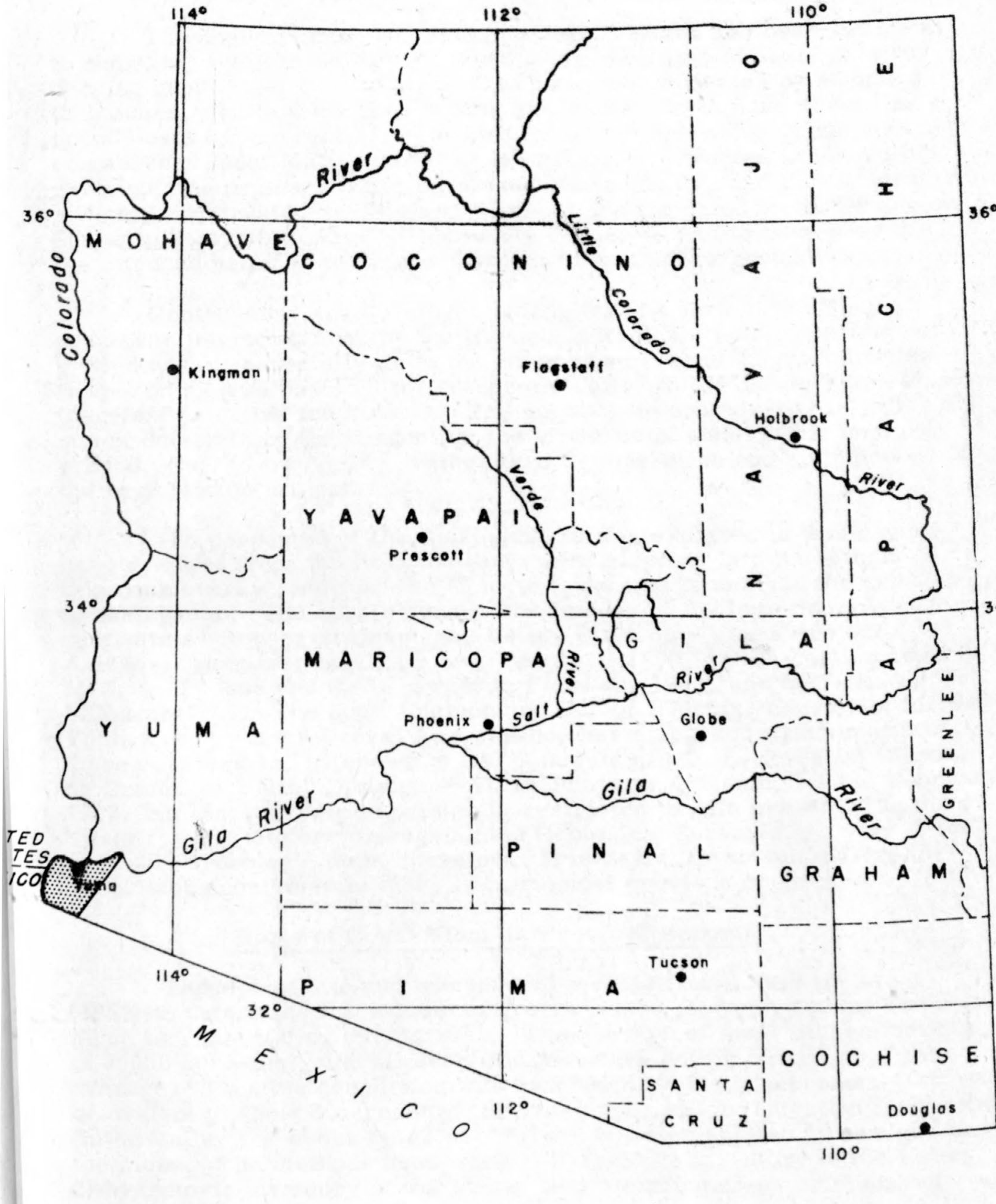

Figure 1.-- Index map showing location of Yuma area, Ariz.

The analysis upon which this report is based has been sufficient to show that the Bureau has collected a large volume of basic data concerning ground water, that these data have been analyzed by standard techniques, and that the conclusions drawn therefrom have served as a sound basis for corrective measures in the ground-water problems encountered. Specifically, the drainage canals constructed in the Valley Division, the drainage wells developed subsequently, and the tile drains recently constructed in the Mesa Division are indicated by the Geological Survey's analysis to have been soundly conceived and to have provided the intended relief to the areas distressed by shallow ground water.

Controversy has developed among water users in the Yuma area over interpretations by the Bureau of Reclamation concerning ground water, especially as to the rates of movement of ground water from Yuma Mesa (hereinafter frequently called the Mesa) to Yuma Valley (hereinafter called the Valley). The question in controversy is primarily one of determining the reason for the presence of undesirable shallow ground water in the Valley, rather than the operation and maintenance of the reclamation projects.

The personnel of the Geological Survey assigned to this review have realized from the first that they were stepping into the middle of this controversy, and that one of their tasks was to analyze the position of each group. The conclusions of the Bureau of Reclamation are presented in a "Report on Drainage, Valley Division - Yuma Project, Arizona," prepared by C. L. Sweet in April 1952, and in earlier reports by J. R. Iakisch and C. L. Sweet in February 1948, and by J. R. Iakisch in March 1946. The Scott Engineering Co. of Phoenix, consultant for the Yuma County Water Users' Association, has disagreed with several of these conclusions, as shown in its "Analysis of [C. L. Sweet's] 'Report on Drainage, Valley Division — Yuma Project, Arizona'," dated February 1953, but that analysis is primarily restricted to data presented in the Sweet report. Before discussing the Geological Survey's analysis of the available hydrologic data, therefore, it is desirable to summarize the conclusions contained in these two principal previous reports.

Basis of Conclusions in Previous Reports

Three separate and independent methods were used by Sweet (1952) to determine the volume of ground-water movement from Yuma Mesa to Yuma Valley during 1951. The average of these determinations is 3,000 acre-feet, and all determinations are within 5 percent of this average. Thus the conclusion was reached that this underground flow was equivalent to about 1 percent of the water applied for irrigation from canals in the Valley, or about 1-1/2 percent of the water applied for irrigation on the Mesa. The methods used were 1) hydrologic inventory of the Valley, 2) hydrologic inventory of the Mesa, and 3) computations by means of Darcy's law.

Hydrologic Inventory of the Valley

A hydrologic inventory is a recognized and valuable technique in many water studies. It involves determining, with the greatest possible accuracy, all items of inflow of water to and outflow from a specified area during a designated period, and checking the computed balance against the actual changes in storage of water within the area. Thus it is an accounting procedure similar to that used in a bank.

The limitations of the technique are hidden in the phrase "greatest possible accuracy." Hydrology is an inexact science, and many items in a hydrologic inventory cannot be measured accurately, particularly those having to do with ground water, soil moisture, and evapotranspiration. Thus judgment may be an important factor in a hydrologic inventory, and most such inventories are properly in the realm of a scientist's "working hypotheses." Even so they may be generally accepted by other hydrologists. But if one is challenged, as the one for Yuma Valley has been, it becomes necessary to examine the degree of accuracy of the component parts of the hydrologic equation.

In the case of the Valley, the most accurate items in the inventory are the measured inflow and outflow of surface water. Examination of these records for 1951 indicates (p.58) that the difference between the surface inflow and outflow was about 200,000 acre-feet in that year, but this figure is accurate only to the nearest 10,000 acre-feet. Evapotranspiration, or return of water to the atmosphere, is not measurable, and estimates of it in the Valley range widely. Sweet shows that the average rate of consumptive use, computed by the Lowry-Johnson formula, is about 3.95 feet a year; but computed by the Blaney-Criddle method the rate ranges from 2.9 to 3.3 feet a year. Thornthwaite (1948, p. 64) indicates that the potential evapotranspiration (the total return to the atmosphere where an adequate water supply is continuously available for plants) exceeds 4.5 feet annually in the Yuma area. Considering this range in estimated rates, an estimate of annual evapotranspiration within 10 percent of the actual is probably better than can be expected. Thus the estimated consumptive use of 170,000 acre-feet in 1951 is accurate only within about 20,000 acre-feet.

In comparison with the net surface-water import and the evapotranspiration, the other items in the inventory are all small. The change in ground-water storage is computed on the basis of estimates of average porosity, and of average change of water levels in many observation wells; in Yuma Valley these estimates could be as much as 50 percent in error, and yet the quantities in the inventory would be off only 1,000 or 2,000 acre-feet. The ground-water inflow and ground-water outflow are unmeasured components which for the Valley have been calculated by differences between the larger items in the inventory. However, as thus calculated, the ground-water outflow (to the Colorado River) is of the order of magnitude of the probable error in estimates of evapotranspiration, and the ground-water inflow (from the Mesa) is far less than the probable error in estimation of the net surface-water import.

Hydrologic Inventory of the Mesa

Inventory of the Mesa was restricted to the area west of the crest of a ground-water mound as shown on a water-table map for December 1951. Here again the large elements of the inventory are the surface inflow (computed on the basis of average deliveries of water to acreages of specified crops), and the evapotranspiration (computed by the Blaney-Criddle formula for consumptive use). If these estimates are accurate within 10 percent, the difference between them, stated as 19,292 acre-feet, may be anywhere between 14,000 and 24,000 acre-feet.

The increase in ground-water storage accounts for a part of this difference: It has been computed on the basis of estimated average porosity, and average rise of water level in numerous wells during 1951. Here, however, there are complications because of the marked differences in water levels in shallow and deeper wells, which raise questions as to the magnitude of the rise and the degree of saturation of the material in the ground-water mound. Depending upon the judgment of the computer, the change in ground-water storage may be large enough to account for all the difference between surface-water deliveries and consumptive use; or it may account for less than half this difference, leaving substantial quantities for ground-water outflow from Mesa to Valley.

Computation by Darcy's Law

From the preceding paragraphs it is evident that indirect determinations of ground-water movement are subject to large error, because these indirect determinations are made by balancing equations wherein the largest components cannot be measured accurately. Direct determination of ground-water movement is possible on the basis of Darcy's law, which states that the rate of movement is dependent upon the change in head. The amount of ground-water movement is thus the product of the head loss and the cross-sectional area and permeability of the material through which the water moves. This is the basis of the third method that has been used to determine the flow of ground water from Mesa to Valley.

All elements in this direct determination of ground-water flow are inexact, because of the fragmentary nature of the information concerning the materials through which the water moves. These materials range widely in all characteristics that affect water movement, and the variations are shown in many ways. The cross-sectional area through which water might move from Mesa to Valley extends along the bluff that forms the common boundary, but the depth is uncertain — sufficiently so that Sweet in 1952 used 5 times the cross-sectional area that had been assumed in earlier computations by Iakisch and Sweet. Data from well logs show that this cross-sectional area encompasses beds of sand, clay, and gravel, and there is thus a wide range in the permeability of individual strata. In most regions the change in head ordinarily can be determined from the form of the water table, but on the Mesa the shallow wells and deeper wells indicate variations in hydraulic gradient with depth; therefore the horizontal component cannot be determined easily.

Because of these uncertainties, the computations of flow using Darcy's law will vary depending upon the assumptions made concerning the water-bearing materials. The cross-sectional area can be limited by assuming decreasing permeability with depth in the upper 200 feet below Yuma Mesa; this assumption is supported by several well logs which show clay beds in the alluvium, beneath the Mesa. Sweet discusses the development of a "semi-perched" water body under the Mesa in terms of the variations in permeability of strata underlying the irrigated area. He also ascribes the steep westward slope of the ground-water mound to lower permeability of materials there than in other parts of the mound.

Direct determination of ground-water movement from Mesa to Valley, as set forth in earlier reports, will prove to be reliable only to the extent that the simplifying assumptions concerning relative permeabilities of subsurface materials and the nature of the flow system can be confirmed by all the available geologic and hydrologic evidence.

Elements of This Review

The prime purpose of the present review is to evaluate the conclusions in the earlier reports as to the rate of movement of ground water from the Mesa to the Valley. The overall problem of ground-water conditions in the Yuma area, of which this is one special aspect, is thus beyond the scope of the present report. It appears that the available basic data, collected chiefly by the Bureau of Reclamation for normal project operations, are not adequate for a general quantitative analysis of the hydrology of the Yuma area, but they are adequate to indicate that there is some question whether it is possible to make a quantitative analysis of the type required to settle the drainage controversy, or whether there is economic justification for making the attempt. Some of the available data concerning the hydrologic conditions in the Yuma area do not bear directly upon the flow of water from Mesa to Valley, but do give indications concerning various facets of the regional flow pattern.

One of the most important elements in this review has been the collection and interpretation of all available data concerning the geology of the Yuma area, because an understanding of the geology is the key to an understanding of the framework through which ground water moves. Unfortunately, no detailed geologic studies have been made in the Yuma area, and some field reconnaissance was thus required as a prelude to this review. Geochemical data provide a valuable supplement to the geologic data. From these data it has been possible to draw general conclusions as to the geologic factors related to the occurrence and movement of ground water.

Most of the data collected in recent years have pertained to hydrologic conditions, and have served as a basis for interpretations of the regional ground-water hydrology, with applications of these interpretations to the problem of movement of ground water beneath Mesa and Valley. Records of water levels in wells, surface-water flows, stages of river, canals, and drains — many of which have been collected for 30 years or more — provide a means for outlining the hydrologic history of the area, starting when the Yuma Project was young and ground-water occurrence was only slightly modified from natural conditions. This hydrologic history shows the effects upon ground water of various natural phenomena as well as of the modifications by man.

Credits and Acknowledgments

For the job of reviewing the hydrologic data concerning the Yuma area, the reviewers had a considerable volume of material that was not available at the time the previous reports were prepared. All continuing records, of course, are now 4 years longer, and thus provide additional historic and correlative information. Additional data have been collected by the Bureau of Reclamation, the Yuma County Water Users' Association, the U. S. Salinity Laboratory, and the International Boundary and Water Commission.

The reviewers received invaluable assistance from the numerous scientists, engineers, and others who have been interested in various aspects of the water resources of the Yuma area. C. L. Sweet provided information supplemental to that contained in his reports. T. J. Ahrens and William Tapp, of the Denver office of the Bureau of Reclamation, discussed data and interpretations of well logs in the Yuma area; and A. H. Wadin, R. Coutchie, T. E. Converse, E. A. Haley, and many others of the Bureau's Yuma Project office were exceedingly helpful in locating, making available, and discussing the conditions of collection of various essential data.

L. V. Wilcox, of the U. S. Salinity Laboratory at Riverside, Calif., and C. S. Scofield, now retired, provided chemical analyses and discussions of the quality of water in the area. L. F. Wingo, of the International Boundary and Water Commission, furnished data on water levels in the floodway of the Colorado River, west of the levee protecting the Valley.

Albert Greene, engineer of the Yuma County Water Users' Association, made special tests of certain Valley drainage wells and canal sections, and provided other basic data. A. J. Eddy, attorney for the Yuma County Water Users' Association, provided valuable assistance in documenting irrigation and drainage developments in the area, and Everett L. Miller, attorney for the Yuma Mesa Water Users, outlined that group's position with respect to the drainage controversy. Donald C. Scott, consulting engineer for the Yuma County Water Users' Association, provided voluminous records from his files that materially expedited the work. Frank Leidendeker, of the Yuma Well Drilling and Pump Co., deserves special recognition for allowing the writers ready access to his excellent files of well records from which were copied the logs of nearly 50 deep wells that he had drilled in the Yuma area.

The analysis of basic data was done by the authors of this report, with invaluable assistance in geologic studies by J. F. Lance, in electric-model studies by H. E. Skibitzke and Mrs. Geraldine M. Robinson, in initial technical review by H. E. Skibitzke, and in hydrologic studies by R. A. McCullough. All the authors participated in the compilation, graphical analysis, and drafting of illustrations, but much of this work was done by Mr. McCullough and by Mrs. Ruth Allison.

GEOLOGY

Regional Relations

For tens of thousands and perhaps hundreds of thousands of years, the Colorado River has dominated the geologic history of the Yuma area, just as it has dominated the human history of that area in recent centuries. If the Colorado River had not pursued a straightforward course across the plateau country — if it had instead turned left and joined the Rio Grande, or turned right and flowed into Great Salt Lake — Yuma might now be a seaport, located like Acapulco on the east coast of the Gulf of California.

Because of the Colorado River system, the Yuma area now has its resources of alluvial soil and underlying sediments which have been contributed by six or seven States. This material is part of the Colorado delta (fig. 2), which has filled the deep trough of the Gulf of California, isolating the northern part and, with the help of the evaporative power of the sun, forming the land areas of Imperial and Coachella Valleys, which are below sea level. The sediments of the delta, if traced to the source rocks whence they came, would provide much data about the geologic history of the Southwest, and this history in turn would answer some of the questions that exist concerning the occurrence and movement of water in the alluvium. But the necessary geologic studies have not been made, and the history of the Colorado River, particularly as it applies to the Yuma area, is still largely speculative. The geology of the Lower Colorado River basin is sufficiently well known, however, to aid in the interpretation of the features seen in the Yuma area, and the regional geologic pattern is therefore summarized in the following paragraphs.

The Colorado River, after leaving the Colorado Plateaus physiographic province, flows across the Basin and Range province, which is comprised chiefly of fault-block mountains and structural basins having a general northerly trend. Thus the river below the Lower Granite Gorge of the Grand Canyon flows alternately through canyons cut in the mountain ranges and broader valleys in the alluvium-filled basins.

The westernmost of the block mountains traversed by the Colorado River is north and east of Yuma; the river cuts through this block in a canyon which forms the walls for Imperial Dam, 15 miles northeast of Yuma (pl. 1). The Gila River, which drains the southern half of Arizona, also has cut a canyon through this block, and joins the Colorado River in the vicinity of Yuma. This mountain block is comprised of three parts that are designated as separate ranges — the Chocolate Mountains north of Imperial Dam and west of the Colorado River, the Laguna Mountains between the Colorado and the Gila, and the Gila Mountains south of the Gila River. However, all three ranges include similar rocks (Wilson, 1933): dominantly gneiss, schist, and granite in the Gila Mountains, and increasing proportions of volcanic rocks to the north; and the trends are such as to suggest a single structural unit.

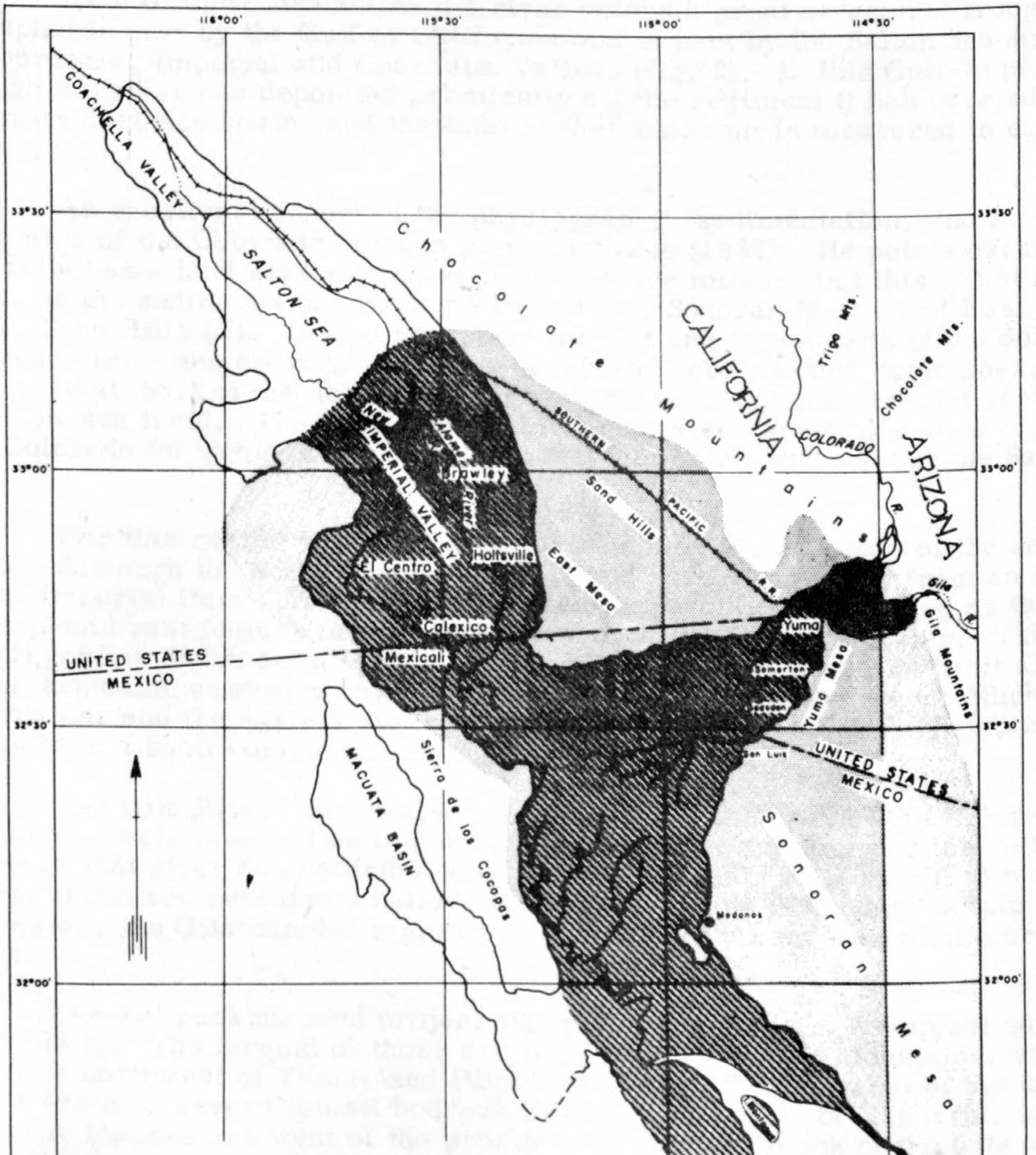

Figure 2.-- Generalized map of the Colorado Delta area.
(Modified from Sykes, 1937)

West of these mountains the river enters a great structural trough, occupied in part by the Gulf of California and in part by the Salton Sea and its bordering Imperial and Coachella Valleys (fig. 2). In this Gulf-Imperial trough the river has deposited practically all the sediment it has carried from its drainage basin, and the total of that sediment is measured in cubic miles.

An excellent account of the physiography, sedimentation, and stream dynamics of the Colorado delta is given by Sykes (1937). He points out that the delta has a land area exceeding 3,300 square miles. But this is not all of it, as the sediments underlying Yuma Mesa, Sonoran Mesa, and East Mesa-Sand Hills (fig. 2) also represent foreset and topset beds of the delta. A person traveling over the land area south and southwest of Yuma sees only a small part of the delta, for, like an iceberg, the greater part of it is below sea level. The Gulf-Imperial trough, after receiving debris from the Colorado for geologic ages, is still 250 feet below sea level at the Salton Sea.

For this review we are concerned with only a small part of the entire delta. Although the delta as outlined by Sykes spreads outward from an apex at the Imperial Dam, the entire Yuma area may well be considered as the apex of this vast feature formed at the mouth of the Colorado River. This apical portion of the delta is rudely triangular, with the northern limit along a line extending westward from the Imperial Dam toward the Cargo Muchacho Mountains, and the eastern limit along the west base of the Gila Mountains, which have a south-southeast trend into Mexico (pl. 1).

The Gila River, which also discharges into the apex of the Colorado delta, may well have had an important role in the development of the delta. Although that river has contributed only small amounts of sediment in modern times, there are reasons to believe that, during some periods of deltaic deposition, the Gila carried a greater volume of sediment than the Colorado River.

Several rock masses project above the sediments in the apical portion of the delta. The largest of these are the Cargo Muchacho Mountains, about 12 miles northwest of Yuma, and Pilot Knob, about 7 miles west of the town. There are also several small bedrock hills in the vicinity of Yuma (pl. 1). All these masses are west of the prominent structural block of the Gila and Laguna Mountains, but they are similarly composed chiefly of schist, gneiss, granite, and acid volcanic rocks. The present flood plain of the river at Yuma is constricted because of the presence of the bedrock hills, and these and other masses in the group undoubtedly influenced the pattern of delta development at various stages in geologic history.

It may be inferred, therefore, that the Colorado River began the development of its delta along a mountainous coastline, depositing sediment first in the lower portions upon bedrocks which are now far below sea level. As the delta was built up, its sediments spread out over progressively broader areas and engulfed progressively higher parts of the rugged bedrock surface. Of the bedrock masses that now project above the delta sediments, some have formed the marginal boundaries of the delta, others have been surrounded by delta deposits, and still others have been completely buried and then subsequently exhumed by erosion of the alluvial materials.

Rock Units in the Yuma Area

By J. W. Harshbarger and J. F. Lance

The rock units in the Yuma area may be grouped broadly under the headings of bedrock and alluvium (pl. 1). Bedrock includes the metamorphic complex, granite, and volcanic rocks in the mountain ranges, and the similar rocks beneath the alluvium of the delta. For the present review the most important bedrock is granitic gneiss forming a buried ridge immediately east of Yuma, which has an important effect on the occurrence and movement of ground water. The sedimentary rocks discussed in this report consist entirely of unconsolidated and semiconsolidated deltaic deposits, designated alluvium. For convenience in discussion the alluvium has been subdivided, in ascending order, into the following units: 1) lower sandy alluvium, 2) coarse-gravel zone, 3) sandy and silty alluvium, 4) upper gravel zone, 5) upper sandy alluvium, and 6) alluvial-fan deposits.

The classification of physiographic and geologic units as shown on plate 1 is the result of several weeks of field work in which the writers examined the geomorphic, stratigraphic, and structural features exposed at the surface in the area. The subsurface lithologic conditions shown in plate 2 are based on well logs collected from the Bureau of Reclamation, Yuma Well Drilling and Pump Co., Arizona State Land Department, and private well owners. The west bluff of the Yuma Mesa was traversed in detail to obtain data on the amounts of clay, sand, and gravel in the outcrop. Samples also were collected from various outcrops for laboratory study of composition and grain size.

Bedrock

Several small hills, alined in a south-southeasterly direction, rise above the general land surface between the railroad bridge over the Colorado River at Yuma and the Army Air Base south of U. S. Highway 80 (pl. 1). The hills are composed of dark-gray coarse-grained granitic biotite gneiss varying somewhat in composition and texture from place to place. These isolated bedrock hills rise as much as 100 feet above the surrounding plain and are believed to represent the peaks of a buried ridge, which may be an extension of the Cargo Muchacho Mountains in California. The hills on both sides of the river at the old Yuma Territorial Prison and Yuma Indian Reservation headquarters are composed of huge, angular blocks of the gneiss. The size and angularity of these blocks indicate that they are very near the parent solid bedrock.

Several wells drilled in the vicinity of these hills have encountered bedrock at relatively shallow depths. It is clear from various drilling records that the ridge has rather steep sides, for a well 2 miles west of the ridge penetrated 1,300 feet of sediments before it encountered granitic rock. The indicated declivity of the slope is comparable to the slopes in the Gila Mountains and other nearby ranges. The saddles between the bedrock hills are filled with alluvial deposits of unknown thickness.

There are several indications that the granitic ridge has influenced the deposition of the deltaic sediments in its vicinity. Thick but discontinuous clay zones are present on both sides of the ridge (pl. 2), indicating deposition in relatively quiet water near the ridge. On the other hand, there are also conglomerate lenses in the vicinity of the ridge, the materials of which may have been eroded from the ridge or may have been dropped from the river at times when the current was deflected by the ridge. The ridge was apparently an isolated steep-sloped island protruding above the delta plain when some of the sediments underlying the Yuma area were deposited. Inasmuch as the ridge is a relatively small topographic feature compared to the delta as a whole, it probably has had only a local effect on the deposition of the deltaic sediments.

Colorado Delta

The unconsolidated materials of the Colorado delta in the Yuma area are here grouped as alluvium, or river-deposited sediments, although it is recognized that some of them may be of eolian, lacustrine, or estuarine origin. For example, the Yuma Mesa is covered in many places with a thin veneer of eolian sand, and there are extensive active dunes, apparently derived from the deltaic sediments, in the vicinity of the United States-Mexico border both east and west of the river.

Details of the initial growth and development of the Colorado delta are lost in antiquity, but Hoover Dam has provided an excellent opportunity to study a delta from the time of inception. Gould (1954, p. 229-237), in his comprehensive account of the sedimentology of the delta in Lake Mead, states: "Deltas are characteristically formed by sediment-laden streams where they enter the ocean or other bodies of stillwater. The growth of the delta may be analyzed conveniently with reference to the point at which the flowing water meets the stillwater: Sediment is dropped in the river bed as water velocities are reduced; additional sediment is carried to the edge of this graded slope and dropped into the deeper stillwater body to form foreset beds; finer material is carried farther out into the stillwater body and there forms the bottomset beds. As deposition continues the foreset beds are built out progressively farther over the bottomset beds, and in turn are covered by topset beds; also the gradient of the stream is modified and sediment is deposited upstream from the original mouth. Thus the delta grows outward in the stillwater body, by deposition of foreset and bottomset beds; by its deposition of topset beds it grows upward; and it also projects backward into the original channel of the stream that provides the source material." It is clear that the delta deposits observed in the Yuma area are for the most part topset beds of the Colorado delta, and this is confirmed by the general horizontality of the bedding in observed sections. Figure 87 of Gould's report is an excellent example of deltaic physiographic development and the relation of the elevation of the stillwater surface to scouring and filling in the topset bed zone.

The construction of the apex of the delta, and therefore the history of alluvial deposition in the Yuma area, may be pieced together from fragmentary evidence from several sources. The lithologic character of the alluvium was studied by examining the exposures along the river banks and terraces, and by compiling data from the logs of numerous wells drilled in the Yuma area. A few wells have been drilled several hundred feet below sea level.

Lower sandy alluvium.--The deepest alluvium in the apical portion of the delta — presumably some of the earliest known deposits by the Colorado River in the Yuma area — is encountered in wells drilled to depths ranging from several tens to several hundreds of feet below sea level. A well at 4 S-1 W,[1] drilled to a depth of about 565 feet below sea level,

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[1] The coordinate system in common use in hydrologic studies of the Yuma area is based on a mile grid originating at the railroad bridge over the Colorado River at Yuma, in the NE cor. sec. 21, T. 8 S., R. 23 W., Gila and Salt River Base and Meridian. The grid coordinates, as shown on plate 1, are used throughout this report for designating well locations.

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has the following drillers' log as recorded by the U. S. Bureau of Reclamation:

Rock description	Thickness (feet)	Depth (feet)	Altitude* (mean sea level)
Sandy and silty alluvium:			
Mesa sand	14	14	170.5
Sand and clay streaks	143	157	24.5
Some water at 74 feet (altitude)			
Soft clay	29	186	-1.5
Coarse gravel zone:			
Good gravel — water	19	205	-20.5
Quick sand and fine broken sandstone strata	19	224	-39.5
Lower sandy alluvium:			
Sand, clay, sandstone streaks	16	240	-55.5
Sand	76	316	-131.5
Sandstone gravel strata	8	324	-139.5
Caliche	6	330	-145.5
Sand, sandstone in layers; water bearing	55	385	-200.5
Sand and some water	41	426	-241.5
Caliche and clay	6	432	-247.5
Sand	18	450	-265.5
Clay	3	453	-268.5
Sand	79	532	-347.5
Clay and sandstone	3	535	-350.5
Sand	19	554	-369.5
Clay and sandstone	18	572	-387.5
Tough clay	8	580	-395.5
Soft clay — sandy	10	590	-405.5
Sand and sandstone strata	4	594	-409.5
Sand	47	641	-456.5
Sandstone, gravel, sand strata; water	29	670	-485.5
Sand	7	677	-492.5
Tough clay	5	682	-497.5
Sandy clay	68	750	-565.5

*(Note: Land-surface altitude = 184)

This well constitutes one of the deepest probes into the deltaic deposit to date, but a few others drilled to depths below sea level confirm the existence of gravel, sand, and clay at considerable depth in the delta apex. Clay bedsin this position might indicate deposition of bottomset beds in quiet water, perhaps at some distance from the entrance of the river into the Gulf. The predominance of gravel and sand beds in these deeper wells, however, suggests that in this early period the river was carrying its finer debris beyond Yuma and depositing it in the deeps of the Gulf-Imperial trough farther west.

Coarse-gravel zone.--One of the major results of the compilation of data from the drillers' logs has been the recognition of a fairly uniform and persistent coarse-gravel zone (pl. 2). Unfortunately, a number of the drilled wells do not penetrate the entire thickness of the gravel, so that it is difficult to determine the true thickness throughout its extent. However, on the basis of available data, the coarse gravel is as much as 50 feet thick. The coarse-gravel zone was encountered near sea level in essentially all wells that were drilled sufficiently deep. This gravel zone is persistent and uniform over a widespread area, more than 100 square miles in the Yuma area alone.

In a sample of the coarse gravel from a drainage well in Yuma Valley (about 3-3/4 S - 1-5/8 W), the particles range in size from fine sand to boulders 12 inches in diameter, but the bulk of the material consists of pebbles ranging from 1/4 inch to 1 inch in diameter. Nearly all particles are well rounded and their composition is similar to that of the gravel in the upper gravel zone. A count of 100 pebbles, selected at random from the sample, showed the presence of the following rock types: quartzite, 40 percent; volcanic rocks, 32 percent; granite, 14 percent; gneiss and schist, 8 percent; and limestone, dolomite, and chert, 6 percent. Sand from the sample studied consists mostly of well-rounded coarse- to fine-grained clear quartz particles.

Although the coarse-gravel zone is widespread and occurs at a persistent level, the upper and lower boundaries are locally quite irregular. The character of the lower boundary is little known because many of the wells do not completely penetrate the gravel zone. The upper boundary within the area of known occurrence (pl. 2) has a gradient of about 10 feet per mile in a southwesterly direction, corresponding to the direction of the river flow. The upper boundary occurs at sea level 5 miles southwest of Yuma and is about 50 feet below sea level 5 miles farther south. This coarse-gravel zone may extend into Mexico, where Stone (1955, p. 7) reports irrigation wells producing water from depths as great as 450 feet below the land surface. The irrigated area is about 25 miles from the Yuma area, and assuming that the depth to the top of the zone is about 300 feet below sea level, the gradient of the gravel zone would be about 12 feet per mile, which is in the same order of magnitude as that in the Yuma area. Thus the coarse-gravel zone may extend far beyond the Yuma area.

The origin of this extensive coarse-gravel zone is not explained by our present incomplete knowledge of geologic history. The zone appears to represent topset beds in the delta, but the gravel bed is graded to a stillwater surface several hundred feet below the present sea level. This may be a clue as to the date of deposition, for sea level is known to have been as much as 400 feet lower during periods of maximum glaciation in the Pleistocene than it is today. Many pebbles in the coarse-gravel zone are similar to rocks that crop out in northern and central Arizona; there are a few scattered outcrops of the same rocks in the Gila River basin in the central part of the State, and large quantities may have been eroded from that basin. The Gila River today is not an important contributor of either water or sediment to the Colorado River, but there are evidences that it was once a dynamic stream having considerable erosive power. Ross (1923) discusses several periods of erosion and alluviation during the early Pleistocene, following periods of block faulting and uplifting in central Arizona, and postulates that at that time the Gila River had abundant water and tremendous cutting power. These bits of evidence, taken together, suggest that the Gila River may have been chiefly responsible for the coarse-gravel zone, and that this deposition may have occurred during a time when continental glaciation was near maximum. The Gila River basin was beyond the limits of glaciation, but it may well have had a wetter climate than today's, with resultant high runoff in the Gila River.

Sandy and silty alluvium.--The alluvium overlying the coarse-gravel zone includes sand, silt, clay, and some gravel, in beds that range from poorly sorted to well sorted. The sediments are predominantly sandy, and practically all are in the range of sizes that are transported by the modern Colorado River. In the absence of detailed field determinations, it is estimated from topography and well-log data that the total thickness of this relatively fine-grained alluvium is of the order of 200 feet. This alluvium underlies both the Yuma Mesa and the Yuma Valley, and it is exposed in bluffs at the edge of the Mesa as well as in bluffs west of the river. However, in the development of the present topography the river has evidently reworked the material underlying its flood plain by scouring and filling to considerable depths; and it is possible that in an earlier stage the river similarly reworked some of the material immediately below the surface of the Mesa.

Continuity of deposition of this alluvium is suggested in the bluff along the west side of the river between Pilot Knob and the Chocolate Mountains. The beds exposed in the lower part of this bluff are predominantly sand, with a relatively small proportion of silt and practically no clay. There are numerous gravel beds, and small granule stringers are quite common in the sand beds. This alluvial unit is overlain by a prominent gravel zone which stands out as a dark-gray band along the bluff, entirely above the level of the Yuma Mesa (fig. 3).

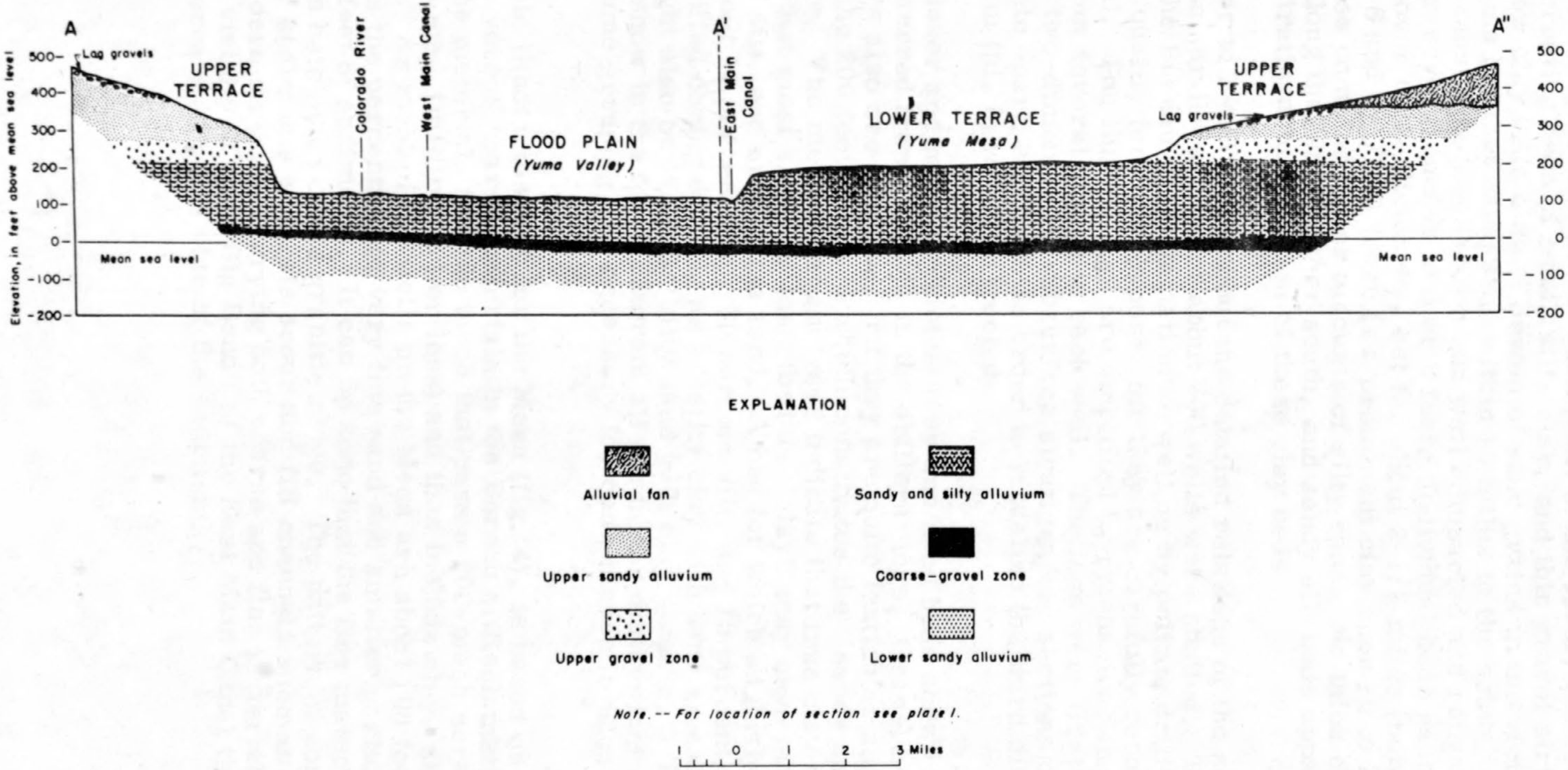

Figure 3.--Generalized geologic cross section of the Yuma area, Ariz.

Along the edge of the Yuma Mesa (east of the river) the sediments consist of alternating beds of sand, silt, clay, and thin gravel stringers. There are a few clay beds almost devoid of sand grains in the vicinity of the City of Yuma but they disappear within 10 miles to the south. The clay beds are mostly reddish brown and well compacted and range in thickness from several inches to 5 or 6 feet. Individual beds generally do not extend over large distances, but for about 2-1/2 miles (between coordinates 1 S and 3-1/2 S) there is a prominent clay zone 10 to 20 feet thick which also contains minor amounts of silty sand. No thick clay beds are exposed along the bluff farther south, and sandy silt beds apparently occur in the stratigraphic position of these clay beds.

In order to learn more about the detailed relations of the sediments under the Mesa, drillers' logs of about 200 wells were studied. The logs furnished by the Bureau of Reclamation as well as by private drillers are of exceptional quality for this purpose, for they are carefully recorded in adequate detail. The Bureau logs are amplified by mechanical analyses of samples from several depths in each well. The logs were first plotted graphically in two-dimensional subsurface stratigraphic sections on coordinates 1 mile apart; and then, in order to visualize the third dimension, a fence diagram (pl. 2) was constructed.

The thicker and more persistent clay and sand beds shown in plate 2 have been inferred from the data in the drillers' logs. Gravel beds or small stringers also are common, but they are quite lenticular and discontinuous in the 200 feet of strata which constitutes the "sandy and silty alluvium" zone. The mechanical analyses indicate that true clay is not common, and that most samples described as "clay" may have sizable proportions of silt, and even some sand. A bed for which an analysis might show about 55 percent clay, 30 percent silt, and 15 percent sand might be identified during drilling as a "silty clay with sand streaks." Such a bed might also be labeled "silty sand with clay streaks." It was impossible to show in the fence diagram all the minor distinctions given in logs, and some grouping was necessary for convenience in illustrative purposes.

A simple lithofacies map for the Mesa (fig. 4), is based on the percentage of fine versus coarse materials in the Bureau of Reclamation test wells. The fine materials include those that pass a 200-mesh screen (roughly 0.125 mm. [millimeter] or less) and thus include clay, silt, and very fine sand. As most of the wells on the Mesa are about 100 feet deep, this map shows the percentage of very fine sand and smaller particles in the upper 100 feet of sediments. It can be seen that the fine materials predominate on both sides of the granitic ridge. The pattern of concentration of finer sediments suggests scour and fill channels such as might be found in modern streams carrying both coarse and fine material. Southward from the vicinity of the "Big Bend" of the East Main Canal there is an appreciable increase in grain size of the sediments.

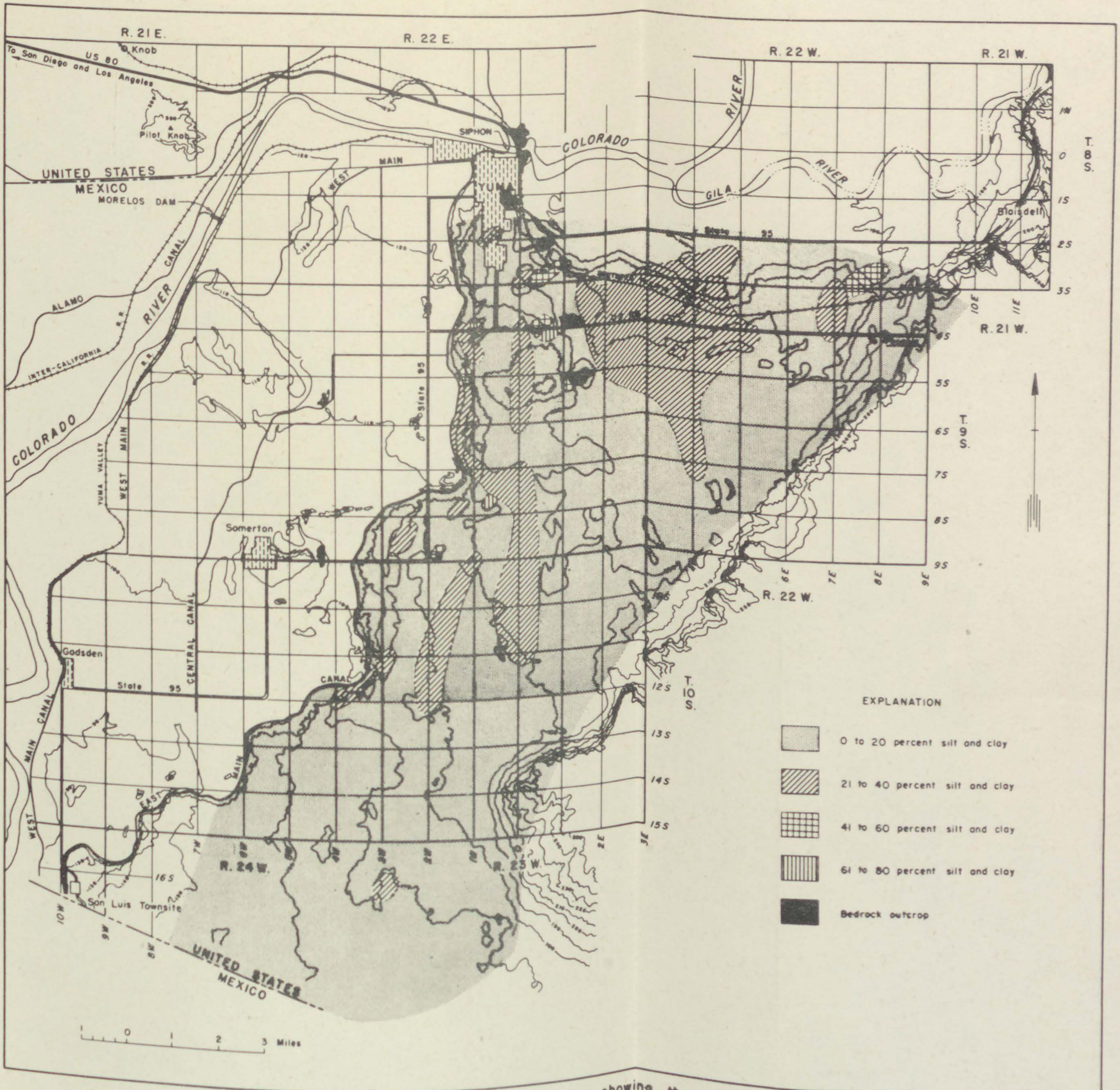

Figure 4.-- Lithofacies map of Yuma Mesa, Ariz., showing the percentage of silt and clay in the first 100 feet of sediments below the land surface.

The fence diagram indicates that some individual beds are continuous for several miles, which is greater continuity than is ordinarily found in alluvial sediments of western streams. Comparison of the detailed logs and mechanical analyses obtained from 2 test wells, however, indicates that there is indeed a considerable degree of continuity over a distance of at least half a mile. The wells were drilled at coordinates 7-1/2 S - 1/2 W and 8 S - 1/2 W, on the Mesa about a mile southeast of the Big Bend. In both wells the greatest proportions of gravel were in 2-foot zones respectively about 140, 157, and 168 feet above sea level, and the proportion was higher in the south well in each case. Sand relatively free of finer material was recorded in both wells in zones 59-76 and 160-192 feet above sea level. There were beds of clay (probably including silt) at 35-54, 114-123, and 132-140 feet above sea level in both wells. At other depths sand predominated, but it was mixed with variable proportions of silt and clay. These similarities suggest that these sediments may be relatively uniform and continuous over considerable areas, as might be expected in a typical delta.

Upper gravel zone.--West of the river in the Yuma area, beds of gravel near the top of the bluff appear to be equivalent stratigraphically to gravel beds exposed in low bluffs east of the Yuma Mesa.

The gravel along the bluff between Pilot Knob and Chocolate Mountains is composed of well-rounded pebbles and cobbles of quartzite, volcanic rocks, and lesser amounts of chert, limestone, gneiss, granite, and quartz; locally these are well cemented by calcium carbonate. A count of pebbles from one of the fine-gravel zones showed the following composition: quartzite, 48 percent; volcanic rocks, 26 percent; chert, 14 percent; quartz pebbles, 8 percent; granite, 2 percent; and gneiss, 2 percent. This sample did not contain any limestone. Chert and limestone are more common in the coarser gravels, and are particularly prominent in the residual lag gravel on the surface which extends several miles west of the bluff. The chert, limestone, and much of the quartzite are similar to Paleozoic rock types which occur in northern and central Arizona but are not known to occur in southwestern Arizona. Some of the quartzite and volcanic pebbles resemble Mesozoic rocks of central and southeastern Arizona. The scarcity of gneissic and granitic rocks suggests that little or none of the material was contributed from the nearby mountain blocks. The well-rounded character of the gravel also strongly indicates transportation over great distances.

The gravel beds southeast of the river are exposed in several pits. There is a very striking similarity of composition and degree of roundness between these gravels and those on the northwest side of the river, and both gravel zones occur at about the same altitude, approximately 200 to 250 feet above sea level (fig. 3).

A sample of gravel from a zone 5 feet above the bottom of a gravel pit in the bluff 1 mile south of U. S. Highway 80 east of Yuma has the following composition: quartzite, 57 percent; volcanic rocks, 25 percent; gneiss, 9 percent; chert and limestone, 7 percent; granite, 2 percent. A sample, 5 feet higher stratigraphically, in the same pit showed the following percentages: quartzite, 66 percent; volcanic rocks, 26 percent; gneiss, 4 percent; chert, 4 percent. Both samples contained much fresh feldspar and some epidote grains mixed in a sandy matrix of well-rounded quartz grains, which suggest some contribution, in smaller size ranges, of material from the adjacent mountain ranges. However, the rounding and composition of most of the pebbles suggest river transportation over long distances. Gravel of the same general composition occurs in pits along the bluff for 8 miles to the south, but the composition varies slightly from place to place. The composition of gravel in a pit 2 miles south of the one just mentioned is: quartzite, 50 percent; volcanic rocks, 26 percent; gneiss, 16 percent; granite, 4 percent; chert, 4 percent. The volcanic rocks in all the exposures on both sides of the river are of rhyolitic to andesitic types.

Comparison of this composition with that of the coarse-gravel zone indicates a similarity in proportion of Paleozoic rock types, but lesser amounts of volcanic and granitic rocks than in the deeper coarse-gravel zone. This difference in composition indicates that the pebbles in the upper gravel zone may have come from a different source from those in the deep coarse-gravel zone.

The upper gravel zone is absent along the base of the Gila Mountains north of U. S. Highway 80. There the alluvial-fan deposits rest directly on sandy alluvium, indicating that the upper gravel zone has been eroded away by the river. Although the relations could not be clearly seen, it is believed that the sandy alluvial sediments also are absent farther north (north end of Gila Mountains), because alluvial-fan deposits there rest directly upon Tertiary sedimentary beds.

The outcrops of the upper gravel zone along the flanks of the Gila Mountains, and between Pilot Knob and the Chocolate Mountains, indicate a layer that originally was quite extensive, perhaps comparable to that of the deeper coarse-gravel zone. The upper gravel zone appears to be roughly parallel to that deeper zone and is approximately 200 to 250 feet above it, and thus may well be a topset delta bed graded to approximately the present sea level. The pebbles in the upper gravel indicate transportation for great distances, but without additional study it cannot be said whether they came chiefly from the Colorado River, the Gila River, or both. Longwell (1946, 1954) found gravel-capped terraces several hundred feet above the present Colorado River channel at various places between Davis Dam and the upper end of Lake Mead; these he has identified as remnants of the Chemehuevi formation of Pleistocene age. However, the relation of these gravels to the upper gravel zone in the Yuma area is not known.

In the Laguna Mountains, Wilson (1933) found weakly consolidated gravel beds containing some sand, silt, and clay, which he considers to have been deposited by the Colorado or Gila River when those streams were at considerable higher level than at present. These may eventually be shown to be related to construction of the present delta above levels presently observed, or they may be deposits long antedating the history summarized in preceding paragraphs. They may also be features of importance in unraveling the orogenic history of the region.

Upper sandy alluvium.--The best exposures of the upper sandy alluvium are on the west side of the Colorado River. Although this unit occurs east of Yuma Mesa, good exposures are not common because of a cover of windblown sand. Examination of the outcrops west of the river indicates that the unit consists primarily of poorly sorted crossbedded sand with minor amounts of gravel beds. No clay beds were found in this cursory examination. The gravel beds occur as discontinuous lenses over short lateral distances. The sandy alluvium is overlain by lag gravels apparently formed by a deflation process. They indicate the removal of an unknown amount of sandy material.

Alluvial fans.--Southeast of Yuma, near the base of the Gila Mountains, the upper gravel zone is covered by alluvial fans composed of material eroded from those mountains, and consisting of angular particles of gneiss, schist, and granite. There is a marked contrast between the fan material and the delta material both in composition and physical characteristics, and the local source of the fan sediments is quite clear.

Erosion and terrace development.--The present land surface in the Yuma area is dissimilar to the relatively smooth plain that must be presumed to have resulted from the deposition of the upper deposits described in preceding sections. The changes have been effected by erosion of the delta sediments, involving both downcutting and lateral planation by the river.

Even the parts of the delta that are now underlain by remnants of the upper sandy zone have been somewhat affected by erosion, for they have a gravelly surface known as desert pavement. Such surfaces are developed when wind blows away the sand, silt, and clay and leaves behind the pebbles, which are thus named "lag gravel." The pebbles settle downward and become so closely spaced as to form a pavement that eventually prevents further erosion by wind. The upper sandy alluvium in the vicinity of Pilot Knob is covered by a classic example of such a desert pavement. The magnitude of wind deposition, and therefore of wind erosion, on the present surface of the Colorado delta is suggested by the extensive areas of sand dunes along the southeastern border of California.

Several periods of erosion and downcutting are included in the delta history. During a series of downcutting periods, terraces were developed by successive stages of lowering of the stream level. After the initial pulse of rapid erosion along the new stream channel and after the downcutting action was stabilized, the stream returned to lateral swinging and eroded the bluffs on both sides. Another downcutting period took place to establish a lower base level before the former terrace level was destroyed. Commonly a terrace could be completely cut away on one side and partially preserved on the other side of the channel.

The first period of downcutting and stripping out of earlier deltaic sediments occurred above the upper terrace level, and the upper terrace represents the approximate base to which this cutting extended. The lag gravels strongly indicate the former presence of an unknown thickness of sediments above the strata now exposed. The upper terrace has a slightly steeper slope than the lower terrace, indicating that the original upper flood plain surface has been modified by erosional processes. Fragments of elephant bones have been found on the upper terrace, suggesting that this part of the delta was subaerial prior to historic time.

The second period of downcutting is represented by the lower terrace, Yuma Mesa, which is preserved only on the east side of the river. This plain is indicative that the river cut its channel below the level it had developed over the upper sandy alluvium, and by lateral planation established a broad new flood plain at this lower level. Most of the upper gravel was removed in the process. The fact that the Mesa exists only east of the river, plus the evidence that the upper gravel near Pilot Knob has survived until recent times and is only now being attacked by the river, suggest that the axis of the flood plain during the planation of the Mesa may have been east of Yuma.

The present flood plain of the river represents a third major stage in the downcutting and lateral planation of the delta sediments. A levee now separates the lands of the Valley Division from the Colorado River floodway, but physiographically both the Yuma Valley and the floodway are parts of the modern flood plain. This plain has been cut about 70 or 80 feet below the level of the Mesa, and the Mesa has thus become a second and lower terrace, rising above the present flood plain. The downcutting in this period extended to the Gulf of California, although the depth of cutting was considerably less in that area. It has also extended northwestward into the Salton Sea depression.

Logs of wells in the flood plain show that silt and sand commonly predominate within about 50 feet of the surface. It is considered that this zone has been reworked by the scouring and filling action of the modern river, which has transported chiefly silt and sand in historic time. The depth of this reworking is not known, but evidently it did not penetrate to the level of the coarse-gravel zone.

Since the completion of Hoover Dam, clear water has been discharged from Lake Mead, and even at Yuma the Colorado River has carried far less sediment than the average prior to 1935. The river channel in the Yuma area has been lowered several feet through erosion by this relatively clear water.

The physiographic units shown on plate 1 are in descending topographic order, the upper terrace, the lower terrace or Yuma Mesa, and the flood plain, which includes both the Yuma Valley and the Colorado River floodway. The lower terrace rises abruptly about 70 feet above the flood plain, forming a conspicuous feature in the area. The erosional scarp between the lower terrace and the upper terrace is less readily discernible because the difference in altitude is only about 15 to 20 feet, and in many places the slope has been graded by erosion or covered by eolian sand.

Geologic Structure

The regional geologic structure in the Yuma area is closely related to the topographic expression seen in the land-surface features. Physiographic evidence suggests a major fault trending northwest, parallel to the Gila Mountains border, and such a fault is inferred on the tectonic map of the United States, published by the American Association of Petroleum Geologists (1944). Mountain blocks to the east of the Gila Mountains are considered to be block-fault mountains (Wilson, 1933), and they have the same general alinement. This alinement is parallel to the trend of the Gulf of California and the Peninsular Ranges of Baja California and southern California, and also to the inferred trend of the San Andreas fault system northwest of Yuma. On the basis of recent earthquakes in the Yuma area, it appears that a branch of this fault zone is still active.

No evidence of faulting was observed in the vicinity of Yuma, but it can be inferred that the ridge of granitic gneiss is a fault block that is related to the Cargo Muchacho Mountains. This buried ridge probably represents a small, narrow horst or tilted block in the delta apex, and it may be of larger extent than indicated on the surface. Pilot Knob may have been formed similarly, and there may be other fault blocks in the delta apex that have been covered with sediments.

The spatial relations between the Gila Mountains and Laguna Mountains on the one hand, and the Cargo Muchacho Mountains and probable extensions such as the granitic gneiss ridge and Pilot Knob on the other (pl. 1), suggest that a cross fault may occur between these two groups of mountain ranges. Faults are known to occur on the north side of the Gila Mountains (Wilson, 1933, p. 188) tilting the Tertiary beds away from the mountains. The resulting structural valley could have served as the early passageway for the Gila River, emptying into the Gulf-Imperial trough. Such structural relationships would also help to account for the occurrence of the coarse-gravel zone on all sides of the buried ridge and would indicate that the Gila River channel was once east of the buried ridge.

Factors Related to Ground-Water Movement

Although the geology of the Colorado delta as outlined in preceding sections has not been studied or reported in detail, the water-bearing characteristics of some of its sediments have long been known in a general way. As pointed out by Wilcox and Scofield (1952, p. 8): "Early in the history of the Valley Project, it had been found that wells drilled to 100 feet or more or approximately to sea level reached an aquifer that yielded water copiously. A number of such wells were established and in use chiefly for domestic supplies, not only in the Valley Division but also on the Yuma Mesa and in the Gila Valley northeast of Yuma." The well drillers in the area — notably Frank Leidendeker, who furnished many of the well logs on which the analysis of the subsurface geology was based — have documented the position of this aquifer by extensive drilling.

Currently the ground water in the Colorado delta in Mexico is being developed, chiefly for irrigation of cotton. Stone (1955) states: "Underground water can only be obtained by drilling in the east and particularly the northeast part of the Valley on the cone extending southwest of Yuma. Several wells have been drilled outside of this area with unsatisfactory results, salt water or no water-bearing gravel. Near Yuma an adequate water supply is available with perforations at 200 feet but farther to the south it is necessary to drill deeper wells due to the strata of water-bearing gravel dipping downward. At the south margin of the available water supply we have found that wells drilled 450 feet deep with rotary rigs and gravel packed, give a very good water supply."

So far as ground water is concerned, several of the geologic units in the Yuma area can be dismissed with a summary statement. The bedrocks form the floor and walls of the delta, and also form ridges within the delta which serve as retaining walls or barriers to ground-water movement. The part of the delta below sea level is saturated with water, but so few wells have been drilled into these deep strata that little is known about them; in any case, their importance in ground-water movement is likely to be small in comparison with that of overlying sediments. The upper gravel zone and overlying sandy alluvium, constituting the highest part of the delta, are not saturated with water, and their significance in ground-water occurrence is limited to the possibilities of recharge by downward percolation of precipitation, which is conceded to be negligible.

The important ground-water units are the coarse-gravel zone, which occurs near sea level in the Yuma area, and the ov erlying sandy and silty alluvium. The coarse-gravel zone is known to be exceedingly permeable, because many wells of large yield have been developed in it. The overlying alluvium is dominantly sandy and presumably has a moderate overall permeability; but within this zone there are considerable variations in permeability, corresponding to the variations in sediment from clay to gravel. The variations in permeability of the delta sediments are items of especial importance in the ground-water problems of the Yuma area.

Permeable Sediments of the Delta

The term "coarse-gravel aquifer" is used in this report as a temporary designation for a unit that deserves a more distinctive name. Wilcox and Scofield (1952) call it the "deep aquifer," but that is hardly definitive, for well drillers report considerable thicknesses of alluvium beneath it, including some beds of gravel. Its position near sea level is distinctive near Yuma, but it dips southwestward into Mexico and is several hundred feet below sea level in the outer part of the delta. It is not known to crop out at the surface, and its character and limits are not well enough known to describe it as a geological formation. Several inadequacies of the designation "coarse-gravel aquifer" are recognized: There are water-bearing gravels in the alluvial beds overlying and underlying this zone; there are coarse-gravel beds in the uppermost part of the delta, although those beds are unsaturated; on the other hand, because of the general variability in river sedimentation it is unlikely that this zone is everywhere a gravel, although it has been so reported in practically all the deep wells of which logs are available.

The continuity of the coarse-gravel aquifer, shown by geologic studies, is also suggested by the consistently high specific capacities of wells that have pumped from that zone. Wells on the Mesa and in the Valley generally have obtained high yields per foot of drawdown from the coarse-gravel aquifer, as shown by the drillers' logs. Also, the water in the coarse-gravel aquifer is distinctive in chemical composition: Wilcox and Scofield (1952) have reported that the water in deep wells of the Mesa is more mineralized, and contains a higher proportion of chloride and a lower proportion of sulfate, than the average water of the Colorado River. Deep wells reaching the coarse-gravel aquifer in the Valley are often perforated in all water-bearing zones, including those above the coarse gravel, and the composition of water from them is then intermediate between that in the deep wells of the Mesa and that in the Colorado River.

The material overlying the coarse-gravel aquifer ranges in thickness from about 100 feet under the Valley to nearly 200 feet under the Mesa. According to drillers' logs this alluvial material includes gravel, sand, silt, and clay, but the dominant constituent is sand. Sieve analyses of samples from the Bureau of Reclamation test wells in the Mesa refine this information considerably — they show that some sand beds are well sorted and of fairly uniform texture, and others contain a considerable proportion of silt and clay — but still the material is predominantly sand. Many of the sand beds contain some gravel, and some beds are predominantly gravel.

Variations in Permeability

The names of the geologic units and rock types that have been described suggest different magnitudes of permeability: presumably least in the crystalline bedrocks, generally low in clay and silt, higher in well-sorted sand, and highest in clean gravel, with numerous gradations for the various combinations that are found in the Yuma area. In the Mesa a major problem is downward movement of water from irrigation, dependent upon permeability normal to the bedding, or "vertical" permeability. There is a similar problem in the Valley, because of the possibility of upward movement of water across the bedding.

At a given horizon, changes in permeability are inherent in discontinuous beds, and are to be expected wherever a lentil of one type of material laps onto or grades into another kind of sediment. Such changes are typical of the Colorado delta sediments, but perhaps to a lesser extent than in the alluvial sediments of most Western valleys, because of the fair degree of continuity observed in some individual strata, both on the outcrop and in well logs.

The bedrock ridge in the vicinity of Yuma, which in large part is buried beneath the delta sediments, constitutes a barrier to horizontal movement of water in the abutting sediments. It has clearly caused changes in permeability over an area extending several miles to the south, because it has influenced the pattern of deposition in the past. The fence diagram shows rather extensive beds of clay and silt under the Mesa to the south of this buried ridge, in contrast to the relatively thin beds of these materials in other parts of the Yuma area. However, the lithofacies map (fig. 4) shows considerable variability in proportion of these finer materials from point to point in the upper 100 feet of sediments under the Mesa. The buried ridge appears to have created an environment favorable for deposition of the finer materials, and the deposition of clay and silt in one area contemporaneous with sand or gravel in another necessarily results in spatial differences in permeability.

There is no evidence, however, that the finer grained materials are concentrated in such a way as to create a zone of lesser horizontal permeability along the west edge of the Mesa coincident with the steep westward slope of the ground-water mound. The lithofacies map shows that the proportion of fine materials along the west edge of the Mesa varies considerably from well to nearby well — as it does throughout the Mesa — but is not consistently greater than in areas farther east. Many of the well logs recording the highest proportions of clay and silt are close to the buried ridge. The fact that some wells showing the lowest proportions of clay and silt are also in the vicinity of the buried ridge emphasizes the significance of that ridge in producing variations in sedimentation that led to horizontal differences in permeability. In other words, conditions that could interrupt or modify the lateral movement of ground water are created by the buried ridge and are most pronounced in its vicinity. The western edge of the Mesa, especially north of the Big Bend (7 S - 1 W), is within this area where the sedimentation pattern was modified by the buried ridge, but so is the entire irrigated area on the Mesa.

The lithofacies map (fig. 4) shows a belt of finer grained materials and presumably lesser permeability along the edge of the Mesa for about 3 miles north of the Big Bend. However, evidence has been presented (p. 20, 22) of considerable continuity of the individual strata in this area. Thus there is no clear evidence of contrasting horizontal permeability along the edge of the Mesa. The vertical sequence of sand and silt or clay beds, however, suggests marked differences in vertical permeability.

Vertical changes in types of sediments are more common and occur in shorter distances than horizontal changes. The contact between a sand bed and an overlying or underlying clay bed may be distinct and sharp, whereas a change from sand to clay in a horizontal direction takes place in a gradational fashion and may occur over a distance of hundreds of feet or even miles. Review of all available data pertaining to geology indicates that the sediments under the Valley and under the Mesa, down as far as the coarse-gravel aquifer, are predominantly sand, and from this fact it may be inferred that these sediments are, on the average, moderately permeable. Vertical variations in permeability are created by the beds of clay and silt within these sediments. A bed of small areal extent will impose its restrictions on vertical movement of water in a correspondingly small area. A bed of clay or silt that is continuous over an area of several square miles will impede or deflect the vertical movement of water within that larger area. There is geological and hydrological evidence that some of the impeding layers are of that magnitude, particularly under the Mesa.

From all available evidence, the permeability of the coarse-gravel aquifer is considerably greater than that of most of the overlying sediments. It is properly classed as highly permeable, therefore, in comparison with those overlying sediments which on the average are only moderately permeable.

EXISTING HYDROLOGIC CONDITIONS

The analysis of geologic data provides a basis for summarizing the framework through which ground water moves, and the control by that framework of the pattern of circulation of ground water. Predominantly sandy and moderately permeable alluvium (unit 3 as listed on p. 13) underlies both the Valley and the Mesa. This alluvium is as much as 200 feet thick under the Mesa, but a part has been cut away by erosion in the Valley area so that the remaining thickness is about 100 feet. Although this alluvium is predominantly sand, there are beds of clay and silt of varying thickness and areal extent, which create marked vertical variations in permeability. Beneath this alluvium is a coarse and highly permeable gravel (unit 2 on p. 13), apparently continuous under Mesa and Valley, and having a thickness as great as 50 feet.

This concept is basically different from any that could be obtained by studying only the shallowest ground water and the overlying unsaturated alluvium. All the test wells in the Yuma area are limited to such a zone, and the data from them therefore pertain only to details of the hydrology of the moderately permeable alluvium above the coarse-gravel aquifer. These data are inadequate to indicate the role of the coarse-gravel aquifer in the hydrology of the Yuma area.

The available data on the coarse-gravel aquifer are of a qualitative nature. Well logs indicate the existence and continuity of the coarse-gravel aquifer, and the yields and operating characteristics of various wells attest to its high permeability. Data from the few tests that have been made in wells tapping that aquifer are inadequate for quantitative determinations of its permeability and other related aquifer characteristics.

Of the hundreds of wells in which water levels are observed in the Yuma area, only two appear to offer a significant record of head changes in the coarse-gravel aquifer. It is obvious, therefore, that the data are insufficient to provide a basis for quantitative analysis of the hydrology of the coarse-gravel aquifer, which in turn would be the key to any general quantitative analysis of the hydrology of the Yuma area.

The course followed in this review, in lieu of quantitative analysis, has been to develop theoretically the possible patterns of ground-water circulation using several different avenues of approach suggested by the qualitative and varied nature of the data. Several aspects of observed existing hydrologic conditions, in both the Valley and the Mesa, are considered and compared with the features suggested by an electrical model. The history and interpretation of changing hydrologic conditions, based on observations beginning as early as 1911, are reserved for the following section.

Theoretical Ground-Water Movement Based on Electrical Analogs

By R. H. Brown and H. E. Skibitzke

As the existing data do not allow a quantitative evaluation of the hydraulic properties of the water-bearing materials, to make a rigorous mathematical analysis of ground-water movement in the Mesa-Valley area would be virtually impossible. However, these data do yield considerable qualitative information permitting relative, rather than absolute, comparison of the hydraulic characteristics of different parts of the flow system. An analysis by electrical analogy permits rapid review of solutions covering many arbitrarily selected combinations of flow-system characteristics.

The hydraulics literature is replete with references to the mathematical analogy between the steady flow of ground water and the steady flow of heat or electricity. Slichter (1898, p. 329-332) pointed to the utility of the Laplace equation in solving, with equal facility, steady-state flow problems in all three fields. There is also an electrical and thermal analogy to nonsteady-state flow, and Rouse (1950, p. 20-22) made significant reference to the use of electrical models for evaluating water-flow patterns. As the complexity of the prototype flow problem increases, however, the model investigator's ingenuity must be equal tothe challenge of transposing into electrical circuitry the boundary conditions and salient characteristics of the real flow system. The electrical solution, whether it be quantitative or qualitative, then accomplishes in minutes what otherwise might require hours of tedious numerical analysis.

Exhaustive study of ground-water movement in the Mesa-Valley area ideally would require three-dimensional analysis. However, the available data did not provide the detail demanded, and the study necessarily reverted to a simpler two-dimensional approach. Fortunately, the boundary conditions in the flow system can be satisfactorily located and identified. The position and general shape of the ground-water mound under the Mesa, discussed at length in a later section, is undisputed; the configuration of the water table in the Valley and the function of the gravity drains are clear; and the extent of irrigated areas and amount of irrigation water applied to Mesa land are reasonably well established. With heavy and essentially continuous recharge recognized in the Mesa part of the flow system, as irrigation water percolates downward into the ground-water reservoir, the problem becomes one of describing the manner in which the superimposed recharge effects are dissipated, and showing the range in distance over which the dissipation process occurs. Fundamentally the recharge aspects of the problem represent superposition of a radial flow pattern on the pre-existing natural flow pattern.

Theoretically, if the flow medium were homogeneous, isotropic, and of uniform thickness and infinite extent, the recharge effects would travel radially outward from the recharge area equally fast over equal distances, and the selection of a vertical section along any particular radial direction would not of itself be prejudicial to the solution. However, in the problem at hand, departures from idealized conditions are significant and there are cogent reasons for examining the head distribution through a vertical section chosen along one particular radial direction. Shown on plate 1 is the trace of the vertical section (B-B') picked for electrical-model study and deliberately positioned so that it extends in a straight line from the Colorado River southeastward across the Yuma Valley. The section roughly parallels the natural southeastward trend of the water-table contours, traverses the approximate center of the Big Bend area, bounded on the east and south by the East Main Canal, where drainage problems have been notably critical, and passes the B-Lift Pumping Plant to cross the Mesa through and beyond the highest part of the ground-water mound. The configuration of the land surface and water table (as of December 1954) along this section is shown in figure 5, together with locations of all drainage ditches and canals that are crossed. The upper limit of the section is the land surface, and the lower limit is the top of the coarse-gravel aquifer which here is close to sea level.

Construction of the electrical model followed simple, well-established principles. A sheet of Teledeltos graphite paper, to constitute the flow medium, was cut to a shape that would provide an appropriate facsimile of the water-bearing zone outlined in section B-B' (fig. 5). Dry-cell batteries in series combinations were connected along the top edge of the graphite paper so that the impressed electrical potentials duplicated the observed configuration of the water table as it appears in section B-B'. It is relevant to explain here that the electrical model was designed to show steady-state conditions. Although this obviously belies the real situation, the approach is considered ultraconservative, inasmuch as the hydrographs of deep wells on the Mesa, presented in a later section (fig. 22, p. 72), show little evidence of leveling off; and if head values in the coarse-gravel aquifer are continuing to rise, as they seem to be, it can be only because the effects of recharge continue to develop and spread. Thus the results of the model analysis represent something less extensive and less severe than the ultimate effects to be expected.

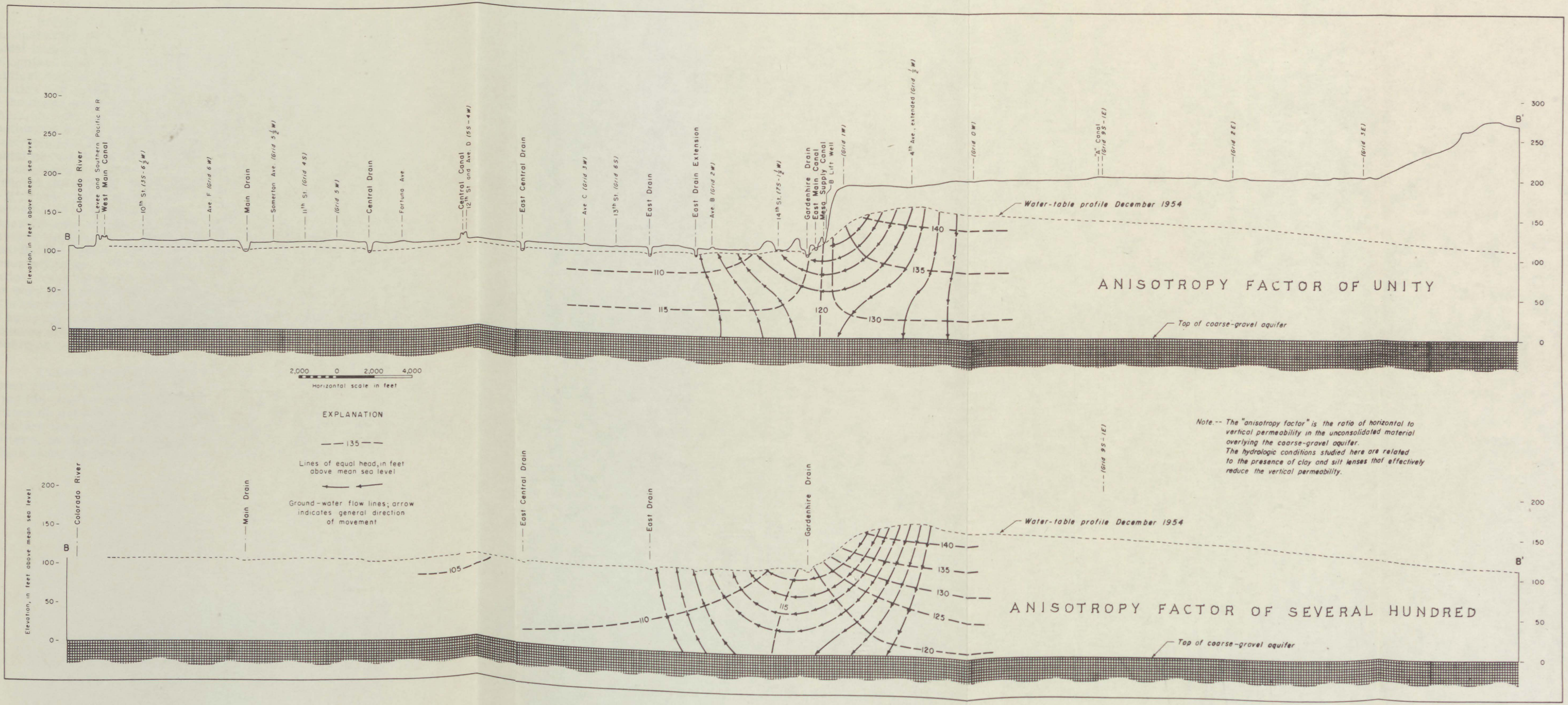

Figure 5.--Equipotential lines along section B-B' on plate 1, as derived by electrical-model analysis.

In lieu of a meticulous detailing of electrical-model construction and operation, it is sufficient to record only the salient features. The model incorporated components designed to duplicate the effects of the recognized hydrologic boundaries and characteristics of the selected vertical section B-B'. These boundaries and characteristics include the position and configuration of the water table; the position (mean sea level) of the upper surface of the coarse and highly permeable gravel aquifer, which, insofar as this selected section is concerned, is assumed to be continuous and of infinite extent; the continuous zone of finer grained materials overlying the coarse gravel; and the substantially higher horizontal permeability of these finer grained materials, underlying the Mesa, as compared with the vertical permeability. With the model thus constructed the voltage distribution (head changes), along the selected section B-B', was traced with a point probe for a number of arbitrarily chosen ratios between horizontal and vertical permeabilities of the finer grained water-bearing material. These ratios ranged in value from unity to several hundred, but, inasmuch as the general head (equipotential line) distribution pattern retained its basic identifying features throughout the observed range, only the conditions representing the lower and upper ratios in the range are exhibited in figure 5. The model provided also for very high permeability of the coarse-gravel aquifer in comparison with the horizontal permeability of the overlying material. In the light of pumping-test data for deep wells, presented later, these selected features of the model are adjudged as conservative approximations of the prototype conditions that apparently exist.

Observe the two head-distribution patterns shown in figure 5. The upper pattern relates to assumed isotropic conditions in the material overlying the coarse-gravel aquifer. Although it is known that the real conditions do not begin to approximate isotropism, the assumption of isotropism provides the means for developing a useful reference base. The lower pattern, in figure 5, relates to assumed conditions of substantial anisotropy which more nearly approximate the real situation.

The head observed in the coarse-gravel portion of the model evidently represents an average of the heads indicated by the water table. It is reasonable to expect that the head in the gravel aquifer would not vary much laterally, inasmuch as the permeability of the gravel is much higher than that of any adjoining material. Thus in the upper diagram (fig. 5) the average head in the gravel aquifer is probably of the order of 120 and in the lower diagram the corresponding value is 115. This comparison of the two head-distribution patterns immediately suggests that one important effect of increasing anisotropy is to lower the head in the coarse-gravel aquifer to a value closer to (but still greater than) the head indicated by the Valley water table. Stated in slightly different fashion, the greater the anisotropy the more effective the low heads (Valley water table) become in the averaging process that determines the average head in the gravel aquifer. This phenomenon is especially significant in the Mesa-Valley ground-water-flow relationships, for it means that the known anisotropic conditions have effectively limited the head rise in the gravel aquifer to something less than the rise that could otherwise have occurred.

It has been mentioned that the average head in the gravel aquifer develops as an average of the head distribution indicated by the water table in the Valley and Mesa. That is to say, the average head in the gravel will be somewhere between the head values represented by the Valley and Mesa positions of the water table. Thus, somewhere along the water-table profile shown in section B-B' there will be a point where the head value is identical to the average head in the gravel. There is thus established one equipotential line, between the point just described and the gravel aquifer below, that is essentially vertical and that has the added significance of being the dividing line between the zone of downward vertical ground-water flow on the Mesa side and that of upward vertical flow on the Valley side. This dividing line shifts toward the Valley as the anisotropy increases, as shown by the arrangement of the equipotential lines in the two diagrams in figure 5.

There is another important comparison to be made between the two head-distribution patterns shown in figure 5. It may be said that the effect of increasing anisotropy, which in this problem means decreasing vertical permeability, is equivalent to extending the vertical dimensions of the model. With increased distance, in the model, between the Mesa water table and the top of the gravel aquifer, there is evidently more opportunity for horizontal migration of the equipotential lines before they intersect and enter the gravel aquifer. Thus in the lower diagram it is obvious that horizontal flow persists over greater distances on both sides of the above-described nearly vertical equipotential line than is indicated in the upper diagram.

Deliberately incorporated in the electrical model was the feature of very high permeability of the coarse-gravel aquifer, in comparison with horizontal permeability of the overlying finer grained material. From the various combinations of boundary conditions explored, it became evident that the permeability of the gravel aquifer would have to be very low — much lower than could possibly be the case — to alter significantly the head-distribution patterns illustrated.

The electrical analogs indicate downward ground-water movement under the Mesa, resulting from intermittent irrigation recharge; horizontal movement toward the Valley from the Mesa; and upward movement beneath the Valley. They indicate also that application of water on the Mesa has caused increases in head in the coarse-gravel aquifer under some of the Valley land. These findings cannot be confirmed in their entirety because of the paucity of data concerning the coarse-gravel aquifer. However, the available hydrologic data support the model analysis on many points, as discussed in succeeding portions of this section.

Vertical Head Differentials

Ground water moves at the sacrifice of some of its head, which is a measure of the potential energy that causes the movement. In the lateral movement of ground water under steady-state conditions, the head loss as shown by the gradient of the water table is determined by the geometry (e.g., the elevations and flow distances) of the route and points of discharge. The rate of movement in steady-state problems is commonly calculated by using the head loss and permeability; if only the head loss is known, the rate is often estimated on the assumption that each type of rock material has permeabilities within a certain range. The validity of such an analysis depends on the validity of the assumptions. Head losses often are determined by measurements of water levels in wells that are assumed to reach the same zone in the same aquifer, but spaced some distance apart. The form of the water table constructed on the basis of such measurements is then used to interpret direction of movement, differences in permeability, variations in rates of movement, and positions of recharge and discharge points. The prime consideration, in determining ground-water movement, is observation of head change along the desired path or plane of flow. If horizontal movement of ground water is under study, the wells used in identifying head loss should probe the same horizontal plane.

In vertical movement of ground water, whether upward or downward, the velocity is similarly dependent upon permeability and head loss. Thus adjacent observation wells finished at different depths may reflect different heads, even though no change in permeability is involved. Components of a vector describing the direction of motion of water away from an area of recharge may be in the vertical plane as well as the horizontal plane. Indeed, the component of motion may be resolved in any plane. The basic law of ground-water motion, Darcy's law, is a simple statement to the effect that if a component of motion exists in any direction a component of head loss also will exist, and that the magnitude of head loss is proportional to the magnitude of the velocity component in that direction. As a result, if vertical components of motion exist, vertical components of head loss will exist. This is an important consideration when the velocity components in a horizontal plane are being sought. Obviously the head losses must be measured in the horizontal plane or must be resolvent in that plane if distorted results are to be avoided. A head differential between adjoining wells of differing depths is prima facie evidence of vertical components of ground-water motion, and serves warning that water-level data from wells must be carefully screened and adjusted before they can be utilized to draw conclusions concerning lateral components of the water movement.

Evidence in Mesa

Data are lacking as to the head differential between water in the coarse-gravel aquifer and any of the overlying less permeable material, but there is abundant evidence of the existence of substantial head differentials between shallow and deep zones in that overlying material. All this evidence is obtained from wells on the Mesa, where water applied for irrigation has for years moved downward to recharge the ground-water reservoir. The evidence is graphically presented in figure 6, where hydrographs for pairs of shallow and deep wells at the sites specified (fig. 7), indicate the range in observed head differentials.

At some locations, where the spread between water levels in the shallow and deep wells is greatest, the clay and silt lenses may have caused perching of water. But the downward movement of irrigation water through the fine-grained, low-permeability materials underlying the Mesa inevitably is at the expense of considerable loss in head, and thus it is to be expected that the water level in a shallow well will stand higher than that in an adjacent deeper well. In other words, even in materials that are entirely saturated and of uniform permeability there will be some measurable head differential, perhaps of the order of several feet, between upper and lower strata in the saturated zone. The hydrographs of wells at 6-1/2 S - 1/2 E and 10 S - 3 W (fig. 6), which show head differentials of 5 to 10 feet, may more nearly reflect the true head differential attributable solely to loss in head with slow downward ground-water movement.

Theory in Valley

Although there are numerous wells in the Valley that are deep enough to tap the coarse-gravel aquifer, there are no records of water levels in any well that is finished exclusively in that zone. Very little is known, therefore, about vertical head differentials in the Valley; hence, this section is headed by the word "Theory" rather than "Evidence."

The evident existence of head differentials in the water-bearing strata underlying the Mesa, and the evidence of persistent upward trends in head values for the deep-lying coarse-gravel aquifer (fig. 22, p. 72) encourage some reflections on possible head relationships that have existed in the Valley under natural conditions, and on the nature of the head changes that surely have accompanied the Valley and Mesa irrigation development. As an aid to this discussion, figure 8 has been drawn to portray possible head situations at three selected stages in the history of the Big Bend area.

Valley and Mesa undeveloped.-- The early or near-natural conditions, prior to extensive irrigation development in either the Valley or the Mesa, are given in sketch A of figure 8. The evidence in the Valley strongly points to considerable natural discharge of ground water. Old maps of the Yuma area show a number of natural sloughs and lagoons, which are immediately suspect as areas of ground-water discharge; and the name "Tule Lagoon" appearing on one old map bears eloquent witness to the kind of water-loving vegetation that was probably native to these discharge areas.

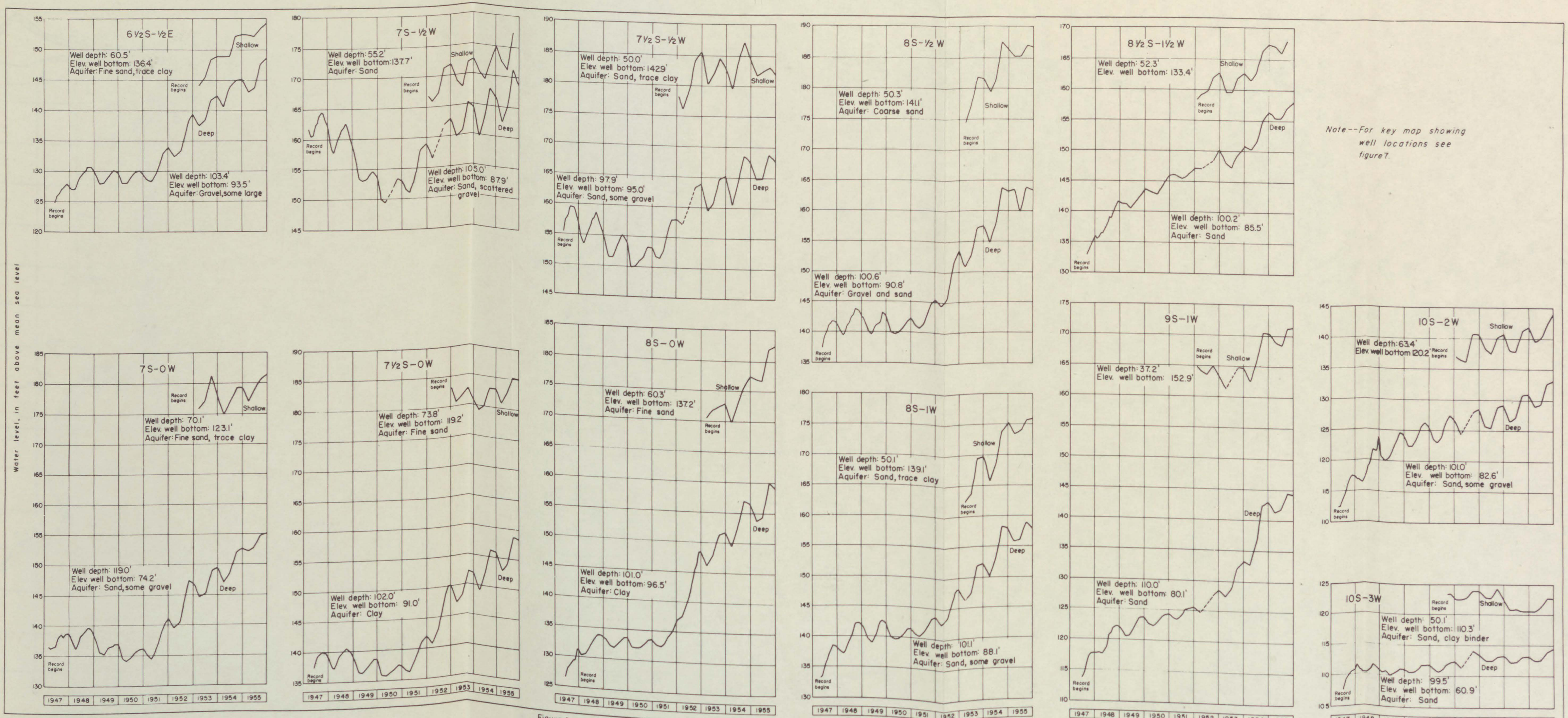

Figure 6. -- Water levels in selected pairs of shallow and deep wells, Yuma Mesa, Ariz.

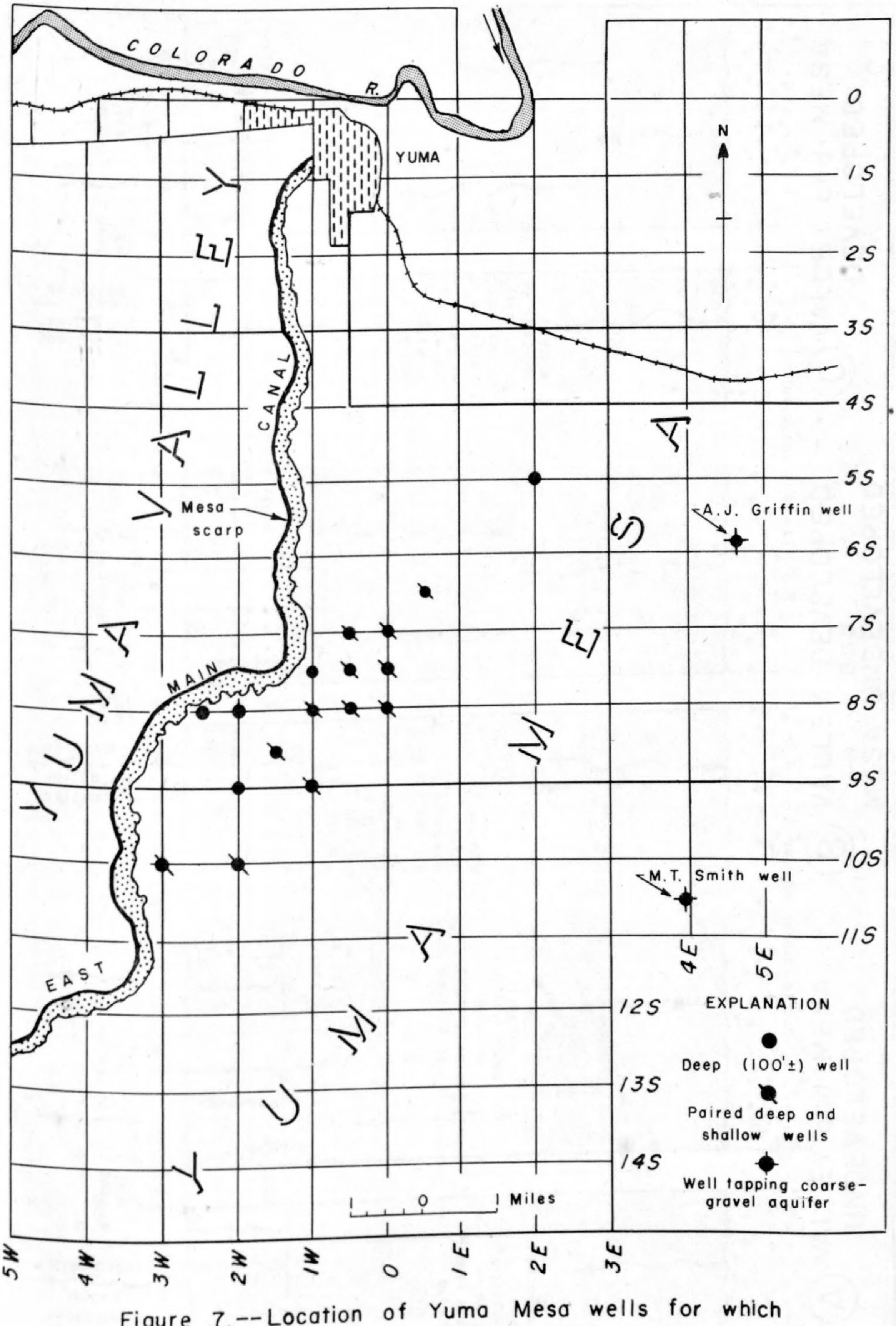

Figure 7.--Location of Yuma Mesa wells for which hydrographs are given in this report.

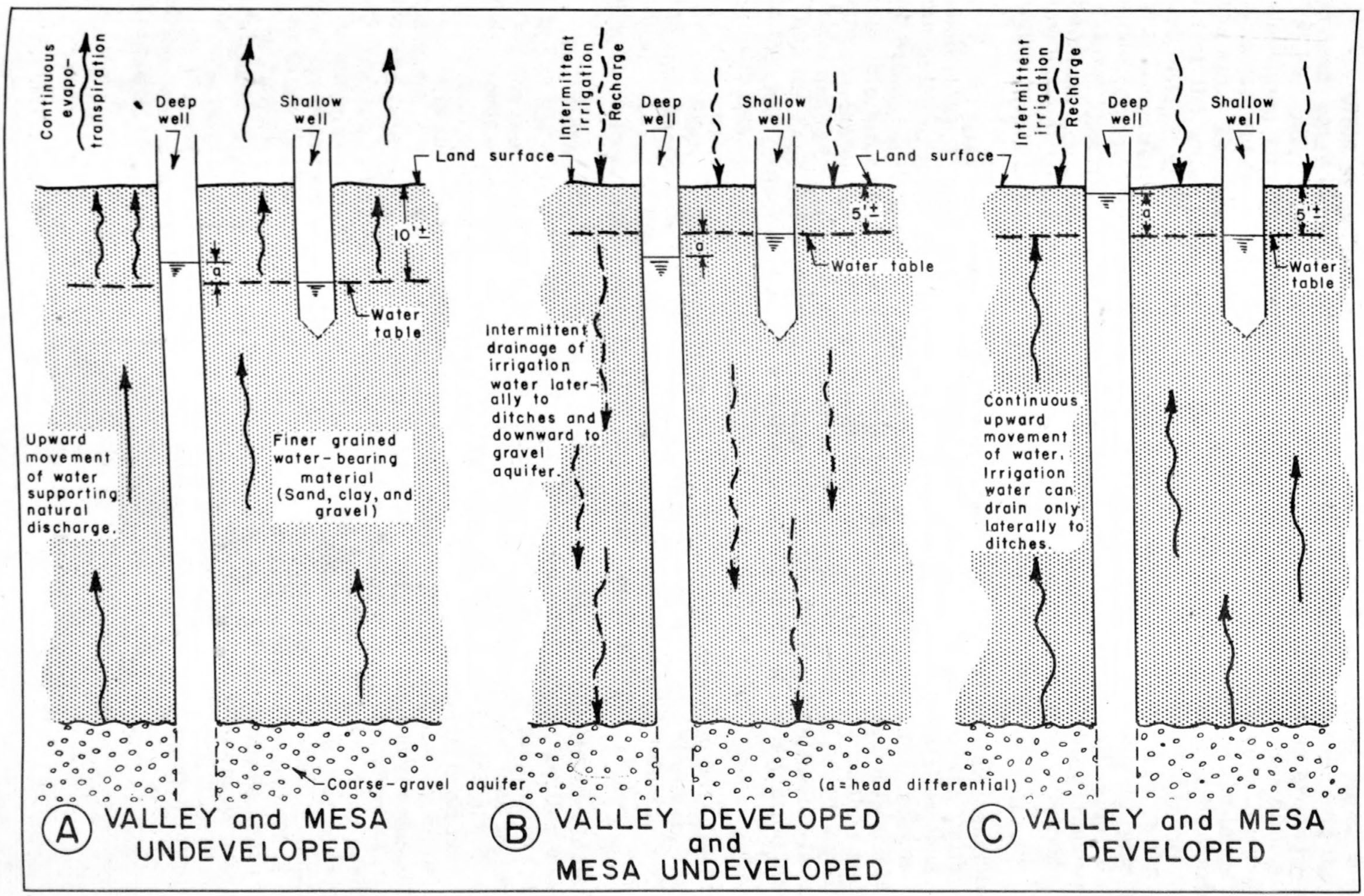

Figure 8.-- Possible vertical head relationships in the Big Bend area, Yuma Valley, Ariz.

What supported or continued to supply this constant drain on the ground-water reservoir? The bowed contours of the water table in the Valley, under natural conditions, (fig. 23, p. 74), indicating ground-water movement into discharge areas, should be recognized as a two-dimensional plan representation of flow that actually takes place in a three-dimensional system. Because ground-water discharge by evapotranspiration tends to lower the water table, upward as well as lateral components of flow are induced. It appears logical to conclude that the highly permeable coarse-gravel aquifer, occurring at or near sea level, is one local source that could continuously support the upward movement and discharge of ground water. Upward movement from the gravel aquifer to the overlying alluvium betokens some loss in head, and accordingly sketch A of figure 8 shows a low head differential "a" which could have been measured by observing water levels in an adjacent pair of deep and shallow wells.

Valley developed and Mesa undeveloped.-- What are the possible head relationships in the Big Bend area after development of the Valley but prior to 1922, with heavy intermittent irrigation of the Valley lands and no extensive irrigation on the Mesa? Sketch B in figure 8 indicates a possible situation. The water table is shown as only 5 feet below the land surface instead of the 10 feet shown in sketch A. This rise would have been accompanied by a much smaller rise in head in the coarse-gravel aquifer. Thus the head differential "a", exhibited by the difference in water levels in the pair of deep and shallow wells, is the reverse of the situation shown in sketch A.

When irrigation water is applied the water table may be raised to the land surface for short periods. There is opportunity, however, for the water applied to drain away both by lateral movement to the drainage ditches and by downward movement to the coarse-gravel aquifer.

Valley and Mesa developed.-- The electrical model has indicated (fig. 5) the manner in which increases in head in the gravel aquifer underlying the Mesa are dissipated, and the extent to which the dissipation process may reach out under the Valley. The model evidence shows head increases in the coarse-gravel aquifer underlying the Big Bend area, and sketch C (fig. 8) is therefore drawn to aid in exploring the consequent head relationships. The general position of the water table in sketch C is 5 feet below the land surface, as it was in sketch B. The head in the coarse-gravel aquifer, as indicated by the water level in the deep well, is inferred to be at some elevation higher than that shown in sketch B, and near but perhaps slightly below the land surface. The head differential "a" is now so large that there is little or no opportunity of overcoming it even when irrigation is in progress and the water table is raised to the land surface. Thus the irrigation water that drains away can do so only by lateral movement to the drainage ditches, and there is continuous upward movement of water from the coarse-gravel aquifer. A significant adverse effect, therefore, of the head increase in the gravel aquifer, is the loss of opportunity for the irrigation water to drain downward.

The Water Table

Where a zone of saturation exists, and its upper surface is not bounded by impermeable material, the water is said to occur under water-table conditions. The water table has been defined (Meinzer, 1923, p. 22) as the upper surface of the saturated zone._/ Points on the water table

_/ Meinzer's definition deliberately excludes the capillary zone in which the water is at less than atmospheric pressure, but it is recognized that in some ground-water studies attention must be given to the saturation that results from capillary rise of water in materials such as clay or silt, which contain very small pores. In irrigated areas where the ground water is shallow, these fine-grained materials may be saturated as much as several feet above the water levels in shallow wells, which constitute supercapillary openings, and those wells thus do not give a true indication of the agricultural difficulties that may be experienced.

are indicated by the levels at which water stands in tightly cased observation wells penetrating a short distance into and screened in, the saturated zone. A water-table contour map can give valuable information concerning water-table gradients — that is, changes in head with respect to flow distance, and general horizontal directions of ground-water movement. Although it is recognized that in the Yuma area, particularly in the Mesa section, irrigation practices cause intermittent recharge of the ground-water body, and that the recharge effects may not occur everywhere simultaneously or in equal magnitude, nevertheless valuable qualitative information can be gleaned from a series of water-table maps. Such a series is presented and discussed later in this report.

Preparation of a contour map depicting the water table generally requires a set of near-simultaneous water-level readings taken from an observation-well network embracing the area to be mapped. In the Valley section of the Yuma area, where the depth to water is generally about 5 feet, the observation wells are commonly constructed as a single 10- or 15-foot section of 1-1/2-inch pipe finished with a well point. The wells thus penetrate the ground-water body very shallowly and to a common depth, and as long as they are properly maintained they will yield data that correctly reflect water-table positions.

A number of conditions have conspired to complicate the mapping of the water table under the Mesa. Prior to the development and irrigation of any Mesa land the depth to water was about 95 feet. Accordingly, the first 97 observation wells were drilled by the Bureau of Reclamation to depths that averaged approximately 100 feet, thus insuring penetration a little below the pre-irrigation position of the water table. The Mesa portion of all water-table contour maps presented in a later section (figs. 23 to 40 inclusive) is based principally on data collected from wells that penetrate to this depth, because those wells are considered the best available indicators of the head changes that relate to lateral ground-water movement, with minimum distortion due to vertical components of movement.

Prior to 1955 there were no drainage canals or similar facilities on the Mesa, and hence all surplus irrigation water, not used by crops or otherwise evaporated or transpired, has moved downward as potential local recharge to the ground-water reservoir. Not all the water that started this downward journey has reached the water table because clay lenses have interrupted or at least greatly delayed the movement at many places throughout the Mesa area. However, a measure of the manner in which the water table has responded to the local recharge is shown in the hydrographs for two Mesa wells (the Smith and Griffin wells) that tap the underlying coarse-gravel aquifer (fig. 22). Unfortunately, these are virtually the only available records that document so convincingly the magnitude and rate of change in water-table position, and these records are from wells situated on the fringe of the irrigated area. The next best data, which may reflect correct orders of magnitude in the water-table response to irrigation development, are considered to be those collected from the "100-foot" wells penetrating slightly below the pre-irrigation water-table positions. Hydrographs for the Smith and Griffin wells, and for the "100-foot" wells (figs. 6, 20, and 21) show no signs of leveling off. Thus in the Mesa area it is not yet apparent what the eventual equilibrium or steady-state configuration of the water table may be. The Mesa portion of any water-table map that is drawn, therefore, should be viewed as an interim picture in a steady trend toward some new and as yet unrealized hydrologic balance. These interim water-table "pictures" have been sharpened to the maximum extent possible by the indicated selection of water-level data.

The Perched Water Table

By R. H. Brown and H. E. Skibitzke

Downward movement of surplus irrigation water to the original saturated zone is retarded in places by clay or silt lenses of relatively low permeability. As a particle of water moves vertically downward in response to gravitational forces, it attains a certain velocity which is dependent on the permeability of the porous media being traversed. The velocity would be constant if the water particle continued to move vertically downward and if the porous medium were homogenous. However, it is evident in the Mesa area that lenses of vastly different permeability are encountered. If one of these lenses has a low permeability, then the velocity at which a water particle can move through it under gravitational influence alone is proportionately low. Accordingly, a water particle arriving at the top of this layer will be slowed down and the particles following it will begin to pile up. In other words, pressure forces begin to build up until the water particle is forced through the less permeable lens or until some alternate flow path around the obstruction is found. This accumulation of water, because of retarded vertical movement, establishes what is here called a perched water table. The water in an observation well that happens to penetrate to a point slightly above the less permeable lens would rise to a height commensurate with the pressure buildup just discussed. Conversely, in an observation well penetrating to a point slightly below this lens there would be no water at all if there were opportunity for gravitational forces to move the water particles downward again without piling up.

The water-level data collected from some shallow wells that have been installed on the Mesa are apparently indicative of pressure buildups or perched water tables caused by scattered lenses of material of low permeability. Figure 9 shows the highest part of the ground-water mound underlying the Mesa, as it is indicated by readings taken in these shallow wells in December 1954. As shown in figure 6, vertical head differentials exceed 25 feet in some paired deep and shallow wells near the crest of the mound. The perched water table may thus be likened to a cap set over the highest part of the water-table mound east of the Big Bend area.

In the shallow well at grid location 8 S - 1/2 W the water level reached a high point within 3-1/2 feet of the land surface in September 1954. Thus the perched water table, rather than the main water table, is of concern to the farmers who are irrigating lands on the Mesa, because it is the perched water that creates the need for drainage. The Bureau of Reclamation, recognizing the impending drainage problem on the Mesa as early as 1950, drilled additional observation wells, collected supplemental data in the critical area, conducted pumping tests on wells in the shallow zone, and after analyzing the results concluded that the perched water table could not be lowered satisfactorily by pumping from wells. Subsequently a gravel-enveloped tile drainage system, installed in 1955 to drain about 420 acres, has produced a very satisfactory lowering of the perched water table in the critical area (Wadin, 1955).

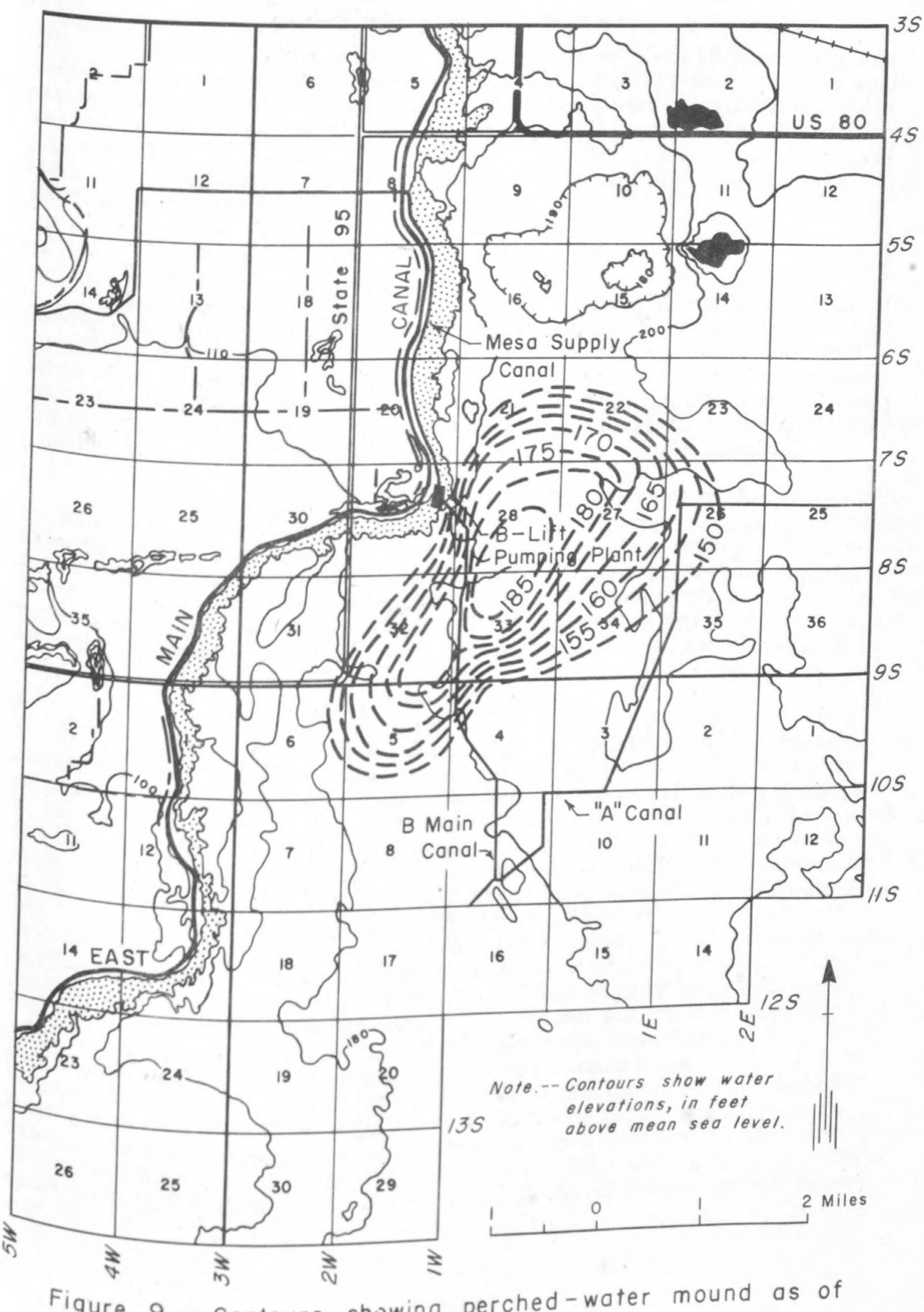

Figure 9.--Contours showing perched-water mound as of December 1954, Yuma Mesa, Ariz.

Irrigation Canals in Valley

Irrigation canals in the Valley are unlined, and because they are parts of a gravity distribution system, their water levels during the irrigation season are necessarily higher than the lands irrigated from them. Therefore the supply canals may be expected to contribute to the shallow ground water, and to raise the water table in their vicinities. The East Main Canal, by reason of its position along the west base of the Mesa, warrants separate consideration.

Central and West Main Canals

The effects upon the water table of the Central and West Main Canals and their numerous laterals are not easily discriminated from the effects of irrigation water taken from them and applied to the land. Some of the observation wells are close enough to the canals that their water levels appear to be affected by canal stages, but observation wells in the Valley generally are not spaced closely enough to define in detail the pattern of water-table contours as they cross the supply canals.

It is reported that the silt-laden water delivered to the Valley prior to 1935 tended to seal the supply canals, thus reducing seepage from them; also that the clearer water in subsequent years, along with periodic cleaning and maintenance, has removed this seal in places, permitting increased seepage from the canals. Although there is no proof of this either way, the reports seem plausible. There are also reports that seepage from canals has been reduced in local areas by spreading clay upon the canal bottom.

East Main Canal

The East Main Canal occupies a crucial position in this review, because it runs along the east edge of the Valley Division and along the west base of the Mesa. Thus along part of its course it is in a position to serve as an alternate source for the water that is claimed by the Valley Division to have flowed from the Mesa. Also, it flows along the west edge of the ground-water mound that is shown on every water-table map of the Mesa since 1947. In and near the Big Bend area the East Main Canal and the adjacent Gardenhire Drain are identified as lines of discharge that control the hydraulic gradient from this mound. The East Main Canal is thus in a position to intercept part of the flow of ground water from the Mesa. However, the canal must be recognized as only shallowly penetrating the vertical section through which ground water may move (fig. 5). Thus it can capture only a part of the flow moving past that section. The remainder can move on toward lower outlets, some to be captured in this instance in the Gardenhire Drain and some at discharge points beyond. During a period of several days early in January 1956, when the main canal system was dewatered, numerous sand boils formed in the bottom of the East Main Canal in the Big Bend area. This attests to water movement from the Mesa and also the canal's role as at least a partial interceptor.

Pumping from drainage well No. 8 (the Davis well) which is northwest of the East Main Canal, causes fluctuations in observation well 8 S - 2-1/2 W, east of the canal (fig. 10). The fact that pumping effects pass so readily beneath the canal is confirmatory evidence of the limited penetration of the canal into the zone that transmits ground water.

Personnel of the Yuma County Water Users' Association have made water-level observations along selected sections at right angles to the direction of the East Main Canal. South of the irrigated acreage on the Mesa the data show the canal to be fairly well isolated from the adjacent ground-water body. In the Big Bend area the data substantiate the canal's position in controlling the Valley end of the water-table surface that slopes downward to the west from the Mesa ground-water mound.

Drainage Wells in the Valley

The 9 drainage wells (fig. 13, p. 56), constructed in 1947 along the east side of the Valley in areas inadequately drained by canals, have provided valuable insight into the relative hydraulic characteristics of the coarse-gravel aquifer and the overlying finer grained material. All wells discharge into East Main Canal except well No. 6 which discharges into East Drain Extension. Individual wells have operated continuously for long periods at high rates of discharge and relatively low drawdowns. Recently the Davis well (drainage well No. 8 at 7-5/8 S - 2-3/4 W) was pumped continuously for more than 6 months at nearly 5,000 gpm (gallons per minute) with a drawdown exceeding 35 feet. This excellent performance supplements the geologic evidence of an extensive and highly permeable coarse-gravel aquifer underlying both Valley and Mesa.

Well Tests

In November and December 1955, recovery-test data were collected by the Yuma County Water Users' Association in a number of shallow observation wells (10 to 20 feet deep) near the Davis well. Most of the data were collected following shutdown of the Davis well, which had been pumped continuously into East Main Canal for 6 months. Out of the array of wells observed during the test, the locations of the 4 wells considered here are shown in figure 10. Plots of the recovery data, given in figure 11, show that at the end of the observation period the Davis well had recovered 36 feet. This is in marked contrast to the performance of the observation wells that penetrate only to shallow depths below the water table in the finer-grained material, in which recovery approached values ranging from 2 to 10 feet, depending on location with respect to the Davis well. The marked differences in recovery are partly related to the range in distances from pumped well to observation well, but of greater significance are the comparative slope and displacement along the time scale of the average curve that might be drawn through the recovery data plotted for each well (fig. 11). The curve for the Davis well is obviously quite flat. Contrast this with the three curves that are indicated by the shallow-well recovery data. All have similar form and are roughly parallel, with displacement along the time scale in accordance with distance from the Davis well. The much flatter slope of the curve for the Davis well, compared with the slopes of the other three curves indicates that the permeability of the coarse-gravel aquifer is many times greater than that of the overlying finer grained material.

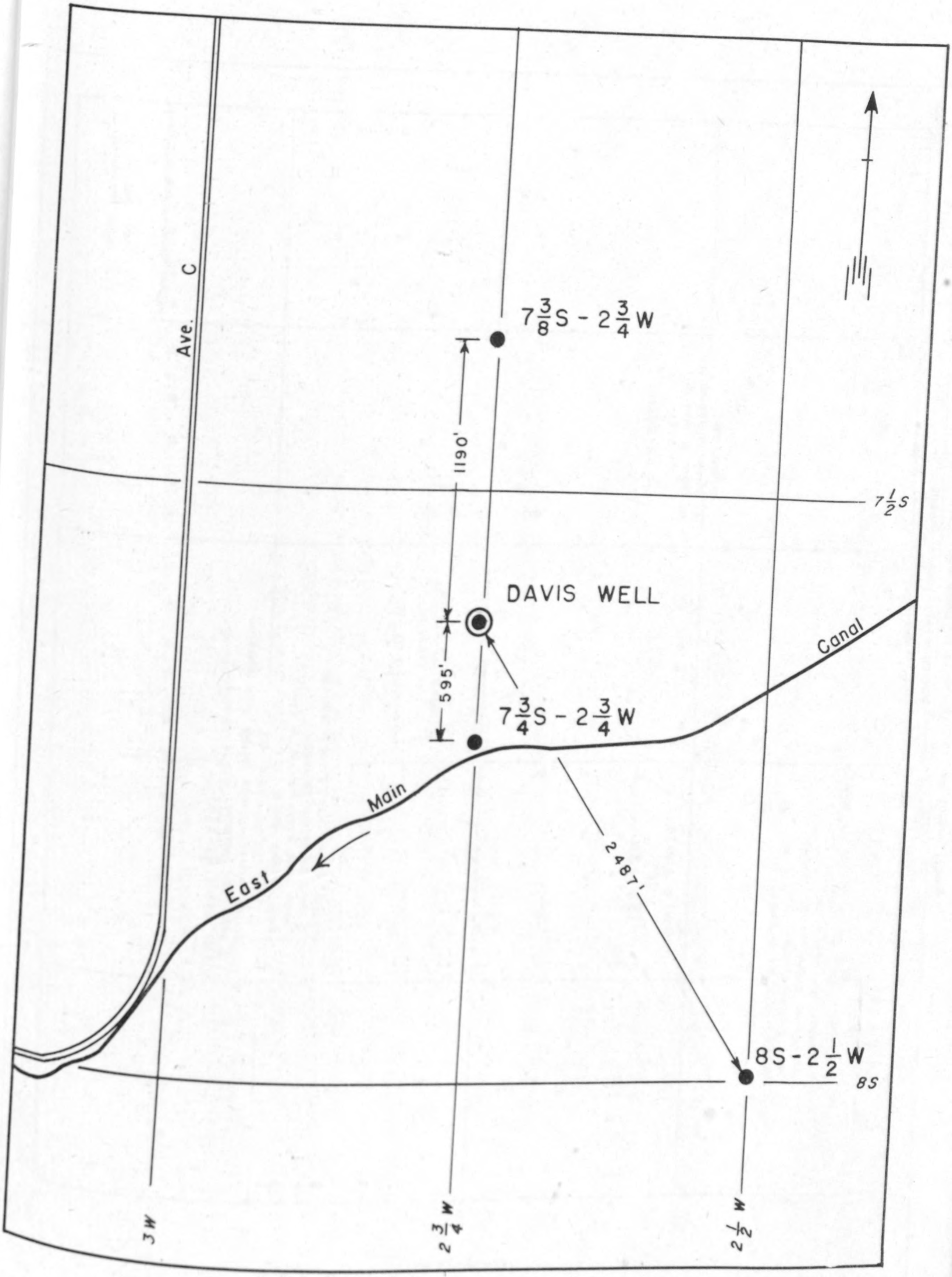

Figure 10.--Location of observation wells discussed in Davis well recovery test.

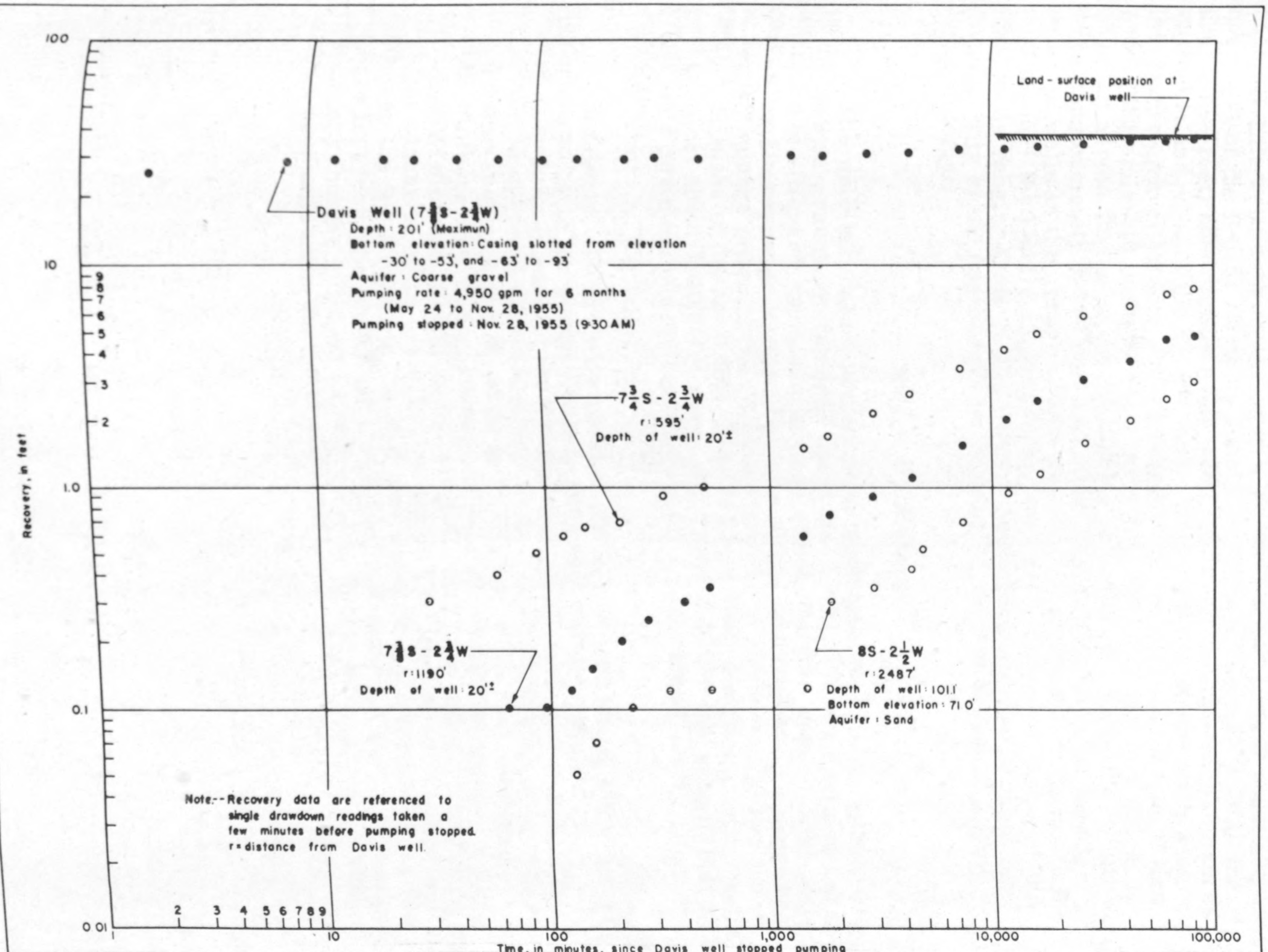

Figure 11.--Plot of recovery-test data, Davis well, Yuma Valley, Ariz.

Data are available also for a drawdown test made in September 1955 by the Yuma County Water Users' Association after redevelopment of the B-Lift well, tapping the coarse-gravel zone at a point about 40 yards northeast of the B-Lift Pumping Plant. Pairs of shallow (50+ feet) and deep (100+ feet) observation wells were constructed at selected distances southeast and west of the B-Lift well. None of these observation wells tap the coarse-gravel aquifer, but the deeper ones are within 50 feet of that zone. Water levels in these wells were observed throughout a 650-hour pumping period during which the discharge and drawdown of the B-Lift well were approximately 3,700 gpm and 20 feet respectively. The data for selected wells in the array, as given in figure 12, show drawdowns in the shallow (50+ feet) wells ranging from 1 to 3 feet, and in the deeper (100+ feet) wells ranging from 13 to 17 feet. Again the plotted data show high permeability of the coarse-gravel aquifer in contrast to that of the overlying material.

Extent of Influence

The well-test data that have been presented indicate large drawdown in the coarse-gravel aquifer near the pumped well, but low drawdown of the water table. Nevertheless, the area in which effective water-table lowering can occur, in response to operation of a single drainage well, approaches at least 2 square miles. The recovery test of the Davis well shows water-table responses of nearly 8 feet about 600 feet away from the pumped well; nearly 5 feet about 1,200 feet away; and 3 feet at 2,500 feet (figs. 10 and 11). Other data reviewed but not plotted suggest a response of nearly 1 foot at 3,200 feet.

Similarly, the drawdown test at the B-Lift well shows the greatest drawdown to be in the pumped well tapping the coarse-gravel aquifer; lesser drawdown in each of the intermediate (100+ feet) wells; and least drawdown in the shallowest (50+ feet) wells. The magnitudes of drawdown in the same sequence are about 20 feet, 16 feet, and 2 feet, with some variations therefrom in accordance with distance from the pumped well and relative elevations of the well bottoms. The area influenced by pumping does not appear to be as great as that affected by the Valley drainage wells. However, the B-Lift well is situated part way up the Mesa bluff only a few hundred feet from the East Main Canal and Gardenhire Drain. The pumping effects may thus be more effectively masked than in other areas because of induced recharge from the canal and drain.

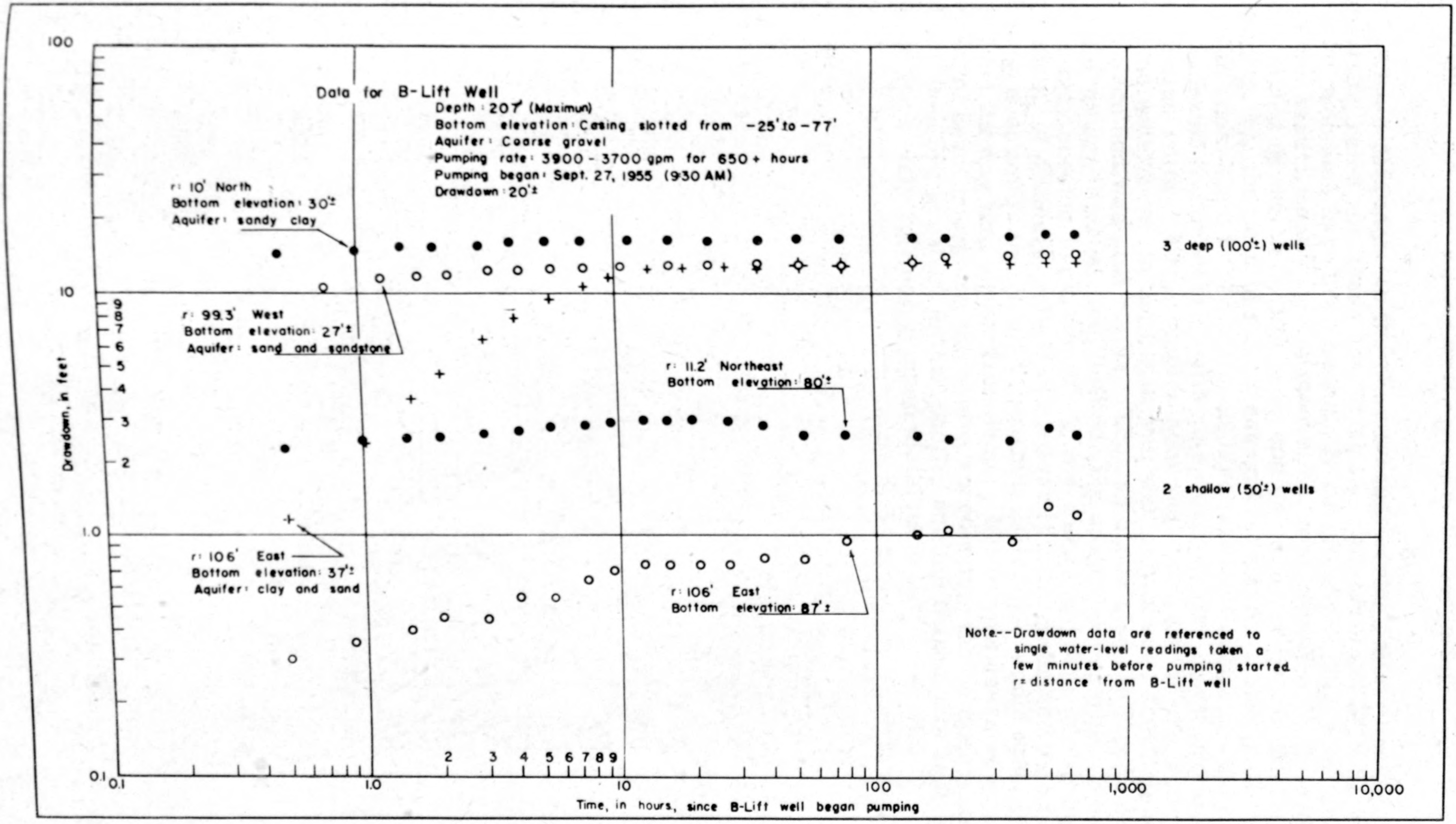

Figure 12.--Plot of drawdown-test data, B-Lift well, Yuma Valley, Ariz.

These data indicate the effectiveness of the Valley drainage wells in providing relief for areas bordering the East Main Canal, where drainage problems have been especially perplexing. They also tend to verify the assumptions made in theoretical consideration of the hydrology. As postulated in sketch C, figure 8, and as indicated by the electrical analog (fig. 5), the head in the coarse-gravel aquifer under present conditions is considered to be high enough so that continuous upward movement of ground water occurs, with no opportunity for downward movement of irrigation water. For example, near the end of the 58-day recovery period the water level in the Davis well was only about 2 feet below the land surface and was still rising. Thus an undue load is placed on the gravity drainage ditches, and, indeed, the upward pressures on the drain bottoms may account in part for their instability and bank-sloughing tendencies. A drainage well drawing heavily and continuously on the coarse-gravel aquifer may not be pumping water that would otherwise have found its way into the surface drains, but it does cause substantial lowering of head throughout the region surrounding the pumped well. The head declines are greatest in the specific aquifer tapped, but lesser declines occur in the overlying finer grained material.

HYDROLOGIC HISTORY

History of Construction and Development

Although agricultural pursuits are by no means new to the Yuma area, having been practiced by various Indian tribes long before the advent of the white man, the present highly developed agricultural economy is most directly related to the Reclamation Act of June 17, 1902. Passage of this act commemorates assumption of responsibility by the Federal Government for reclaiming the arid lands of the West. The Congress, in 1904, authorized the Yuma Project, thereby sponsoring the first Federal irrigation development on the main stem of the Colorado River, and providing the newly created Reclamation Service with one of its first irrigation projects.

Yuma Valley

Encompassed by the Yuma Project are 68,000 acres of the flood plain of the Colorado River at and near Yuma, of which 53,000 acres in Arizona constitute the Valley Division, extending from Yuma southward to the Mexican border. Some lands within the Valley Division had been irrigated for several years before the Yuma Project was authorized. By 1904 more than 10,000 acre-feet of water was being diverted from the Colorado River by pumps and gravity, and distributed through more than 50 miles of canals. However the supply was dependent on river stage, and therefore erratic.

The original diversion structure for the Yuma Project was Laguna Dam, located on the Colorado River about 10 airline miles northeast of Yuma. Design of the dam was patterned after similar weir-type structures that had found successful use in India. Construction began in 1905 and was completed in 1909, but the Valley Division did not receive water from Laguna Dam until the Colorado River siphon was completed in 1912. During these construction years the Bureau of Reclamation delivered water to the Valley by pumping about 50,000 acre-feet a year from the river. First water deliveries to the Valley Division, through the Colorado River siphon, occurred on July 1, 1912. Water diverted at Laguna Dam, on the California side, flowed by gravity about 13 miles through the Yuma Main Canal, crossing into Arizona at Yuma about 1/4 mile downstream from the present railroad bridge. Since that date, water service to farm laterals in the Valley has been via three supply canals, for the most part unlined, designated the East Main, Central, and West Main Canals (pl. 1). Water in excess of irrigation needs has been discharged or wasted from the Valley Division at various times during the periods indicated as follows:

Location of gaging station	Period of wastage	First year annual wastage totals are available
East Main Canal across border into Mexico	May 1914 to date	1924
West Main Canal across border into Mexico	May 1915 to 1944	1924
West Main Canal into Colorado River at 21-mile Wasteway	March 1939 to date	1939
West Main Canal into Colorado River at 11-mile Wasteway	1913+ to date	1924
Cooper Lateral into Colorado River at Cooper Wasteway	March 1927 to date	1934

Early in the history of the Valley Division the possibility of drainage problems was foreseen, and 22 shallow wells were constructed in 1911 (fig. 23), in order to make periodic observations of water level. During subsequent years the network was expanded until at present periodic water-level readings are taken at monthly intervals at more than 350 wells and staff gages. Construction of gravity drainage ditches began in 1916; annual progress as documented by Sweet (1952) is shown in figure 13. This interconnecting system was designed wherever possible to follow the natural sloughs. Iakisch and Sweet (1948, p. 49) call attention to the need for maintaining the water table 4 feet or more below the land surface if conditions satisfactory to agriculture are to be realized. In general the drains were extended into local areas as the water table approached or rose above this critical position. Water collected in the open drains flows ultimately into the Main Drain and southward to the Arizona-Mexican border, where the Boundary Pumping Plant, completed and put into operation in July 1918, lifts it about 12 to 15 feet to discharge into Mexico.

Prior to the closure of Hoover Dam in February 1935, the levees and canal system of the Valley Division were repeatedly threatened by Colorado River floods. In addition to the virtual elimination of flood threats, the completion of Hoover Dam decreased the sediment content of the water supplied for irrigation. The magnitude of the change can be appreciated by noting that in the period 1911 through 1934 the average annual sediment load of the Colorado River at Yuma was 180 million tons, whereas in the period 1936-42 it was less than 13 million tons (U. S. Dept. Interior, 1946, p. 163). Maintenance of the canal system has been facilitated by the decline in silt load, although undoubtedly seepage losses have increased wherever the relatively silt-free water has eroded deposits that had previously constituted more or less effective canal lining or seal.

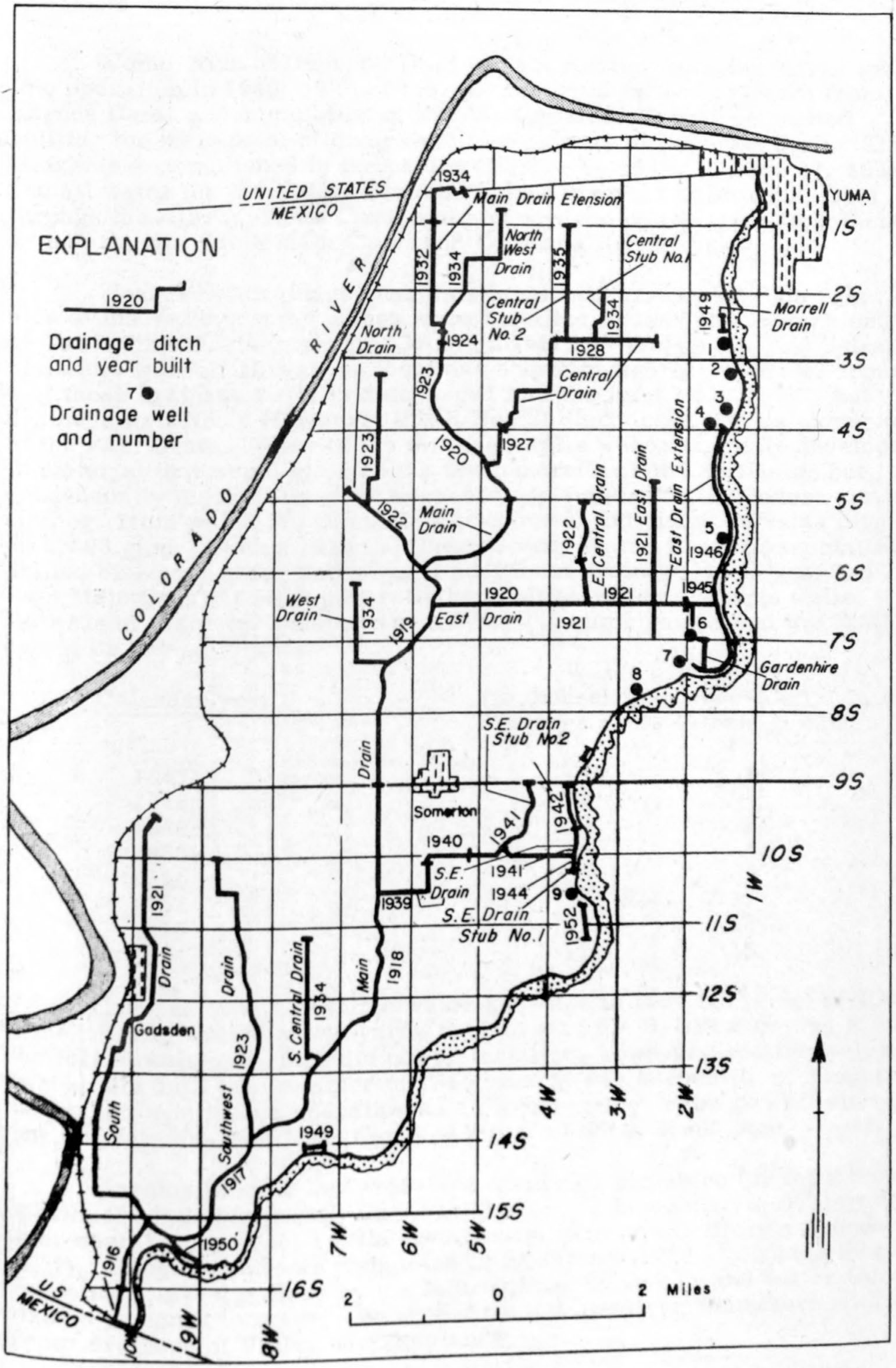

Figure 13.-- Location of drainage canals and drainage wells, Yuma Valley, Ariz.

Completion of Imperial Dam and its related desilting works (put into operation in 1940) on the Colorado River, 5 miles upstream from Laguna Dam, and completion of the All American Canal, permitted shifting the main point of diversion from Laguna to Imperial Dam. The shift was accomplished in the period October 8, 1940, to June 27, 1945, and all water for the Valley Division is now diverted at Imperial Dam through the All American Canal and siphon-drop power plant, and thence, as before, via Yuma Main Canal and Colorado River siphon.

Because of drainage problems in certain areas along the east side of the Valley, sump pumps were installed in 1947 at the south end of Gardenhire Drain (near grid location 7-1/2 S - 1-3/4 W), and 9 drainage wells were drilled at the locations shown in figure 13. Water from 8 of these drainage wells is discharged into the East Main Canal, but drainage well No. 6 (formerly USBR No. 2) discharges into an extension of the East Drain. Some of the drainage wells were originally developed in material that would yield only a few hundred gallons a minute, but subsequently these wells were deepened and finished in the coarse-gravel aquifer, from which the pumps now produce at individual rates as high as 5,000 gpm. During 1955 the Yuma County Water Users' Association drilled or equipped for use several additional drainage wells near the East Main Canal at sites generally between the older drainage wells. Records of the water pumped annually by the sump pumps and the drainage wells are as follows:

Calendar year	Water pumped (in thousands of acre-feet)	
	Drainage wells	Drain sumps
1947	4	8
1948	8	7
1949	9	6
1950	8	6
1951	8	6
1952	8	11
1953	9	13
1954	11	15

Concern over a possible water shortage in 1934 led to the drilling of the "B-Lift" well about 40 yards northeast of the B-Lift Pumping Plant. The feared water shortage did not materialize, however, and the well remained idle until late summer of 1955 when it was deepened, redeveloped, and put into continuous operation as an intercepting drainage well discharging into the East Main Canal at a rate of about 3,600 gpm.

Morelos Dam, a low weir-type diversion structure for the Alamo (previously called Imperial) Canal in Mexico, is located on the Colorado River near Yuma, about 1 mile downstream from the California boundary (pl. 1). Construction was completed in September 1950, following thorough preliminary investigations by the International Boundary and Water Commission designed to make certain that the dam would not interfere with the proper drainage of Valley Division lands.

The Valley Division irrigation and drainage works were constructed, operated, and maintained by the Bureau of Reclamation until July 1, 1951. At that time operation and maintenance of all Valley Division facilities were turned over to the Yuma County Water Users' Association, which still retains that responsibility.

The records of development of irrigated acreage in the Valley Division, the net water imported into the Valley, and drainage water pumped out of the Valley at the Boundary Pumping Plant are summarized in table 1.

The figures shown in table 1 deserve some explanation, because they appear to be more rounded and less precise than those commonly quoted in the Yuma area. This rounding has been done because the techniques of measurement are not precise enough to justify more exact figures. The explanation may be developed as follows: Consider the streamflow data given by Sweet (1952, p. 40) for the calendar year 1951, relating solely to determining the net amount of surface water brought into the Valley Division. Note that this involves taking the discharge as reported for the Colorado River siphon and deducting from it the total water pumped or wasted at 5 other stations. The daily discharge record for the Colorado River siphon is rated as excellent, which means that the error of any single determination is adjudged to be 5 percent or less. The precision of the annual discharge figure, which represents the combination of 365 daily discharge figures, would be exceedingly difficult to compute and would require detailed knowledge of such things as the number of individual stream-gaging measurements actually made, a study of the current meter used for each measurement, and knowledge of the individual techniques and characteristics of each hydrographer who made a measurement. It appears reasonable to assume, for the sake of argument, that the annual discharge figure has a precision of ± 1 percent. This means that the discharge through the Colorado River siphon in 1951 is somewhere in the range 368,653 to 376,099 acre-feet. In other words, all but the first two digits in the total are in doubt. Accordingly, the annual figure for 1951 is rounded and used as 370,000 acre-feet.

In identical fashion the discharge records for Cooper Wasteway, 11-mile Wasteway, 21-mile Wasteway, and East Main Canal at Arizona-Sonora boundary were examined. By assuming that the daily discharge records for these stations may be considered accurate within 5 percent, 10 percent, 10 percent, and 5 percent, respectively, and that the annual discharge values, in the same order, have precisions of 1 percent, 2 percent, 2 percent, and 1 percent, the following analysis can be made:

Table 1 .--Valley and Mesa Divisions — yearly summary of acreage irrigated, of net water imported for farm use, and of drainage water pumped a/

Calendar year	Valley Division			Yuma Auxiliary Project	
	Acreage irri-gated	Net water imported	Drain water pumped at Boundary Plant	Acreage irri-gated	Water pumped or diverted
1909	7,000	49			
1910	8,000	44			
11	7,000	48			
12	10,000	b/			
13					
14	19,000				
1915	21,500				
16	22,500				
17	28,500				
18			c/		
19			15		
20			20		
1921	41,500		30		
22	42,500		35	200	1
23	42,000		45	650	7
24	41,000	190	55	640	5
25	43,500	190	50	800	5
1926	47,500	180	45	720	3
27	42,000	210d/	50	1,050	4
28	43,000	160d/	55	1,250	6
29	43,500	130d/	50	1,350	7
30	43,500	170d/	45	1,400	9
1931	43,000	230d/	35	1,450	8
32	38,500	210d/	35	1,450	8
33	41,000	230d/	30	1,400	8
34	41,500	220d/	25	1,350	10
35	44,500	210	25	1,200	10
1936	44,000	270	40	1,200	10
37	43,500	270	50	1,250	10
38	44,000	250	65	1,250	10
39	44,500	250	70	1,500	15
40	44,000	260	65	1,450	15

Continued next page

Table 1 .--Valley and Mesa Divisions — yearly summary of acreage irrigated of net water imported for farm use, and of drainage water pumped a/ -- continued

Calendar year	Valley Division			Yuma auxiliary proj.		Mesa Division	
	Acreage irrigated	Net water imported	Drain water pumped at Boundary Plant	Acreage irrigated	Water pumped or diverted	Acreage irrigated	Net water pumped
1941	46,000	230	70	1,500	15		
42	46,000	230	70	1,500	15		
43	46,000	250	70	1,650	20		e/
44	45,500	240	65	1,550	15	1,000	T5
45	45,500	240	55	1,600	20	4,000	55
1946	46,000	270	70	2,100	25	5,500	110
47	45,500	270	90	2,000	35	6,000	120
48	46,500	270	85	2,050	35	6,500	120
49	46,500	270	95	2,100	35	6,500	100
50	47,500	280	90	2,350	30	7,000	105
1951	46,000	290	90	2,150	30	8,000	140
52	47,500	300	110	2,250	35	10,500	175
53	47,000	290	110	2,100	35f/	14,000	195
54	45,500	290	105	2,250	35	14,500	235
55	51,500		105	2,500	35	14,500	215

a/ Figures for water imported or pumped are given in thousands of acre feet. Data are taken from USBR yearly Project History reports, the Sweet (1952) report, operating reports of the Yuma County Water Users' Association, and USGS Water-Supply Papers 918 and 1313.

b/ Colorado River siphon put into service supplying water to Valley Division as of July 1, 1912. Related discharge records, required to determine net water imported, unavailable prior to 1924.

c/ Operation began in July 1918.

d/ Estimated by the writers, using published fragmentary discharge records. Errors attributable to estimation judged to be within ± 10%.

e/ Water first pumped into Mesa canals, largely for construction use, Nov. 23, 1943.

f/ B-Lift Pumping Plant, discontinued as of July 6, 1953, delivered 18,000 acre-feet of total.

Location of gaging station	Precision of annual discharge (percent)	Probable range of annual discharge (acre-feet)	Rounded or usable value of annual discharge (acre-feet)
Cooper Wasteway	±1	3,119 to 3,813	3,500
11-mile Wasteway	±2	24,739 to 25,749	25,000
21-mile Wasteway	±2	6,395 to 6,655	6,500
East Main Canal at Mexican border	±1	13,267 to 13,535	13,000

If the four rounded values of annual discharge given above are deducted from the similar value for annual discharge through the Colorado River siphon the result is 322,000 acre-feet. The error inherent in this result is obtained by determining the square root of the sum of the squares of the products of the five individual precision percentages, multiplied by the respective rounded values for annual discharge. The error computed in this manner is 4,000 acre-feet and thus the calculated total of 322,000 acre-feet should be rounded and used as 320,000 acre-feet.

Two discharge quantities must be subtracted from this total in order to determine the difference between net surface water imported into and outflow from the Valley. Both these quantities involve pumping-plant discharge, which in turn involves such elements as pump characteristics, operating head, and operating time. Although pumping-plant performance is rated from time to time, it is likely that the greater part of the error always present in any discharge determination is of the determinate rather than the random type. This could well have the effect of carrying into the annual discharge values for the two pumping plants percentages of error almost as large as the percent error believed to be inherent in any single discharge computation. For either the Boundary Pumping Plant or the B-Lift Pumping Plant, if it is assumed that a single discharge computation is accurate to within 10 percent, it is not unreasonable to expect that the annual discharge has the same order of accuracy. The discharge for the B-Lift Plant, then, should be rounded and used as 30,000 acre-feet and for the Boundary Plant the usable value is 90,000 acre-feet. Subtracting these two quantities from 320,000 leaves 200,000 acre-feet as the difference between surface inflow to and outflow from the Valley Division in 1951. The first two digits of this figure are significant, which indicates that the difference is determined only to the nearest 10,000 acre-feet. Similar reasoning is the basis for determining the significant figures of the other quantities shown in the table.

Yuma Mesa

Early in the century private enterprise, intrigued by the potentialities for irrigation development on the Yuma Mesa, put into production a limited acreage of citrus groves along the west side of the Mesa in an area that is now the southwestern residential section of Yuma. By Congressional Act of January 25, 1917, the Yuma Mesa Auxiliary Project was authorized, which envisioned bringing 45,000 acres ultimately under irrigation. Initial construction was directed toward that portion termed "Part I, Unit B," containing about 6,300 irrigable acres along the west side of the Mesa. Inasmuch as the northern boundary of Unit B was 8 miles south of the Colorado River siphon near the so-called Big Bend in the East Main Canal, that canal became the logical supply source for the necessary irrigation water. The diversion point chosen was at the junction of the East Main and Central Canals, and a new unlined 3-mile supply canal was dug southward therefrom, parallel to and several hundred feet east of the East Main Canal. At the southern terminus of the new canal, the B-Lift Pumping Plant (pl. 1) was constructed to lift water about 72 feet up to the Mesa through a pressure main at a design rate of 106 cubic feet per second. Distribution to the system of laterals on the Mesa was via the unlined Unit B Main Canal. Construction was completed in time to make water available by May 1, 1922, but little irrigation took place on the Mesa until 1923. Records of the development of irrigated acreage under the Yuma Auxiliary Project and the water pumped for that acreage are given in table 1.

Construction work on the Yuma Mesa Division of the Gila Project began in June 1936. Water diverted at Imperial Dam now flows 21 miles through the Gila Gravity Main Canal to Pumping Plant No. 1 (pl. 1), completed in October 1941, located near the Fortuna siding of the Southern Pacific Railroad about 9 miles east of Yuma and 1 mile north of U. S. Highway 80. The pumping plant is designed to raise the water at a maximum rate of 700 cfs (cubic feet per second), from an elevation of 165 feet in the Gila Canal to an elevation of 216 feet in the lined gravity-supply-canal system serving the Mesa. Some water was available through this system for land leveling and other predevelopment work in 1944, and by the end of 1947 about 5,900 acres of Mesa Division lands were being irrigated. Development in subsequent years may be traced through the data given in table 1.

Although the desirability of obtaining periodic water-level observations from a network of observation wells on the Mesa was recognized early in the construction period, the installation of such wells was not as simple a matter as it had been in the Valley Division. In the few private wells drilled on the Mesa during the pre-irrigation era, the depth to water was of the order of 100 feet, and observation-well construction on any large scale thus would have entailed considerable expense and the use of conventional drilling equipment. In December 1946, however, work began on drilling 1-1/2 inch observation wells averaging 100 feet in depth; 3 were completed in 1946 and 94 in 1947. Monthly water-level readings began as soon as wells were completed, and in subsequent years new wells were added to the network so that as of the end of 1955 readings were being taken in nearly 200 observation wells. Beginning in 1952 a number of new wells were installed alongside the old, in areas where the greatest buildup in ground-water levels had been observed, using 3/8-inch open-end pipe driven and jetted to depths just below the top of the first zone of saturation encountered. In the latter half of 1955 about 31,000 linear feet of tile drain was installed in sections 28 and 33, T. 9 S., R. 23 W. Two sump pumps lift all water collected by the tile drains and discharge it into a lined lateral.

Completion of the "A" Canal southwestward to join with the distribution system for the Yuma Auxiliary Project made it possible to deliver water for that project via the Mesa Division. Beginning in July 1953, the Auxiliary Project has been supplied in this manner and the B-Lift Pumping Plant has been shut down and dismantled.

History of Changes in Ground-Water Occurrence

Many of the features of construction and development, as outlined in the preceding section, have left their impress upon the occurrence and movement of ground water in the Yuma area. Many natural phenomena during the past half century — as, for example, floods of the Colorado River, droughts, and even an earthquake in 1940 — also have had their effects. The periodic measurements of water levels in wells, begun by the Bureau of Reclamation in 1911, and increasing in volume in recent years, provide the basis for describing the historic changes in ground water.

The data are shown graphically in two ways: by hydrographs for selected wells, which show the progressive changes at a single point (figs. 14 to 18 inclusive; also figs. 6, 20, 21, and 22); and by maps prepared for selected years, which show the form and position of the water table in the Yuma area (figs. 23 to 40 inclusive). Key maps showing location of wells and staff gages for which hydrographs are given appear on figs. 7 and 19. The hydrographs and maps are presented at small scale intentionally — partly for convenience in handling, but chiefly in order to present major trends and regional patterns without obfuscation by local detail. The maps are drawn, whenever practicable, for December of the year chosen, partly because in years prior to regulation by Hoover Dam the Colorado River stages were most stable at year end, and partly because irrigation is near minimum at the year end. The graphs and maps are interpreted on the basis of the geologic and hydrologic conditions as developed in preceding sections of this report.

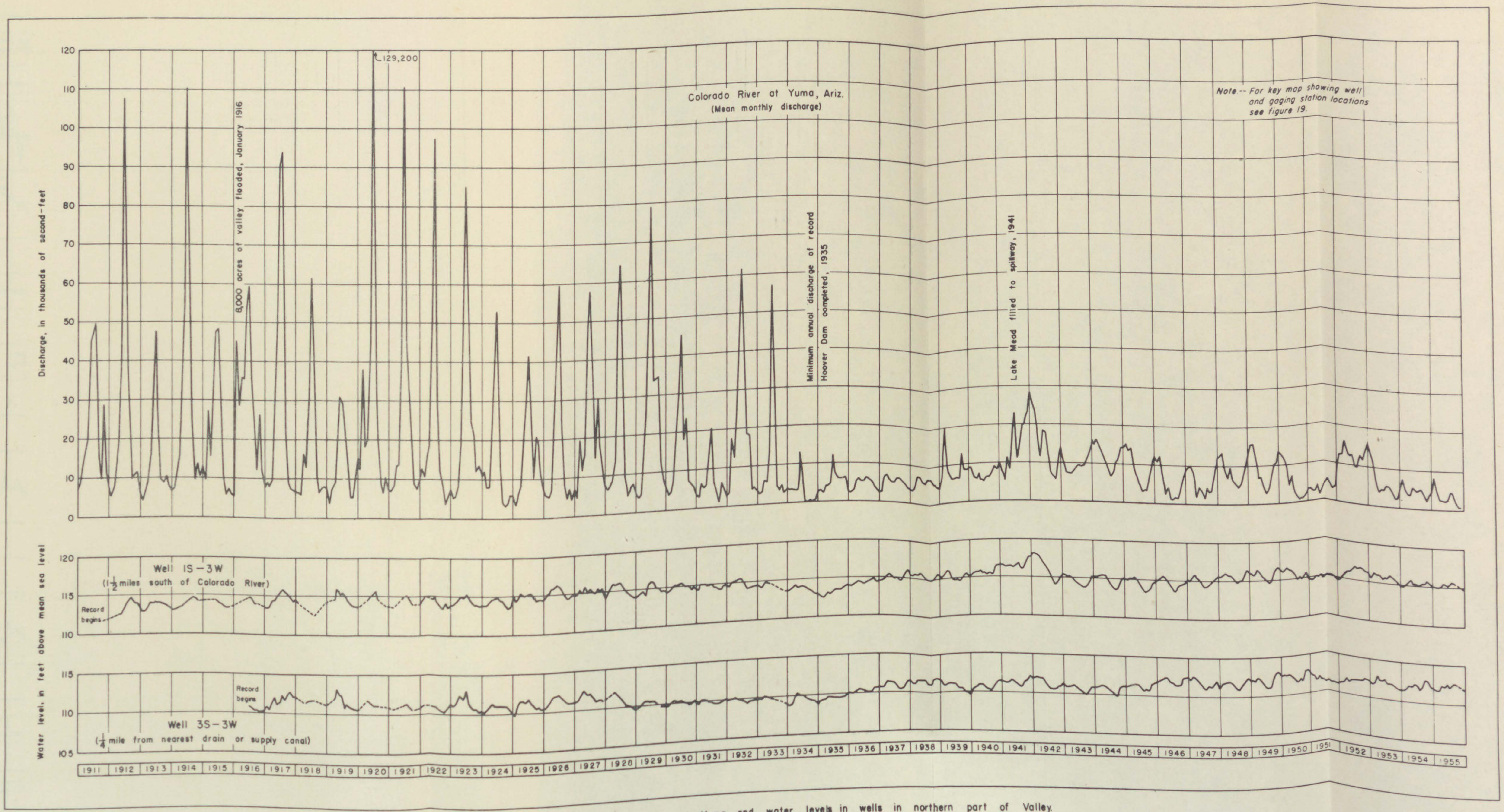

Figure 14.-- Discharge of Colorado River at Yuma, and water levels in wells in northern part of Valley.

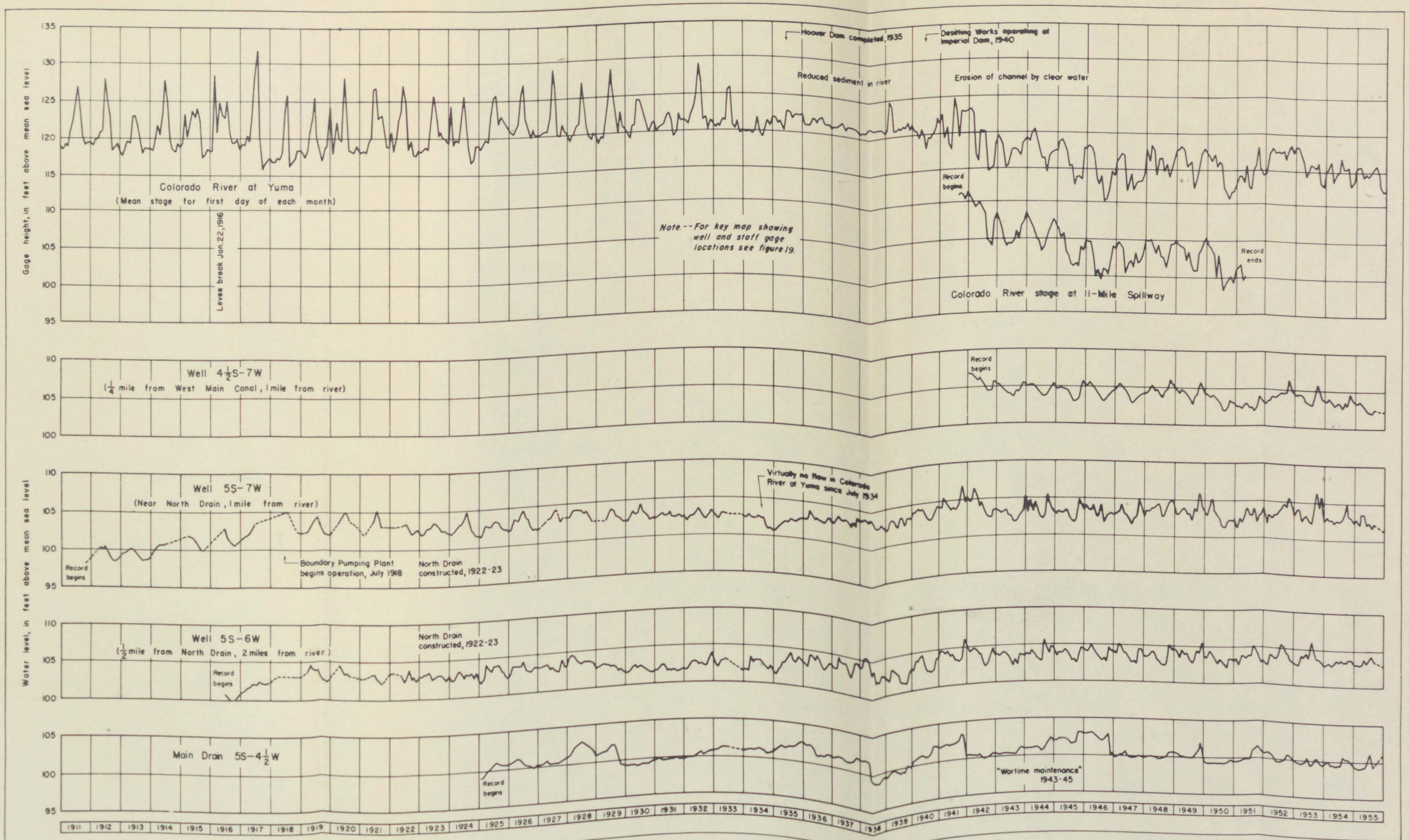

Figure 15.--Stage records and water levels in wells along Valley section between Colorado River and Main Drain.

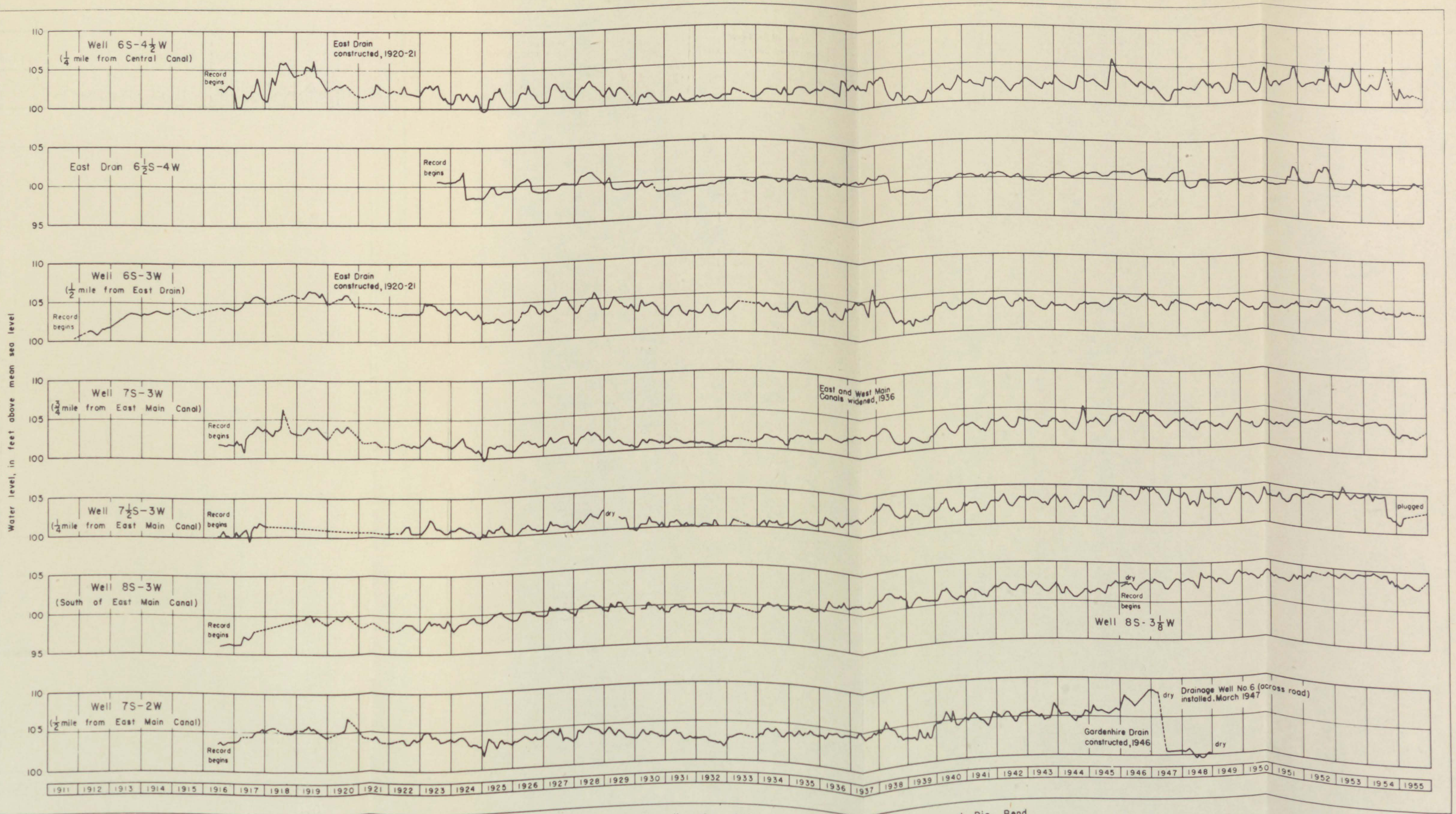

Figure 16. -- Drain stages and water levels in wells along Valley section between Main Drain and Big Bend.

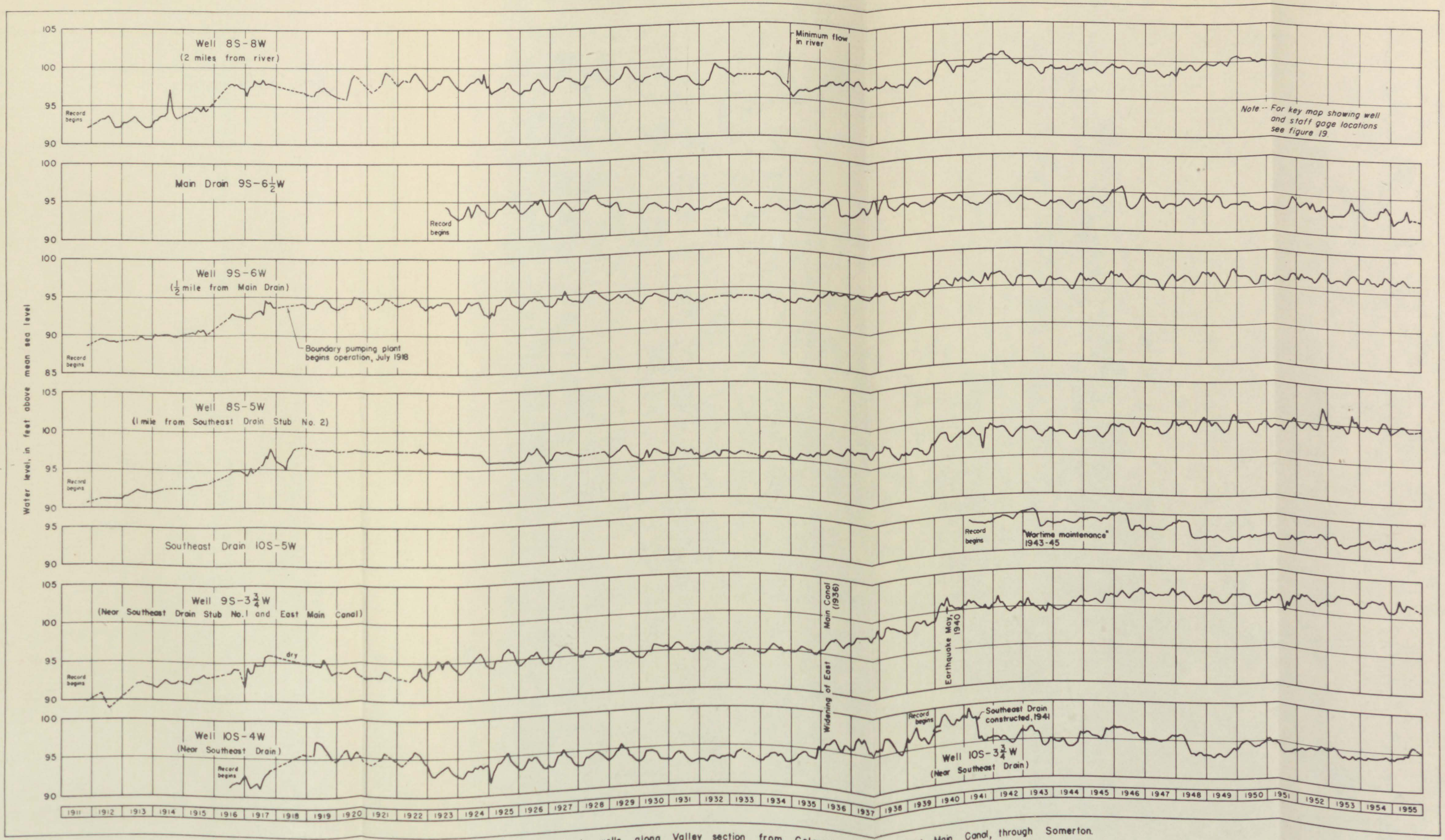

Figure 17. -- Drain stages and water levels in wells along Valley section from Colorado River to East Main Canal, through Somerton.

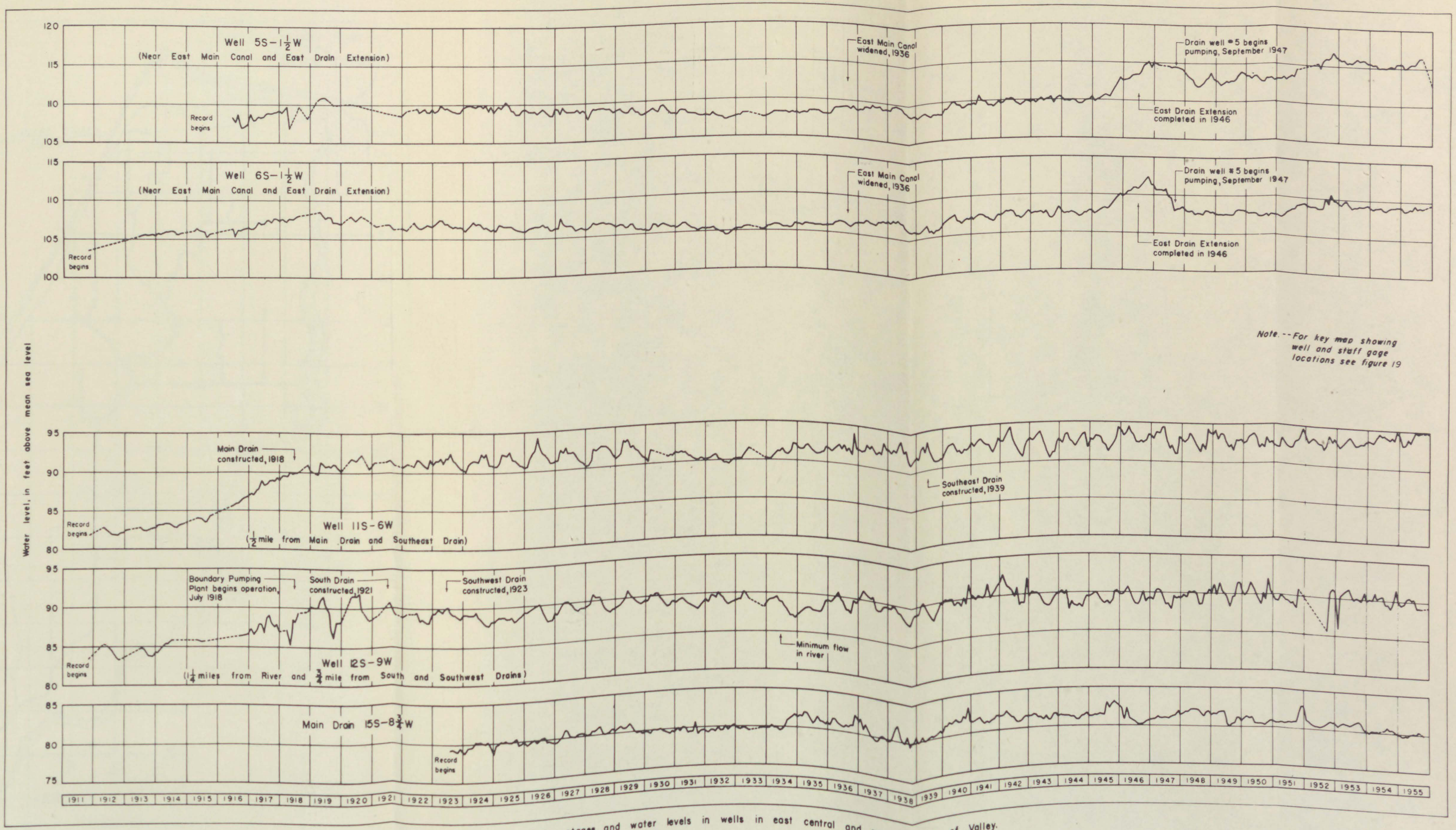

Figure 18. -- Drain stages and water levels in wells in east central and southern parts of Valley.

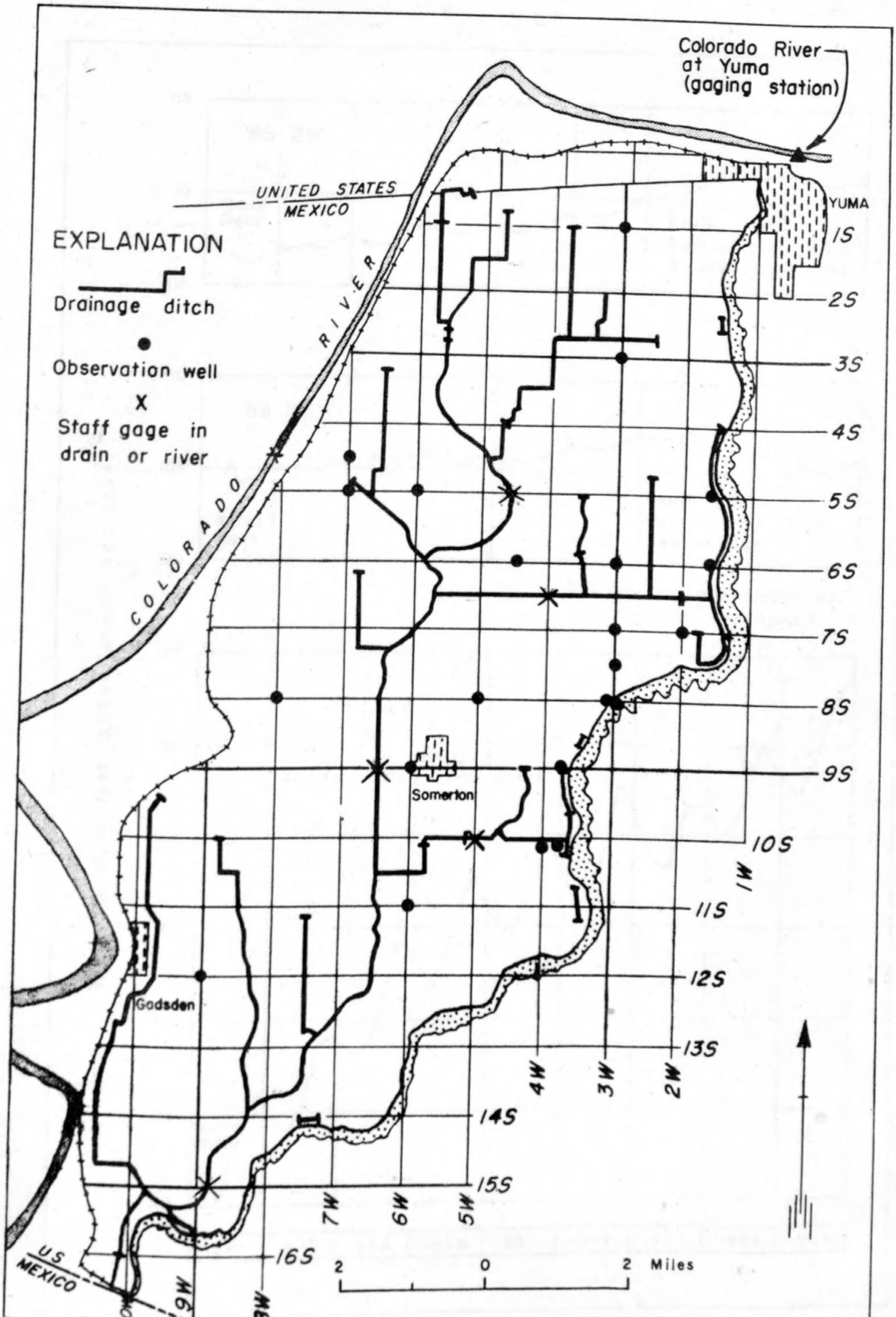

Figure 19.-- Location of Yuma Valley wells and staff gages for which hydrographs are given in this report.

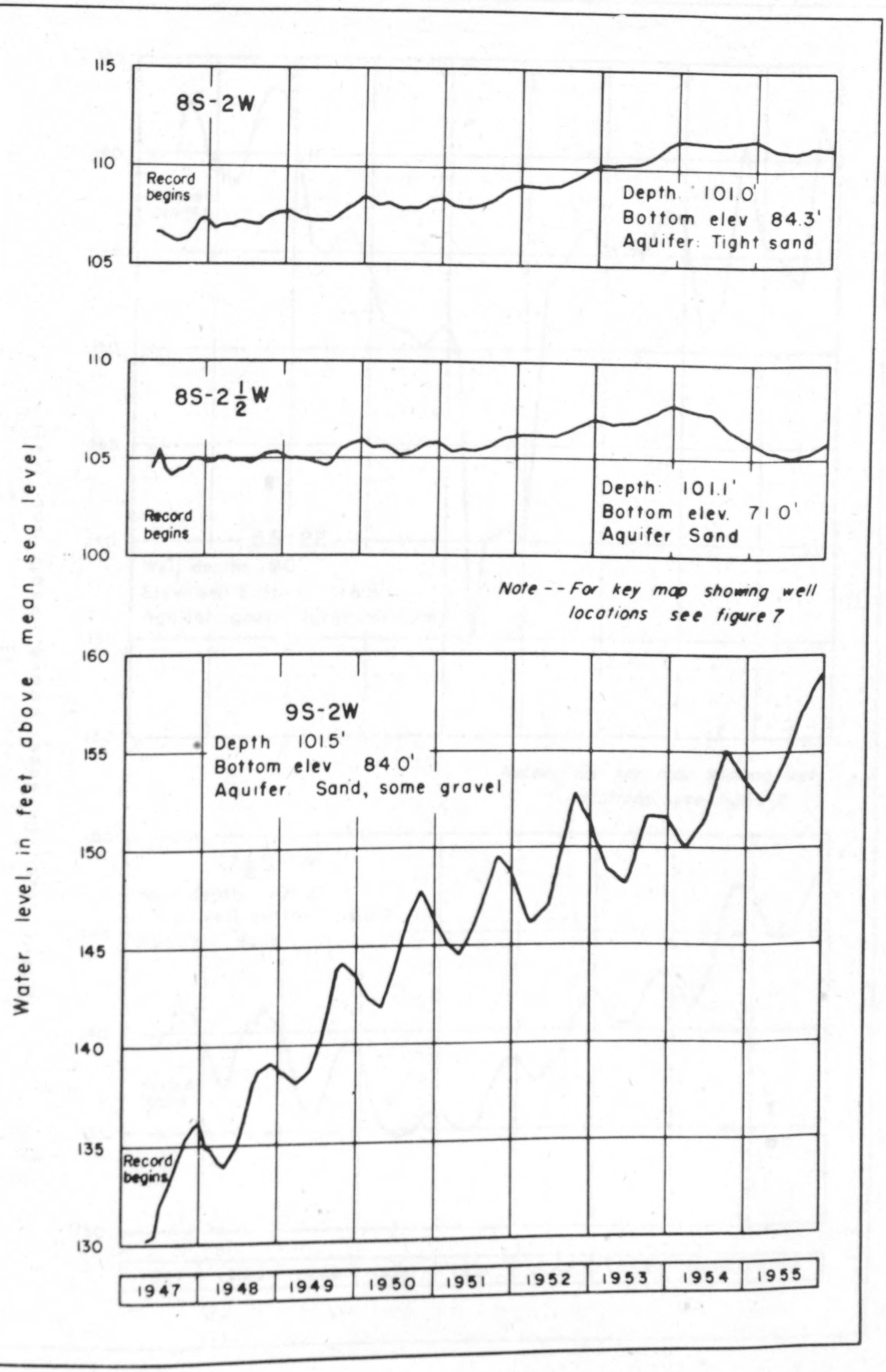

Figure 20. -- Water levels in selected observation wells, Yuma Mesa, Ariz.

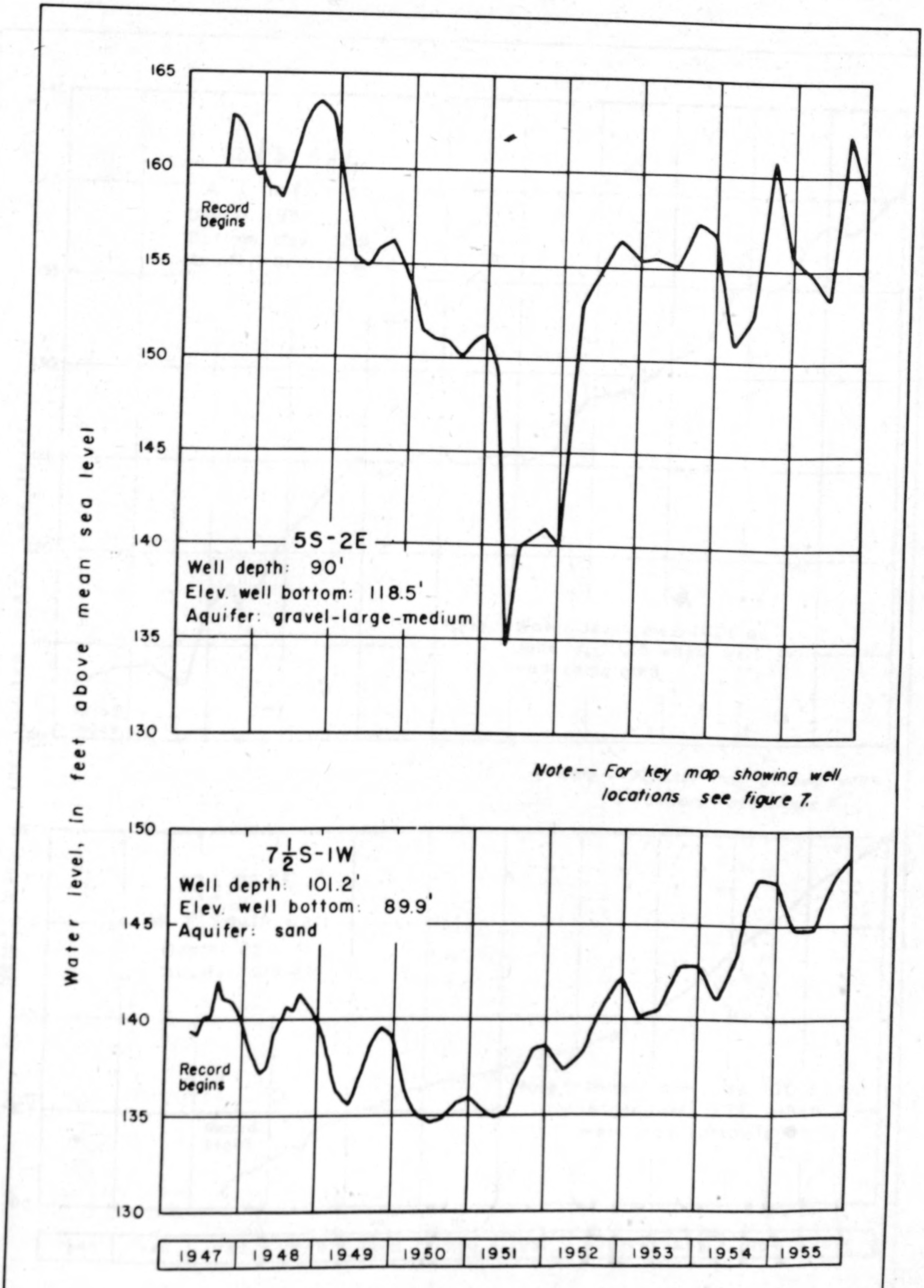

Figure 21. --Water levels in selected observation wells, Yuma Mesa, Ariz.

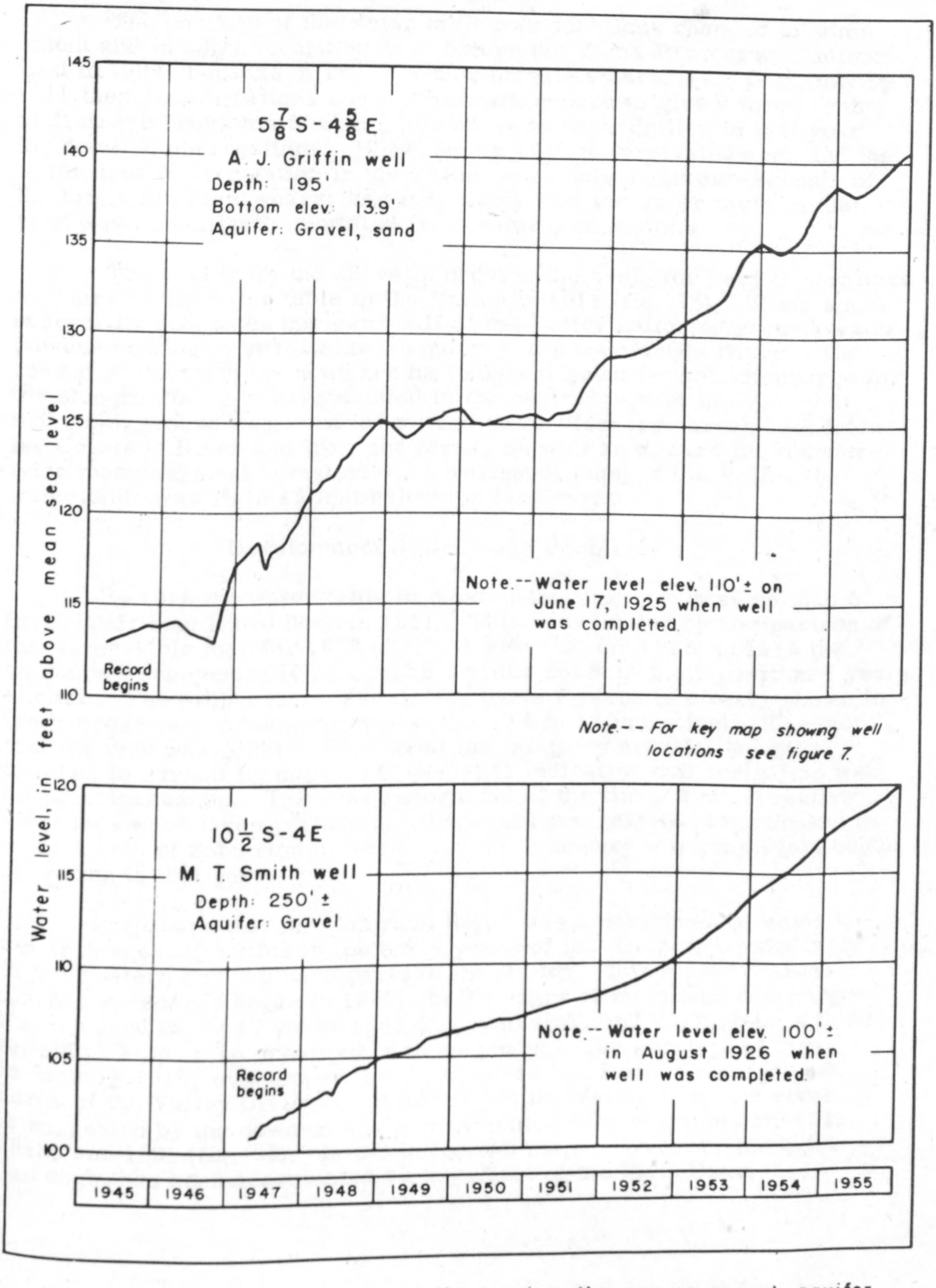

Figure 22.--Water level in two wells tapping the coarse-gravel aquifer, Yuma Mesa, Ariz.

Natural Conditions

The position of the water table was doubtless changed to some extent and in some localities even before the Yuma Project was authorized in 1904, because of irrigation by private enterprise. Certainly by 1911 these modifications were significant enough to give a forewarning of drainage problems to come, for 22 wells were drilled in that year for detailed observations. However, in 1911 the irrigated area and the water used for irrigation in the Valley were only about one-seventh of the totals in recent years, and it is likely that the water table in that year was only slightly modified from natural conditions.

The data from the 22 wells provide the basis for very generalized contours of the water table in the Valley in 1911 (fig. 23). Their southeastward trend in the northern half of the Valley indicates ground-water movement roughly parallel to the course of the Colorado River. The curved contours in the southern half suggest ground-water discharge in the sloughs known to have existed in the central part of the Valley at that time; ground water moved toward these discharge areas both from the Colorado River and from the Mesa, as well as upward from underlying more permeable material. Throughout most of the Valley the water table was 10 to 15 feet below the land surface.

Development of Drainage Problems

By 1918 the water table in most of the Valley was more than 5 feet higher than it had been in 1911. This is indicated by comparison of the water-table map for 1918 (fig. 24) with that for 1911; in 1918 the contours were generally more than 2 miles south of their position 7 years earlier. The progressive rise during those 7 years is clearly shown in the hydrographs for several wells (figs. 14 to 18 inclusive). The fact that the rise was general throughout the irrigated area (although it differed in amount from place to place) is indicative that irrigation was the principal cause. This was recognized at the time, and corrective measures were taken. The Main Drain had been extended northward to a point west of Somerton by 1918, and the Boundary Pumping Plant began operating in that year.

It appears that the Colorado River was a contributing factor to the drainage difficulties in the early years of the project, particularly in the western and southern parts of the Valley. In the period since discharge records began in 1902, the 10 years of maximum discharge all occurred in the 17 years 1905-21, inclusive, and the highest 4 flood crests at Yuma also occurred in those years. The greatest of these, in January 1916, overtopped the Yuma levee and flooded nearly 8,000 acres of the Valley Division. Recharge to the Valley from the river is suggested by the down-river bend of contours on the maps for 1911, 1918, and 1921 (fig. 25). In the latter two maps, however, the bend has doubtless been accentuated by the effect of the Main Drain.

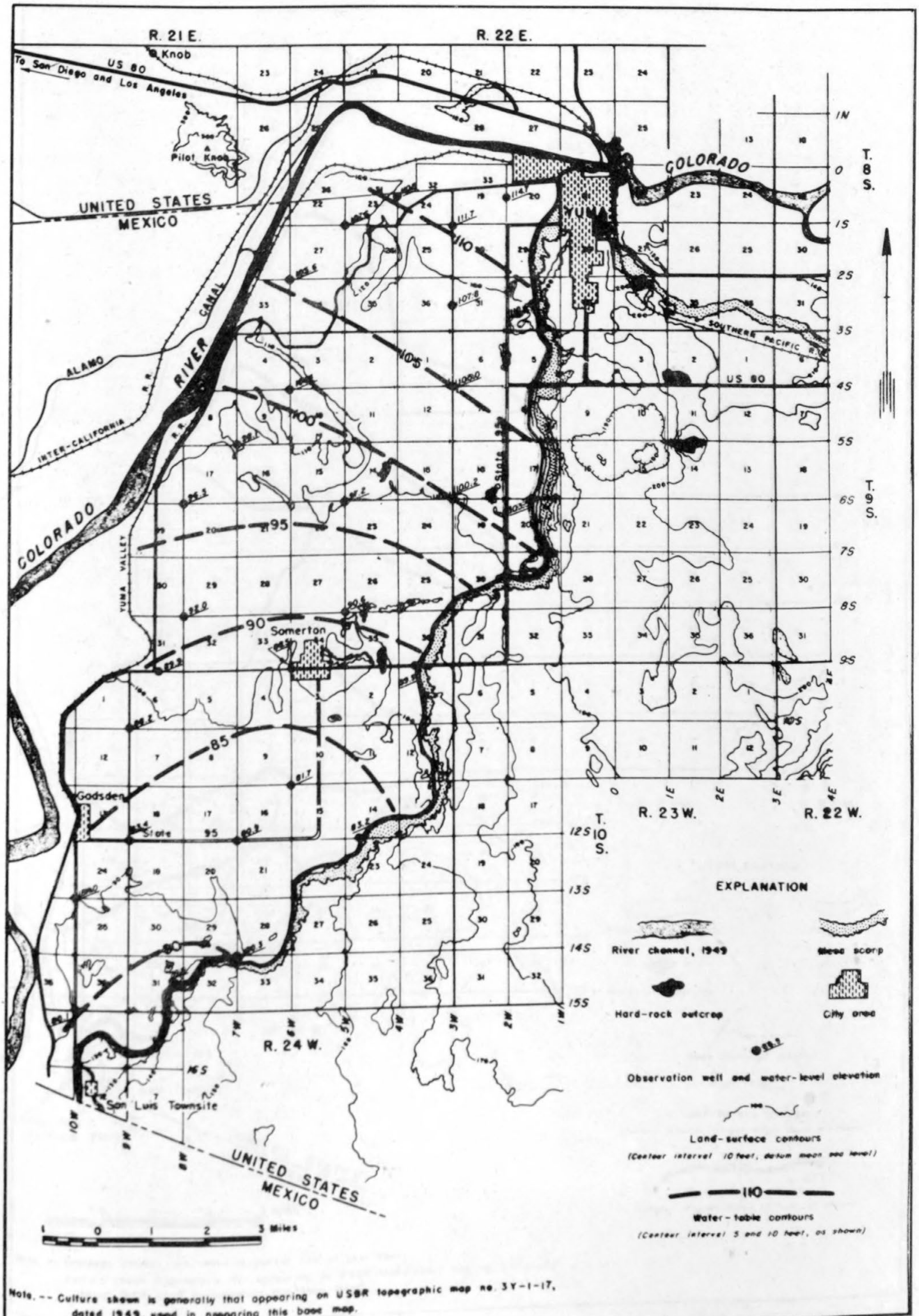

Figure 23.--Map of Yuma area, Ariz., showing water-table contours as of October 1951.

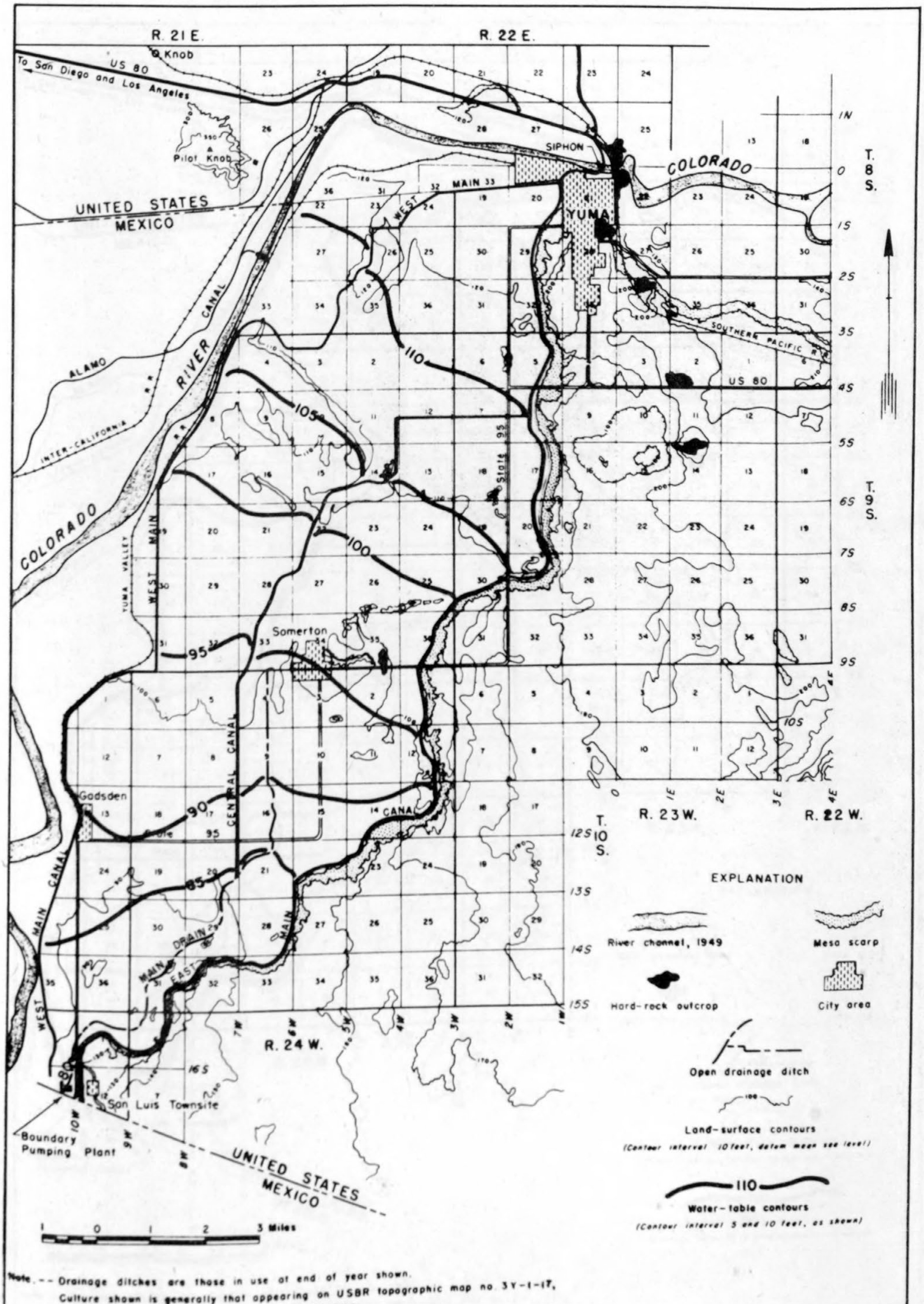

Figure 24.--Map of Yuma area, Ariz., showing water-table contours as of December 1918.

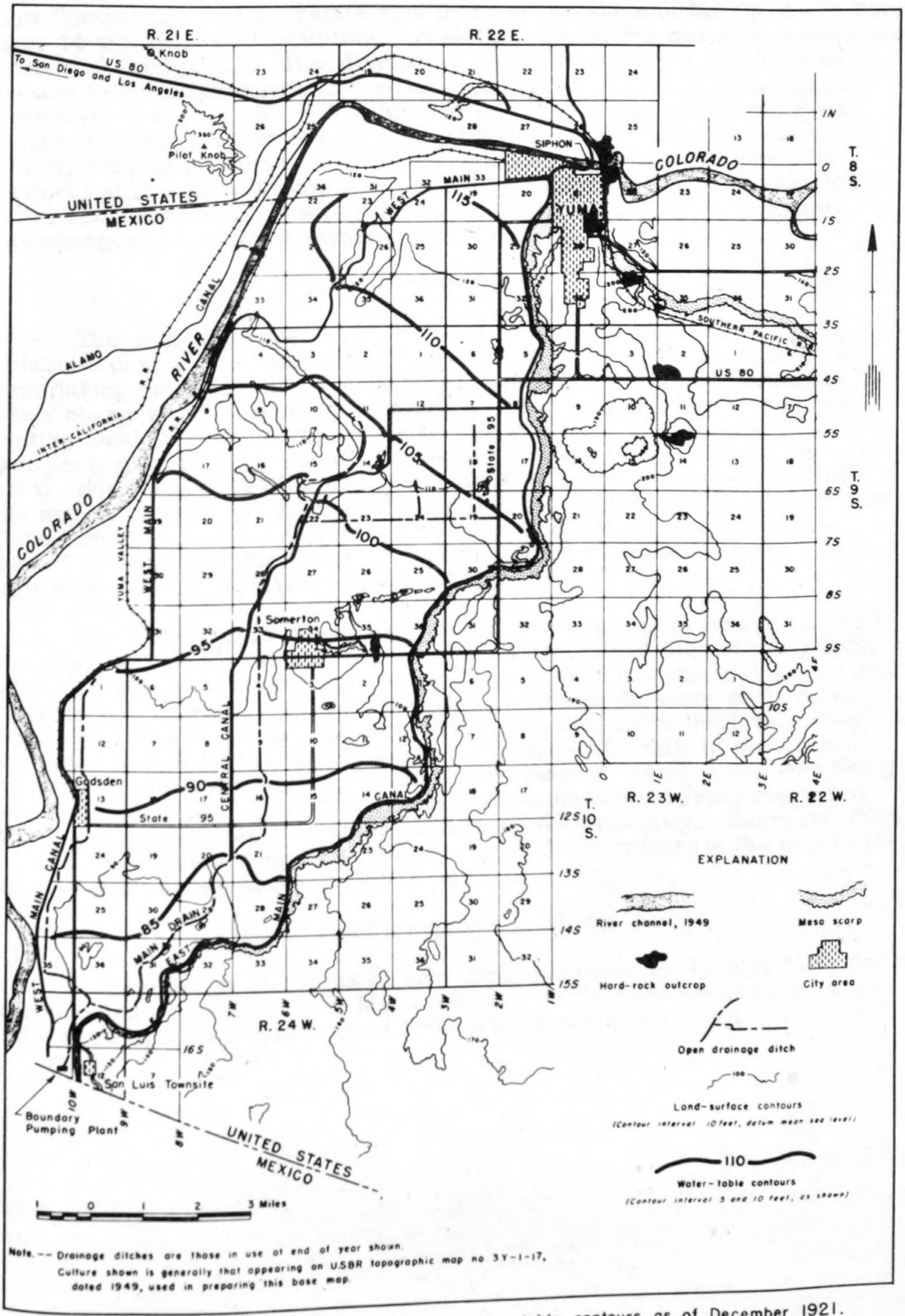

Figure 25.--Map of Yuma area, Ariz., showing water-table contours as of December 1921.

The hydrographs for several wells in the western part of the Valley show fluctuations that correlate with those of the stage of the Colorado River (figs. 14 and 15). Generally the correlation is best for wells closest to the river, and fainter at greater distance. The effect of river fluctuations appears to extend as much as 3 miles from the channel, as shown in the hydrograph for well 3 S - 3 W. An interesting question of that time was whether the rising water levels in some wells meant that river water was actually moving into the well. The question was answered by periodic chemical analyses by Wilcox and Scofield (1952) of the water in selected wells, and the conclusion was reached that the fluctuations represented only changes in head ["transmission of a hydrostatic impulse"].

Stability in the Valley

The maps for 1921, 1925 (fig. 26), 1931 (fig. 27), and 1935 (fig. 28) indicate a period of relative stability of the water table in the Valley, at least during the year-end periods represented by the maps. There are minor changes in positions of contours in different places, perhaps reflecting local fluctuations in application of water or effectiveness of drainage, perhaps reflecting changes in the observation wells or their measurement. But the overall picture as portrayed by these maps changes little. The map for 1921 depicts conditions for the last year prior to development of the Yuma Auxiliary Project; the map for 1931 shows conditions in a year of drought over the Colorado Basin; and the map for 1935 marks the beginning of Colorado River regulation by Hoover Dam.

The hydrographs provide details concerning this period of relative stability. All show seasonal fluctuations as a result of the seasonal application of water for irrigation. In many wells there is a gradual downward trend from maxima established in 1921 or earlier. In some wells close to the river this downward trend may have resulted from the lower river discharge in this period than in earlier years, but in most of the Valley the trend showed the effectiveness of the drainage system, which was being extended each year. The hydrographs for drains drop sharply every few years, presumably after cleaning, and then rise gradually. Corresponding fluctuations in the hydrographs for nearby wells demonstrate the beneficial effect of good maintenance of drainage.

Beginning of Irrigation on Mesa

Except for small tracts of land irrigated since early days for private enterprises, irrigation on the Mesa began in 1922, when about 1,000 acre-feet was pumped to irrigate about 200 acres of the Yuma Auxiliary Project.

Very little is known about the position of the water table under the Mesa prior to 1922, and, in fact, information is very fragmentary before 1946 when the Bureau of Reclamation started drilling observation wells. All available information collected from 1920 to 1931 has been utilized to provide the sketched contours shown on the map for 1925 (fig. 26). The fact that these bits of information agreed sufficiently with each other to permit drawing any contours suggests: 1) that the water table under the Mesa was relatively stable throughout the period; and 2) that irrigation on the Mesa during the early developmental years did not create significant changes in the water table. In 1925 the irrigated acreage on the Mesa was about 800 acres, and the pumpage to it, about 5,000 acre-feet.

The sketched contours of the water table under the Mesa in 1925 have a general east-southeastward trend, continuing approximately their trend across the Valley. As with the contours under the Valley in 1911 (slightly modified by natural conditions), these contours under the Mesa suggest the natural movement of ground water parallel to the Colorado River. In other words, the Colorado River along the west side of the Valley Division, did not constitute, with the possible exception of flood periods, a well-developed source of recharge or a clearly-defined outlet for the local ground-water reservoir.

Effects of Drought

The Colorado River basin in 1931 was drier than in any year since 1901, and the discharge of the river at Yuma was less than one-third of the long-term average. Afterward, the discharge was slightly less than average in 1932 and slightly more than half of average in 1933; then came 1934, with less than one-fifth of the average discharge. Similar low discharges continued at Yuma for several years because of regulation at Hoover Dam to fill Lake Mead, beginning in 1935. The low discharge of the river, particularly in 1934, is reflected by the low water levels in the wells closest to the river: 1 S - 3 W (fig. 14), 5 S - 7 W (fig. 15), 8 S - 8 W (fig. 17), and 12 S - 9 W (fig. 18).

The stage of the Colorado River at Yuma in December 1935 was higher than at the times represented by the water-table maps for earlier periods. In fact, the minimum stages throughout the 1930's, when the annual runoff was low, were considerably above those of earlier years when runoff was above normal. The variation in relation of stage to discharge, explainable by the scour and fill of the river, can be seen by close comparison of the graph showing Colorado River discharge (fig. 14) with the one showing fluctuations in stage at Yuma (fig. 15).

Comparison of the water-table contours for 1931 and 1935 (figs. 27 and 28) shows little effect from the intervening years of low Colorado River discharge. If anything, the water table in most of the Valley was slightly higher in 1935 than in 1931. At the south end of the area, part of the reason may be the decreased discharge of drain water by the Boundary Pumping Plant, which pumped less in 1934 and 1935 than in any year since 1920, resulting in higher water levels in the Main Drain (fig. 18).

Figure 26.--Map of Yuma area, Ariz., showing water-table contours as of December 1925.

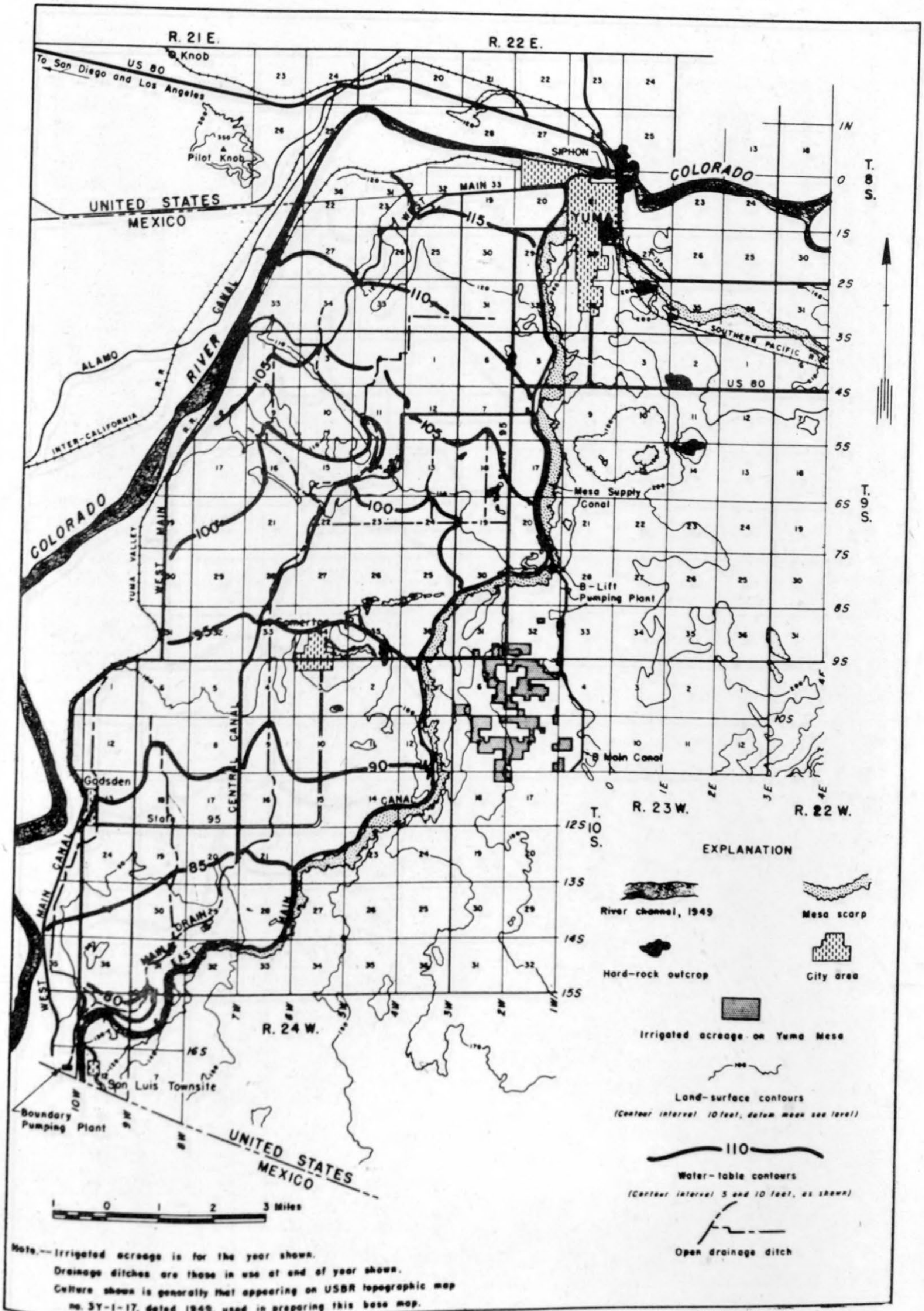

Figure 27.--Map of Yuma area, Ariz., showing water-table contours as of December 1931.

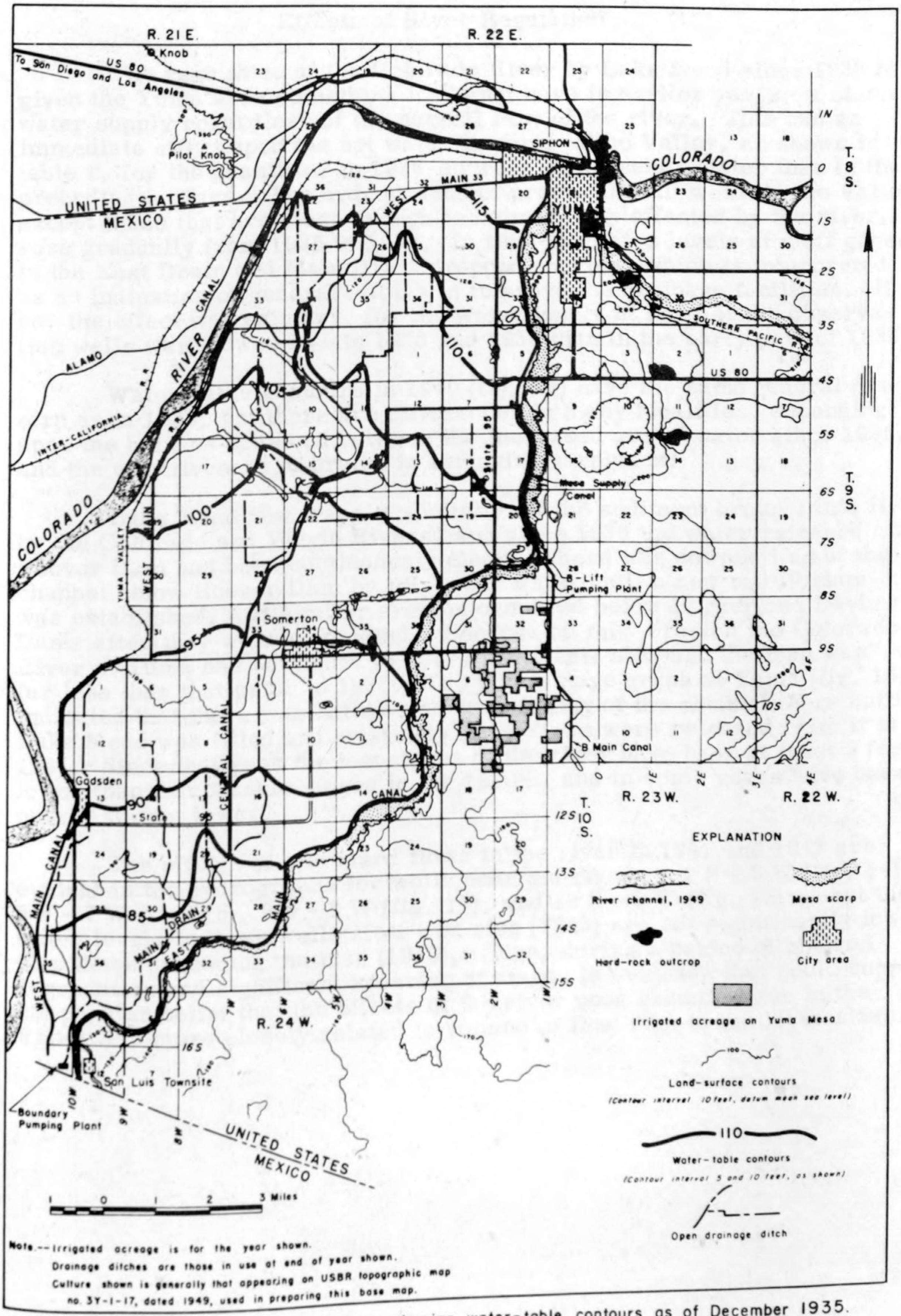

Figure 28.--Map of Yuma area, Ariz., showing water-table contours as of December 1935.

Effects of River Regulation

The regulation of the Colorado River by Lake Mead since 1935 has given the Yuma area something it did not have in earlier years: a stable water supply regardless of the natural flow of the river. This had an immediate effect upon the net water imports to the Valley, as shown in table 1, for the quantities in 1936-40 were 20 percent greater than in the preceding 5 years. The hydrographs of practically all wells in the Valley, except those that are close enough to be markedly affected by the river, rose gradually from 1935 to 1938. In 1938 the water levels at staff gages in the East Drain and Main Drain dropped sharply, which is interpreted as an indication of general efforts to improve the drainage facilities. If so, the effect was salutary, for the water levels in most of the observation wells were lower in late 1938 and 1939 than in the early part of 1938.

Water-table contours in 1940 (fig. 29) have the same general pattern as in 1935, but there are differences in many localities, depending upon the balance achieved between the increased use of water since 1935, and the effectiveness of drains in removing surpluses.

Lake Mead now traps essentially all the sediment brought into it by the Colorado and Virgin Rivers, and since 1936 the water released at Hoover Dam has been continuously clear. There was downcutting of the channel below Hoover Dam by this clear water until a new equilibrium was established, and similar erosion occurred below Parker and Davis Dams after they were completed. Because of this erosion the Colorado River at Yuma has continued to carry sediment, although the load was far less than that prior to 1935. The river-stage graph at Yuma (fig. 15) indicates that there was little or no downcutting of the channel there until Lake Mead was filled and relatively large flows were released from it in 1941. Since that year the low stages of the river have been at least 5 feet lower than comparable stages in the 1930's, and in some years have been nearly 10 feet lower.

The effects of increased flows in the river in 1941 and 1942 are evident in the hydrographs for wells near the river — 1 S - 3 W (fig. 14), 5 S - 7 W (fig. 15), 8 S - 8 W (fig. 17), and 12 S - 9 W (fig. 18) — but the water levels in these wells after that rise (1943) are not significantly lower than those preceding the rise (1940). Here, during a period of channel degradation and significant lowering of stage, is evidence that could support the popular belief that the effects of the river upon ground water in the Valley are more closely related to volume of flow than to the river stage.

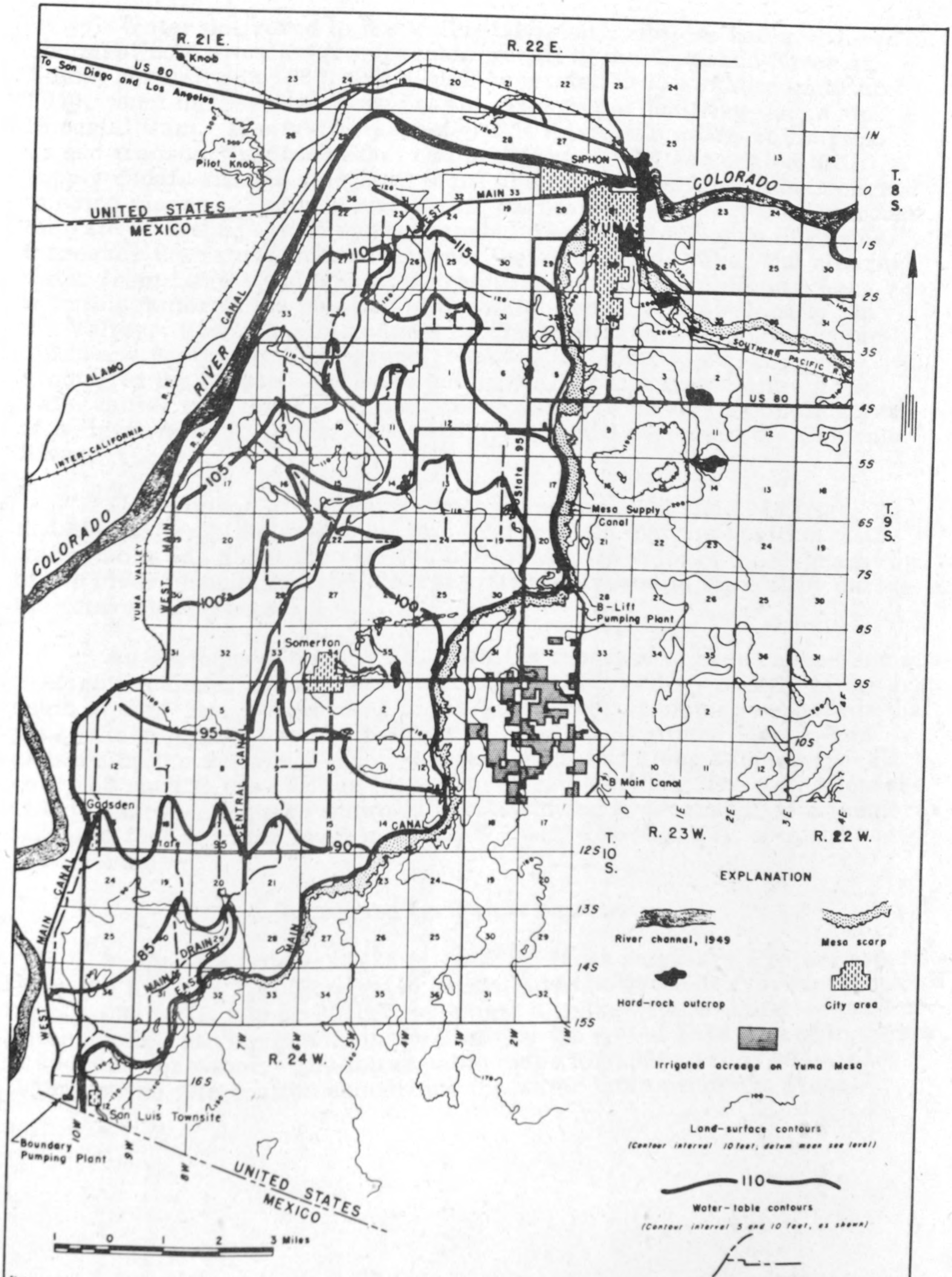

Figure 29.--Map of Yuma area, Ariz., showing water-table contours as of December 1940.

Water delivered to the Valley Division doubtless had a reduced sediment concentration (comparable to that of the Colorado River at Yuma) beginning in 1935, and a further reduction to a minimum after 1940, when the supplies were passed through the desilting works at Imperial Dam. It might be expected that this clear water would pick up and transport sediment that had previously lined and sealed the supply canals and laterals, and there are reports that this has occurred in some places. The removal of this seal might be expected to increase the rate of seepage from supply canals, just as the cleaning of drains increases the rate of inflow of ground water to them. Thus the clearer water from Lake Mead and later from Imperial Dam would be a contributing factor in the position of the water table, at least locally, in the Valley. However, this cannot be discriminated as a dominant factor in any particular hydrograph, because the details of sealing or eroding of the supply canals are not known. If this factor affects the water table, it is masked by such other variable factors as application of irrigation water, effectiveness of drains, and effects of the Colorado River.

Comparison of the water-table maps for 1940 and 1943 (figs. 29 and 30) confirms the evidence from hydrographs that the position of the water table was about the same in both years, in spite of the degradation of the river channel and the clearer water delivered to the Valley during the intervening years.

An earthquake on May 18, 1940, is reported to have caused serious damage to canals, drains, and structures in the Valley, chiefly in the area south of Somerton. According to the Yuma Project history report for that year, the bottoms of some drains rose to adjacent ground levels, and geysers by the thousands spurted from the ground along surface cracks, carrying sand to the surface from considerable depth. The only apparent effect of this earthquake shown in accompanying hydrographs is a temporary rise of 1 foot in water level in well 9 S - 3-3/4 W (fig. 17), 2 miles east of Somerton.

Increased Irrigation on Mesa

During the interval 1925 to 1943 the Mesa Auxiliary Project expanded from 800 to about 1,600 irrigated acres, and the water deliveries increased from 5,000 to 15,000 or 20,000 acre-feet a year. The cumulative total of water applied for irrigation on the Mesa by the end of 1943 was of the order of 200,000 acre-feet. The water-table maps for 1931, 1935, 1940, and 1943 show no information concerning the water table under the Mesa.

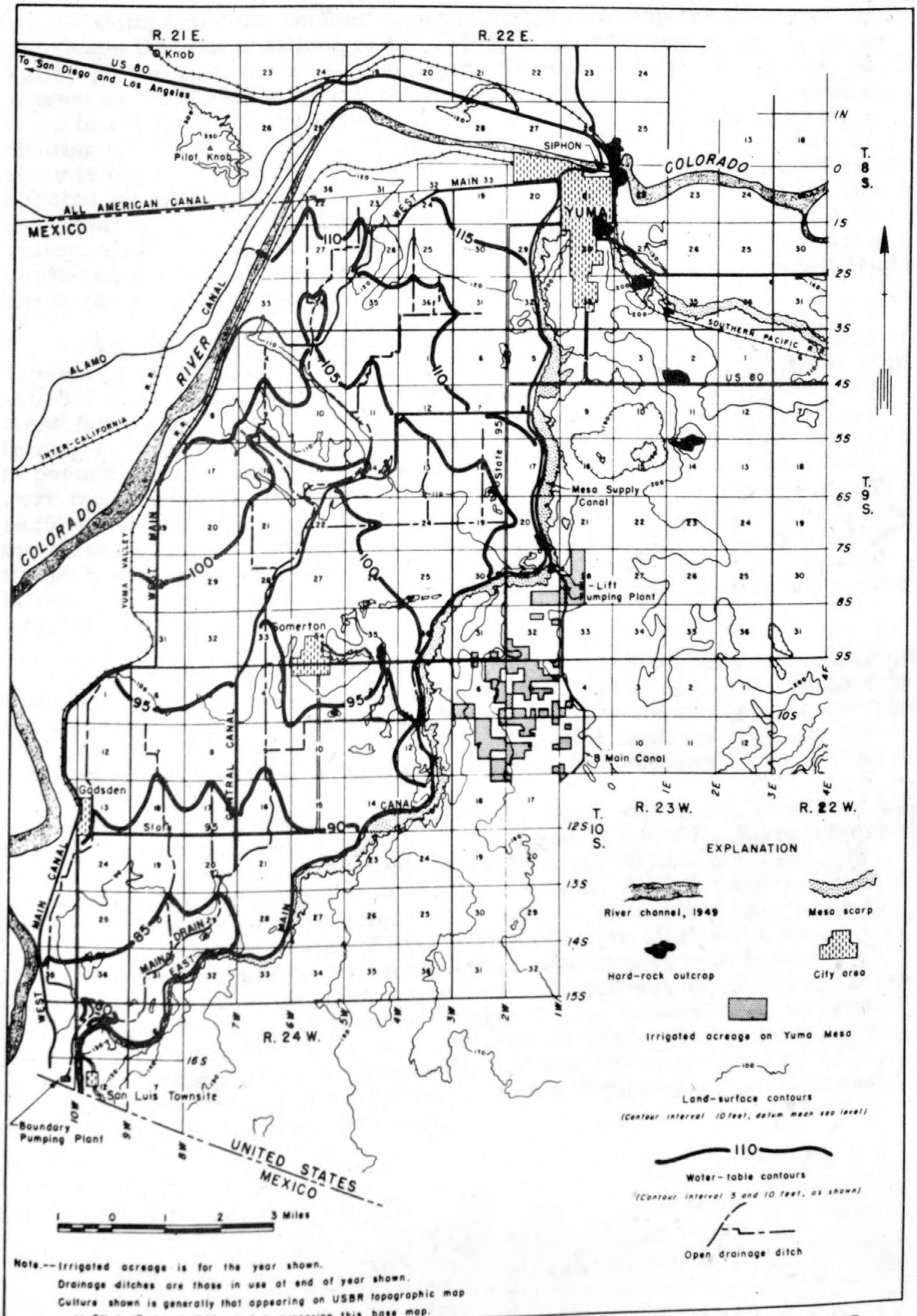

Figure 30.--Map of Yuma area, Ariz., showing water-table contours as of December 1943.

Comparing the contour maps for 1925 (fig. 26) and 1943 (fig. 30), it appears that the positions of the 115-foot and 110-foot contours in the Valley just west of the Mesa are nearly the same. In the part of the Valley nearest to the Mesa Auxiliary Project, the 105, 100, 95, and 90-foot contours in 1943 were more than a mile south of their positions in 1925, indicating a 2 or 3-foot rise of the water table in the area. However, this alone is not sufficient evidence that the irrigation on the Auxiliary Project affected the water table in the Valley, because of the known effects of variable application of irrigation water and drainage maintenance within the Valley; also, in this area, seepage from the East Main Canal may have increased since 1935 because of canal widening and the cleaning effect of clear water in the canal.

The development of the Mesa Division of the Gila Project began in earnest in 1944, and by 1946 about 5,500 acres were being irrigated with 110,000 acre-feet of water. The cumulative total of water applied to the Mesa for irrigation had exceeded 400,000 acre-feet by the end of 1946. During 1946 there were not enough measurements of water levels in wells to permit drawing contours for the Mesa. The few measurements that were made and that are shown on figure 31 indicate, by comparison with 1925, no change of water levels in wells along the north and east edges of the Mesa; a rise of about 7 feet in a well along the edge of the Auxiliary Project; and rises as great as 18 feet under parts of the newly irrigated lands of the Mesa Division. These estimates may well have an error of 5 feet or more.

The water-table contours of the Valley in 1946 show, in comparison with 1943, a southwestward displacement of the 115, 110, and 105-foot contours along the eastern edge of the Valley opposite the newly irrigated lands on the Mesa. The positions of the 95 and 90-foot contours opposite the older Auxiliary Project, however, are virtually unchanged.

Among the hydrographs, a few show declining trends of water level in the years immediately preceding 1946; most of these fluctuate with river discharge and were declining from the high flows of 1941 and 1942. In practically all other observed wells there was an upward trend prior to 1946. Various factors that might contribute to these rises have already been noted: increased rates of application of water after Lake Mead afforded a firm supply, increased seepage from supply canals after flushing with clear water, and decreased effectiveness of the drainage system. The last item is especially important in these years, because normal maintenance of drains was curtailed in 1942 owing to wartime restrictions in manpower and equipment, and was not resumed until 1946. This was unquestionably a major factor in the rising water table throughout the Valley during the war years.

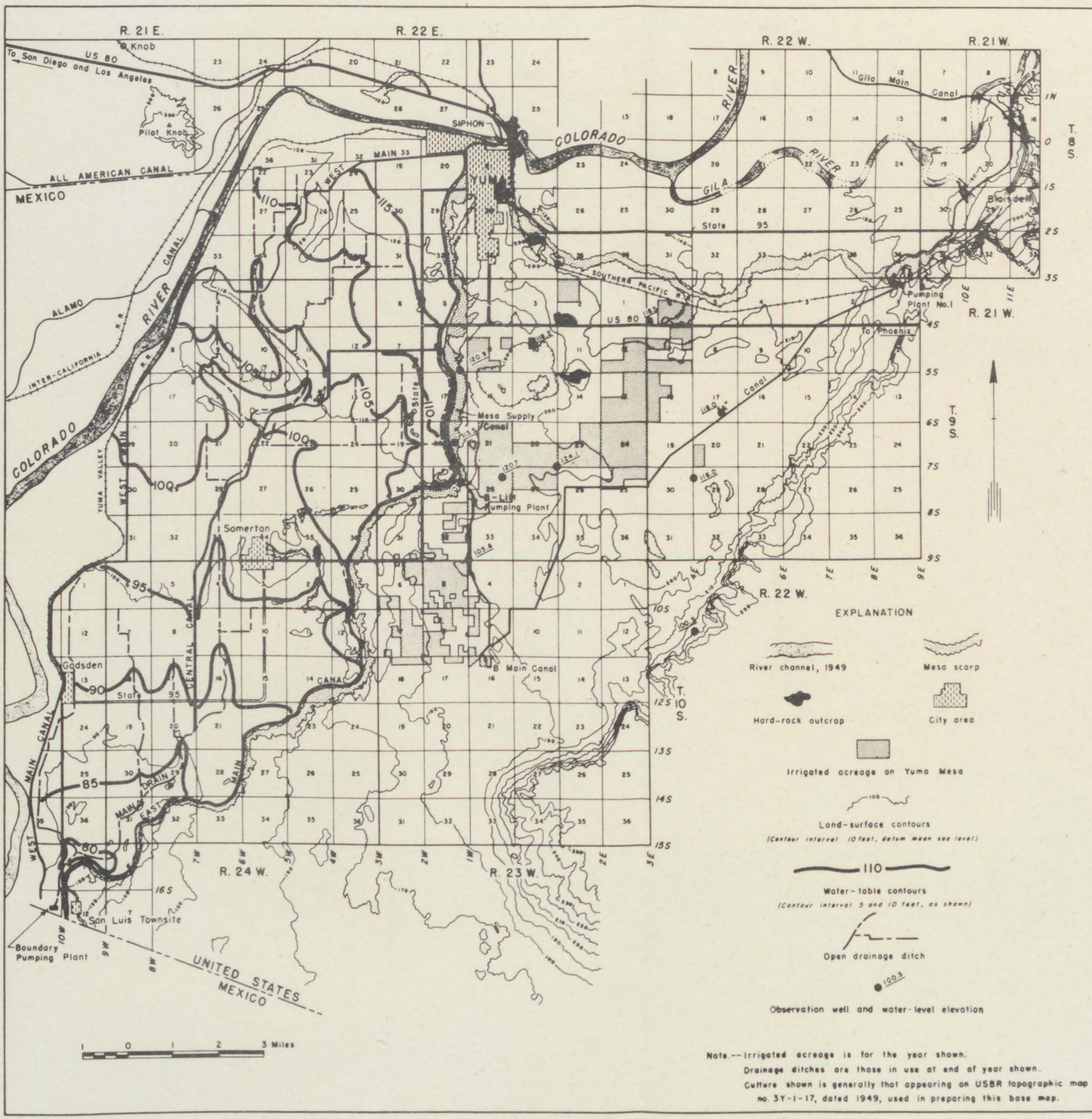

Figure 31.--Map of Yuma area, Ariz., showing water-table contours as of December 1946.

The possible effect of Mesa irrigation, therefore, cannot be identified in these hydrographs unless it can be discriminated from the effect of nonmaintenance of drainage. The stage graphs for several drains suggest the periods of cleaning: After 1941 the first cleaning of the Main Drain was apparently in 1946, beginning in February at the southern end and progressing northward through the year; the graph for the East Drain suggests that the first cleaning after 1941 occurred in the winter of 1946-47. The effectiveness of this renewed maintenance, and the degree of control of the water table effected by maintenance, are indicated by the fact that the trend of water levels in many wells, rising gradually through the war years, was arrested or reversed in 1946.

Three wells do not conform to this general picture. Instead of a gradual rise throughout the war years, their hydrographs show little change in water level in 1941-44, and then a rise of 3 to 5 feet by the end of 1946. In well 5 S - 1-1/2 W (fig. 18) the high level of 1946 was maintained throughout 1947; in well 7 S - 2 W (fig. 16) it continued into 1947 until operation of a new drainage well less than 100 feet away caused the observation well to go dry; and in well 6 S - 1-1/2 W(fig. 18), the water level by 1948 had returned to its pre-1945 level. The rise of water level in these wells occurred during and after resumption of drain maintenance in the Valley, and seems not to be attributable to poor drainage conditions. But all three wells are within half a mile of the edge of the Mesa, north of the Big Bend area, and the rise of water levels in them correlates with the increasing rate of use of water in the Mesa Division. The water-level declines in wells 5 S - 1-1/2 W and 6 S - 1-1/2 W during 1947 appear to be related to completion of the East Drain Extension in 1946, and of drainage well No. 5 which was put into service in August 1947. The two wells are adjacent to the drain and are respectively 1/2 mile north and south of the drainage well.

Development of Ground-Water Mound Under Mesa

The test wells drilled by the Bureau of Reclamation in 1947 provide, during that year, the first detailed information on the water table under the Mesa. On figure 32, the 85- and 90-foot contours have an eastward trend across the Mesa, a continuation of their general trend across the Valley. The 95-foot contour at the eastern edge of the Mesa has about the same position as in 1925, but farther west it is bowed southward around the south edge of the irrigated area. From here northward there is clear evidence of a ground-water mound, encompassing the irrigated area of the Mesa. The 100-, 105-, 110-, and 115-foot contours, after crossing the Valley, bend sharply southward and then outline a spur of this mound under the irrigated area of the Auxiliary Project. Doubtless this part of the mound had been in existence for several years, owing to irrigation in the Auxiliary Project.

Figure 32.--Map of Yuma area, Ariz., showing water-table contours as of December 1947.

Most of the ground-water mound — particularly that enclosed by the 125-foot contour — is of recent origin, because it underlies areas first irrigated in 1946 or 1947. Two peaks are indicated on this mound, one just east of the Big Bend, the other southeast of the airport. The materials beneath the surface of the Mesa are known to differ greatly in permeability, and some test wells bottom in materials less permeable than others. Presumably these contrasts would be particularly influential in the first and least stable stages of ground-water recharge. The contours in figure 32 are therefore drawn with considerable doubt as to their accuracy. This is especially true for each of the two peaks, because all contours above the 140-foot elevation are based on water-level records in only two wells.

The progressive change in shape and height of the ground-water mound is indicated by the maps (figs. 33 to 38, inclusive) showing the water table at the end of each of the years 1948-53, inclusive. For these maps the 5-foot contour interval is used only below 130 feet, and the upper part of the mound is depicted by a 10-foot contour interval. The history of the mound during these 6 years may be summarized as follows: it expanded, first eastward and northward and then southward; the peak east of the Big Bend became lower and then rose again, and the peak near the airport disappeared and then reappeared and finally merged with the mound east of the Big Bend. These general changes, as well as the numerous changes in detail shown by the maps, are indications of the unstable conditions of occurrence and movement of ground water throughout the period.

A major cause for this instability has been explained in the discussion of head differential among wells of various depths. The graphs assembled for figure 6 are selected examples of many that might be cited in available records, and the number of instances could doubtless be multiplied indefinitely if wells were constructed to the top of each of the less permeable lenses underlying the irrigated area. The head differential above and below these less permeable zones will remain as long as irrigation and resultant recharge continue; but after an initial period of instability, with fairly constant cyclic recharge balanced by lateral movement from under the irrigated area, the differential may approach a smaller and fairly constant value — as, for example, in wells 10 S - 2 W and 10 S - 3 W in the Auxiliary Project area. By contrast, at 9 S - 1 W, also in the Auxiliary Project, the head differential between adjacent shallow and deep wells was 40 feet when first observed in 1951, and had decreased to 25 feet in late 1955. Most of the hydrographs shown on figure 6 indicate that the water levels, which were widely divergent at the start, are slowly converging toward lower and possibly constant differentials.

For 1954 there are maps showing the water table as defined by the 100-foot wells (fig. 39) and also the perched water table as defined by shallow wells (fig. 8).

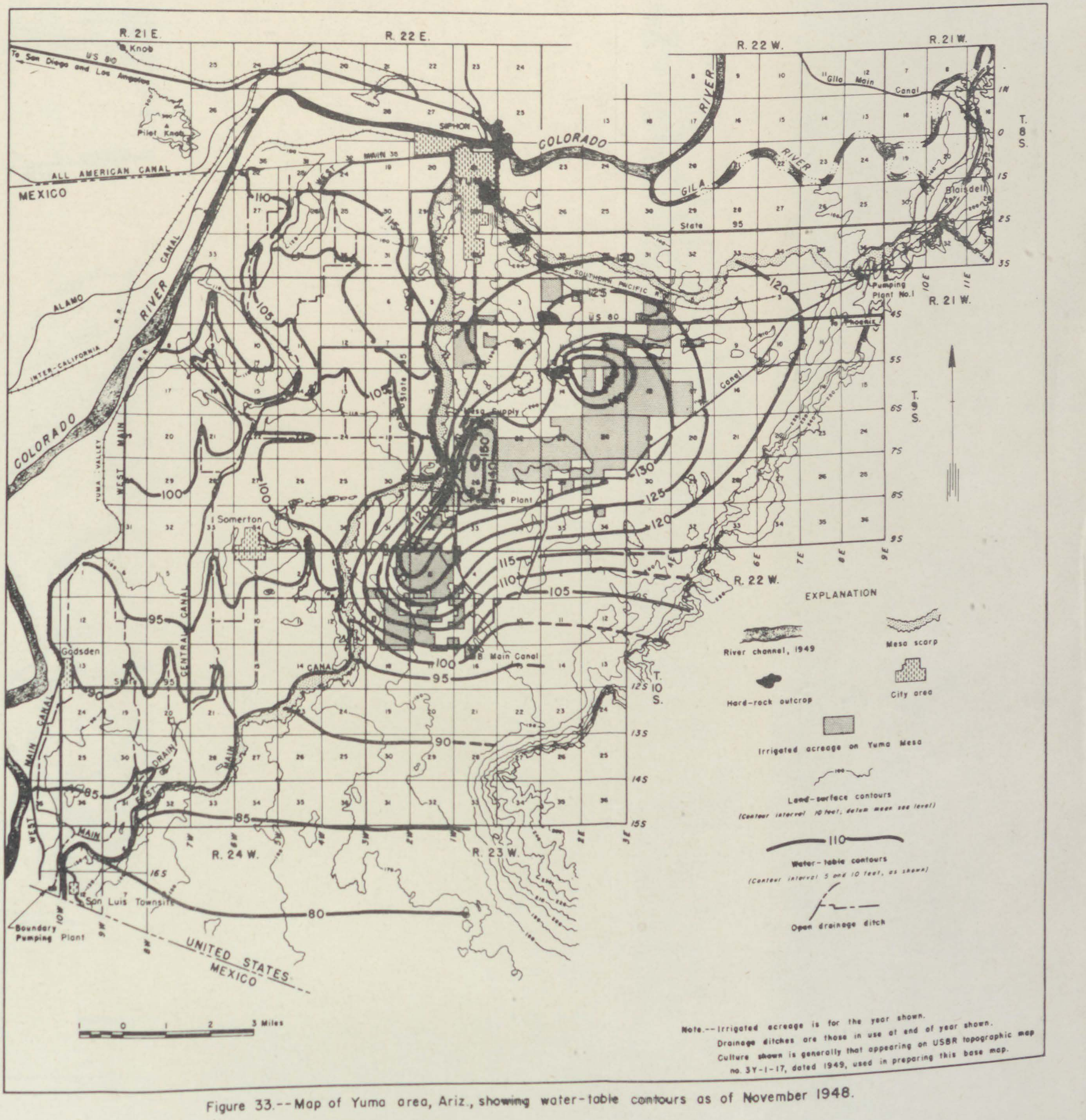

Figure 33.--Map of Yuma area, Ariz., showing water-table contours as of November 1948.

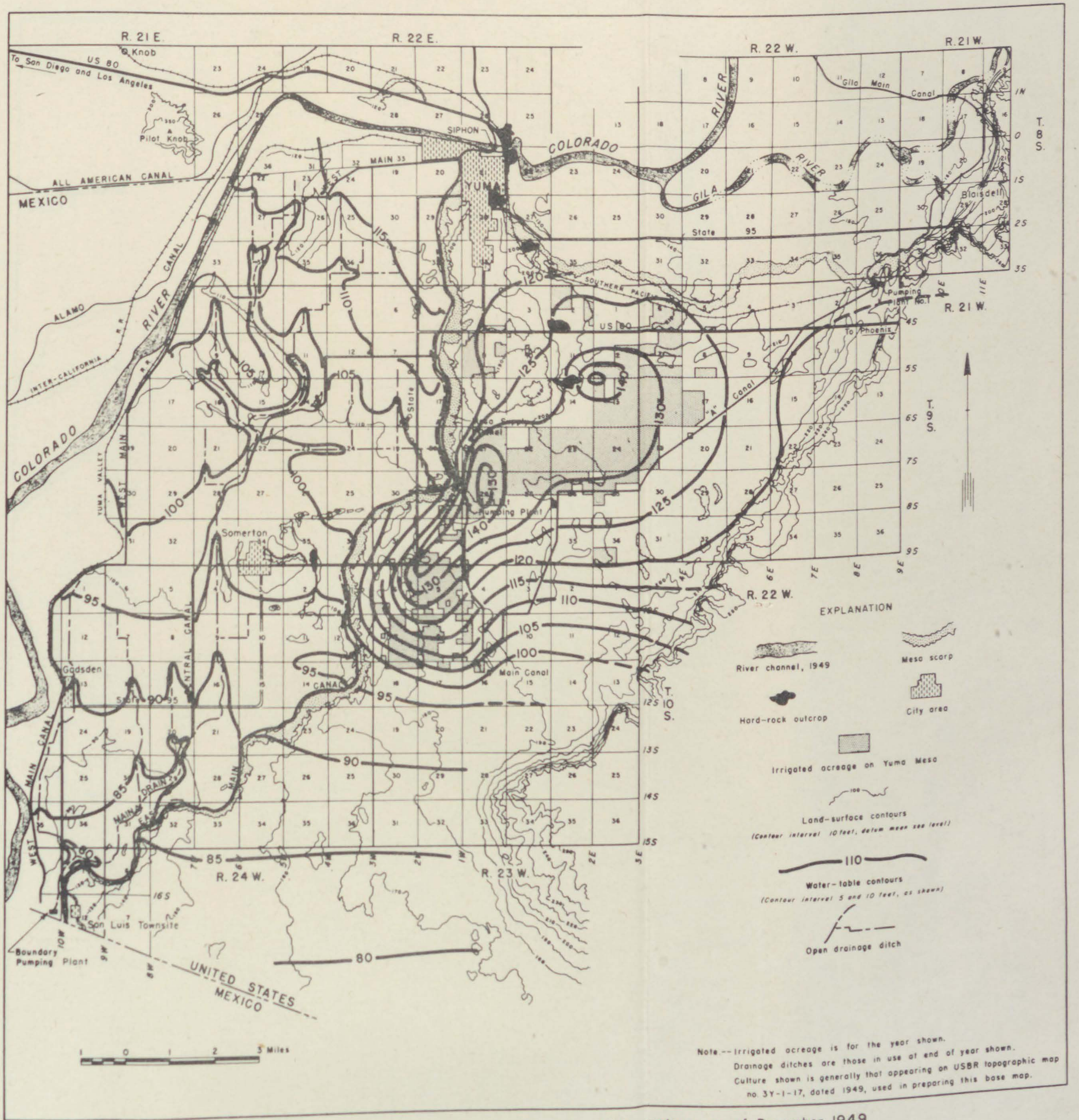

Figure 34.--Map of Yuma area, Ariz., showing water-table contours as of December 1949.

Figure 35.--Map of Yuma area, Ariz., showing water-table contours as of December 1950.

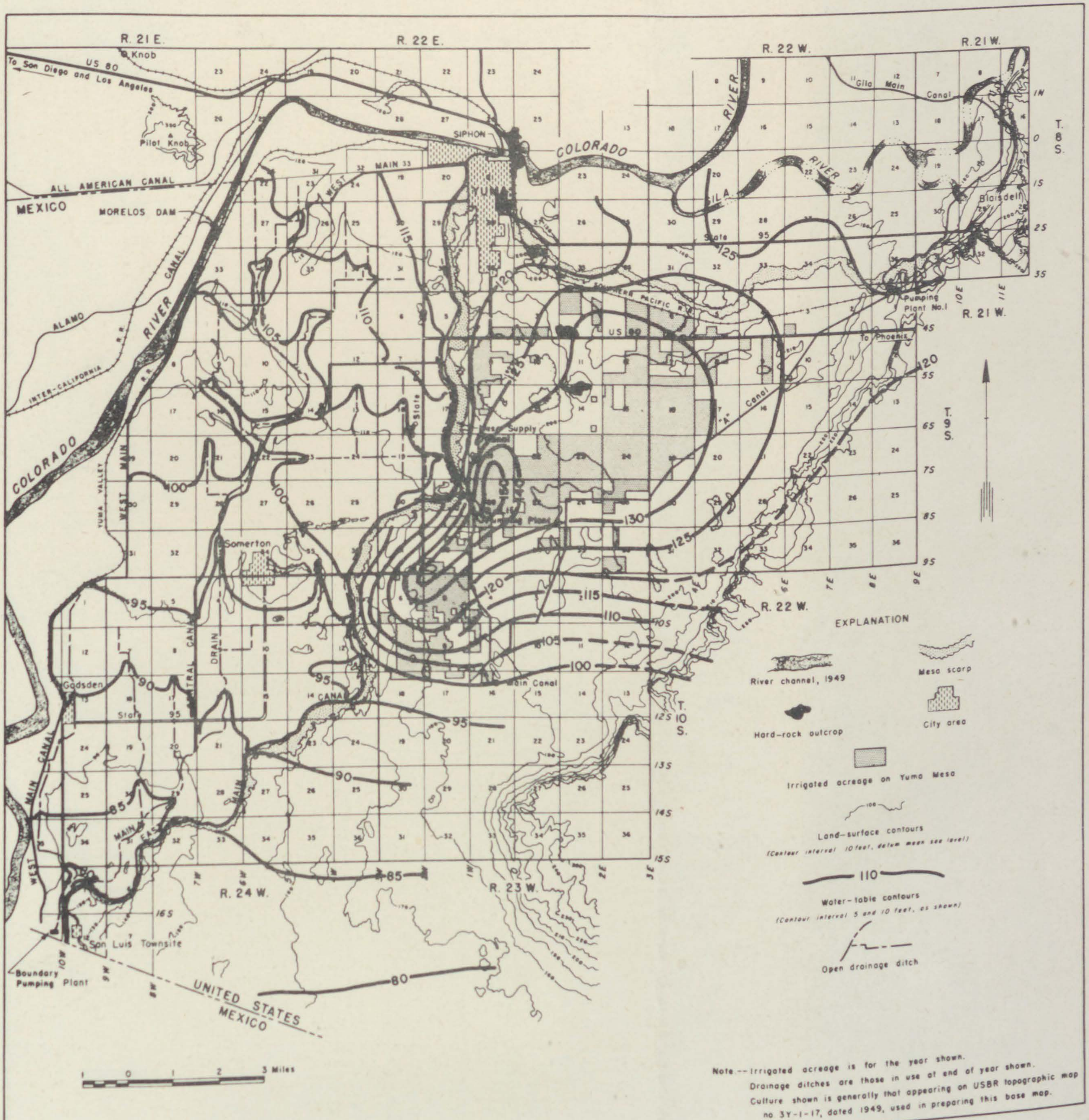

Figure 36.--Map of Yuma area, Ariz., showing water-table contours as of December 1951.

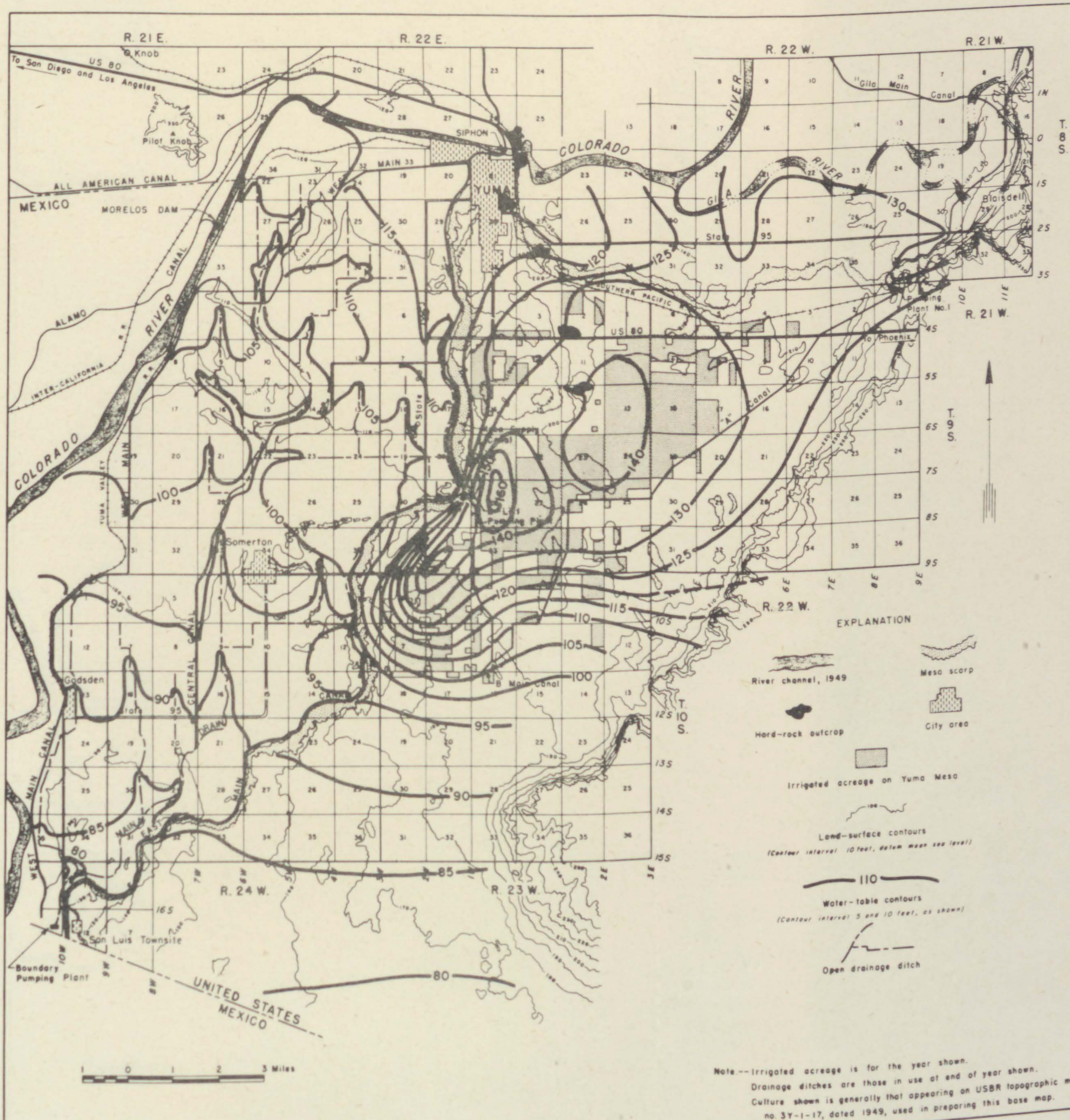

Figure 37.--Map of Yuma area, Ariz., showing water-table contours as of December 1952.

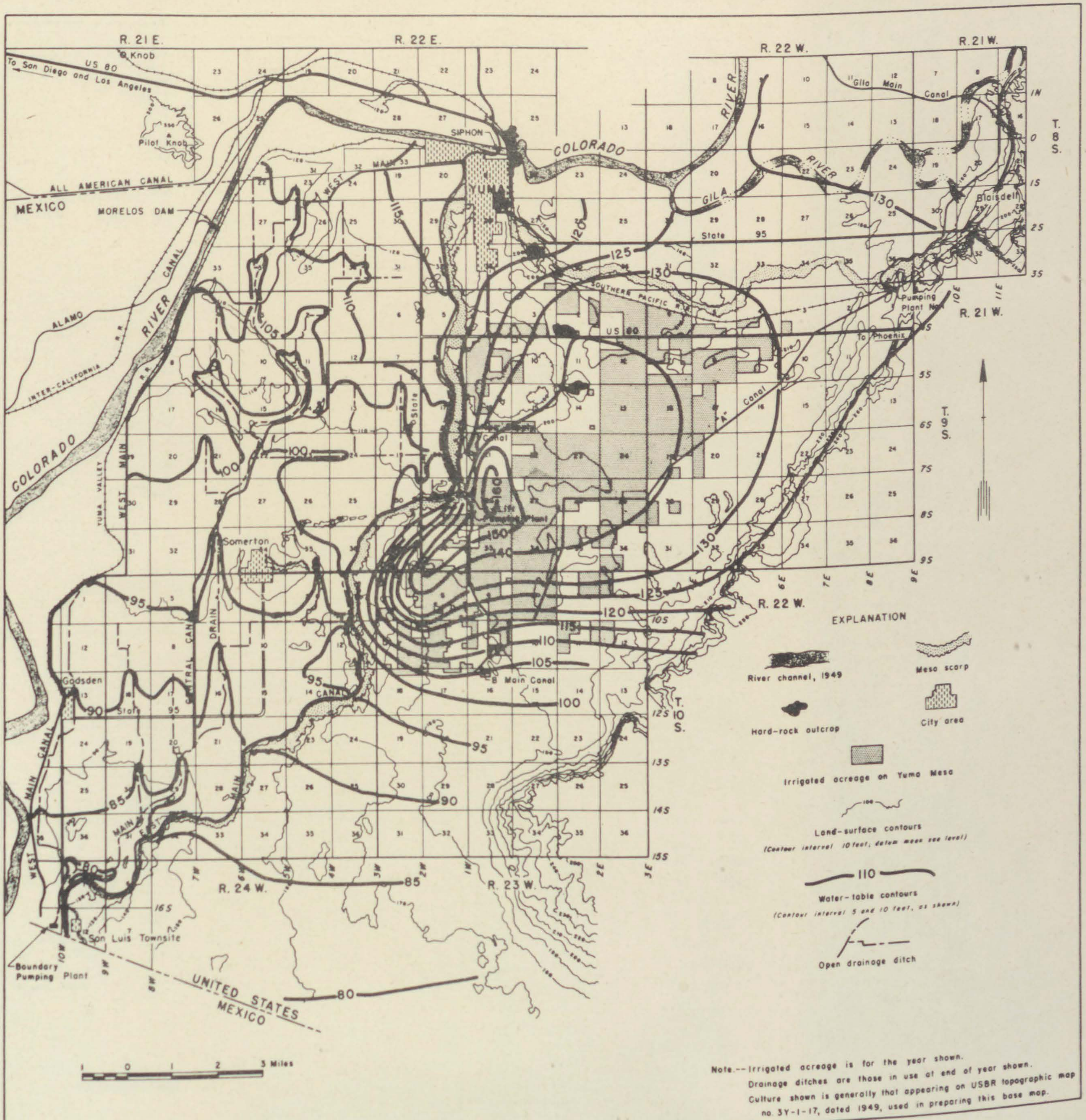

Figure 38.--Map of Yuma area, Ariz., showing water-table contours as of December 1953.

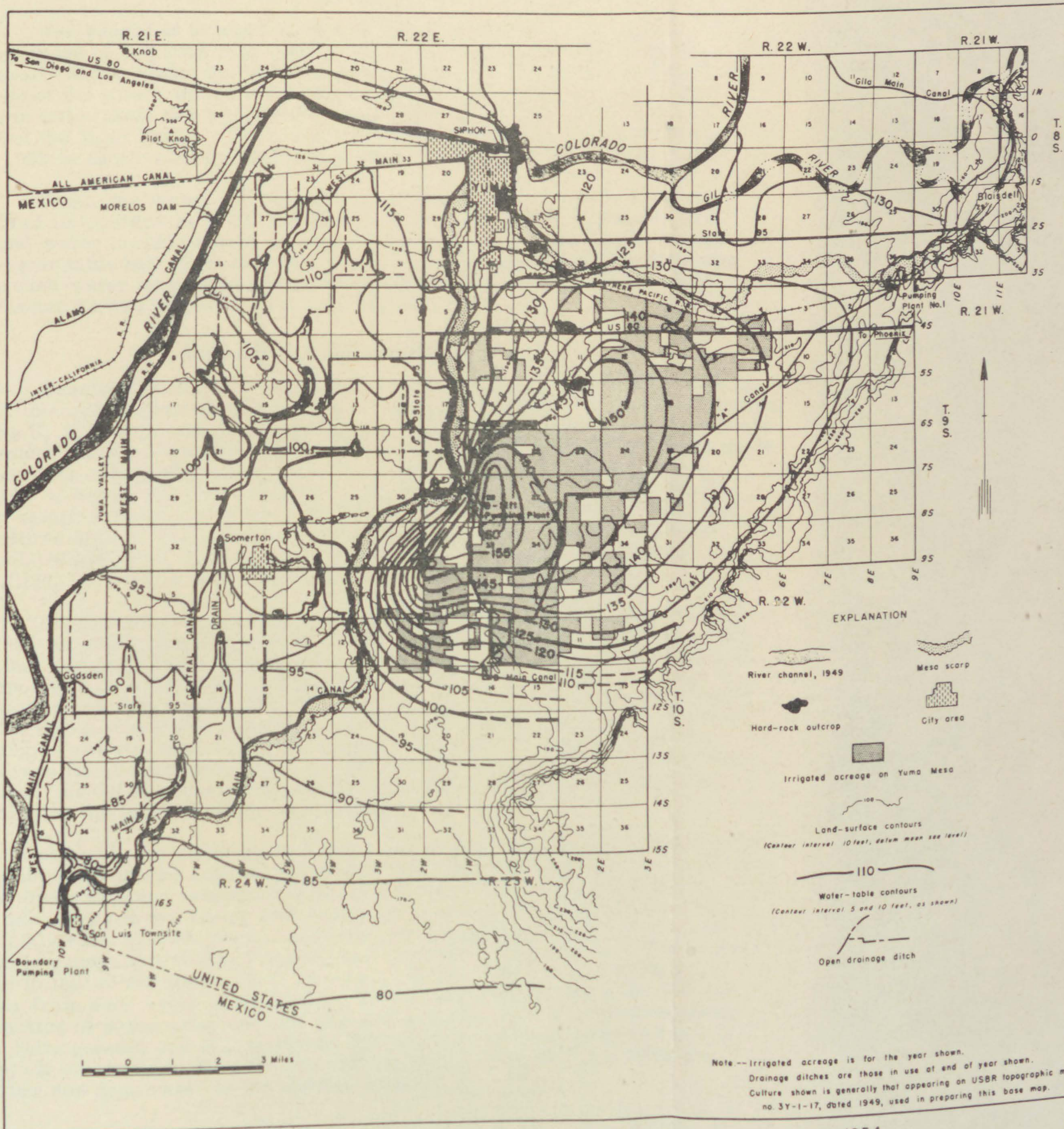

Figure 39.--Map of Yuma area, Ariz., showing water-table contours as of December 1954.

The record is brought up to date by the map for 1955 (fig. 40). Comparison of this map with that for 1925 shows that the water table is generally higher under the Valley, except along the western edge within a mile of the levee, where it is influenced by the Colorado River. The rise in water table has been generally greater in the part of the Valley east of the Main Drain. The general rise of water levels between 1925 and 1955 is shown also by the hydrographs of figures 14 to 18, inclusive.

Under the Mesa, the 95-foot contour in 1955 is 1-1/2 to 4 miles south of its position in 1925, and its trend is more nearly eastward. The ground-water mound extends at least to the east edge of the Mesa, where the water table has risen 20 feet. North of the irrigated land the direction of ground-water movement has been reversed, so that water now moves northward toward the South Gila pumping district.

Changes in Chemical Quality

Practically all the information concerning quality of ground water in the Yuma area comes from the U. S. Salinity Laboratory and its predecessors of the U. S. Department of Agriculture. Since 1929 the Laboratory has made chemical analyses of waters in the Yuma area. The analyses have been made on samples collected from some of the wells drilled on the Mesa by the Bureau of Reclamation in 1947; from some of the deep wells on the Mesa first sampled in 1929; and from several Valley drainage wells. Also, the quantities of salts in the water entering and leaving the Valley have been calculated annually, in order to determine the salt-balance conditions (Scofield, 1929-44; Wilcox 1945-51).

Wilcox and Scofield (1952), in summarizing the data collected prior to 1936 including chemcial analyses of water samples from 65 wells, point out that the ground water under the Mesa is markedly different in chemical composition from the shallow water in the Valley. The water under the Mesa is somewhat more highly mineralized, but the most easily recognized distinction is that it has a higher proportion of chloride, and a lower proportion of sulfate, than the shallow irrigation water of the Valley or the Colorado River from which the shallow water is derived. For the present review, the Cl/SO_4 (chloride/sulfate) ratio has been used as a means of identifying the types of water in the Yuma area.

All wells on the Mesa that were sampled by Wilcox and Scofield prior to 1936 penetrate the coarse-gravel aquifer. The Cl/SO_4 ratio in the water from these samples ranges from about 4 to 11. The waters from two of the deep wells in the Valley that reach the coarse-gravel aquifer also have a Cl/SO_4 ratio of 4 or more, but in the other deep wells in the Valley the ratio is generally between 2 and 3, and in some it is as low as 1.2 — equivalent to that of the shallow ground water. In discussing these analyses of water from deep wells in the Valley, Wilcox and Scofield point out that the "practice of perforating the well casings opposite all water-bearing strata was quite general and it is probable that most of the deep wells are of this type. If this is true, then the low Cl/SO_4 ratios result from mixing the shallow and deep water at the time of pumping."

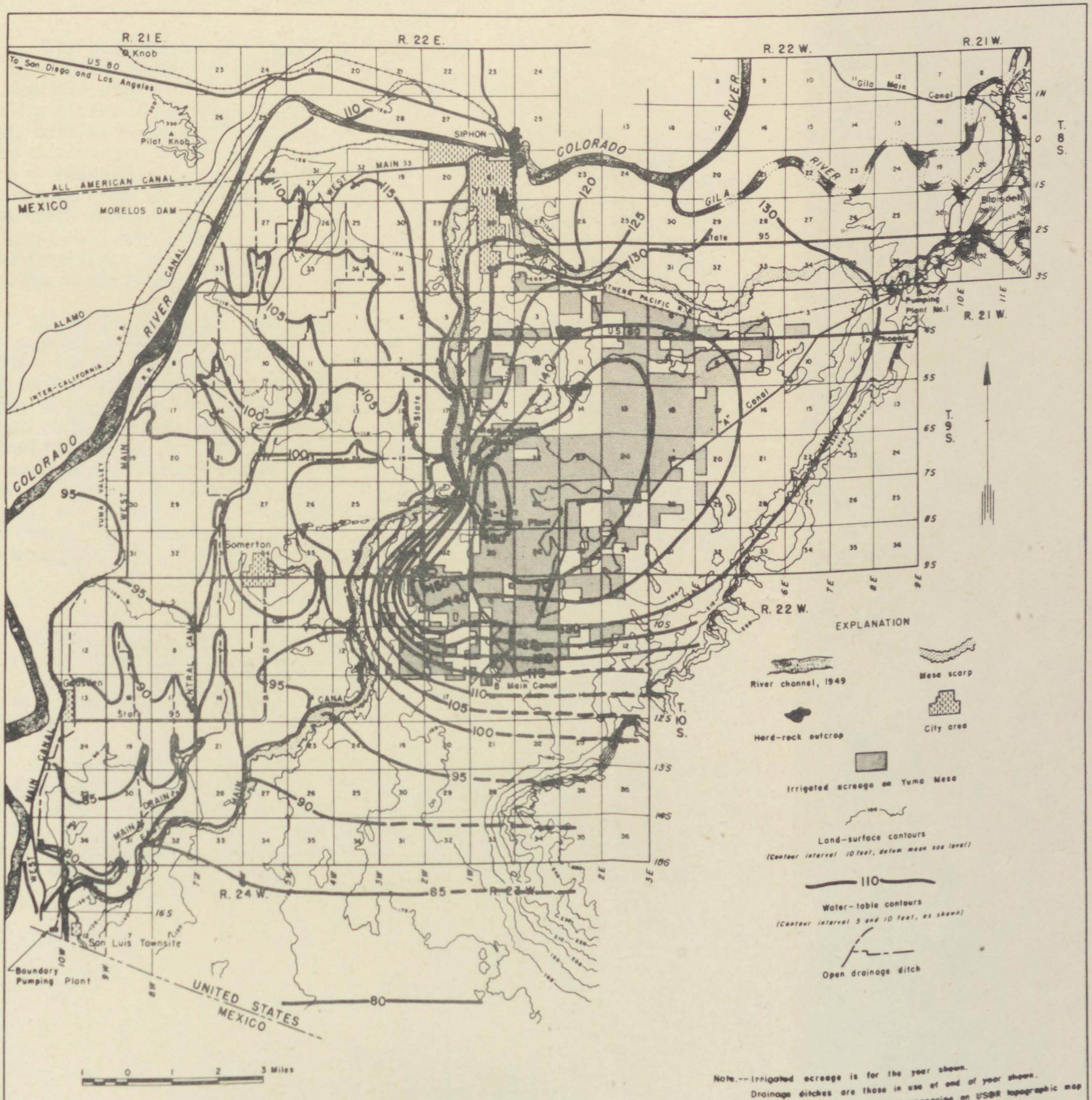

Figure 40.--Map of Yuma area, Ariz., showing water-table contours as of December 1955.

The occurrence of a high Cl/SO_4 ratio in the ground water under the Mesa is not easily explainable from available data. However, Wilcox and Scofield suggest that the source of the water under the Mesa may be the Gila River, which joins the Colorado just north of the Mesa and commonly carries sodium chloride water. Owing to the occurrence and extent of the coarse-gravel aquifer, as determined from the geologic studies, there is reason to believe that a large measure of the ground-water underflow comes from the Gila drainage. A cursory plotting and examination of the ground-water flow lines and iso-Cl/SO_4 lines in the Mesa area strengthens the hypothesis that high-Cl/SO_4 water moves southwestward. The ground-water flow lines also suggest that the ground water moves southwesterly from the northern part of Yuma Mesa.

The Gila River has discharged practically no surface water into the Colorado since 1941, and in a well just south of the Gila channel (7/8 N - 10-1/4 E) the Cl/SO_4 ratio in samples collected periodically in 1952-55 has been approximately the same as that of the Colorado River water, which is believed to be indicative of recharge from the water applied on the land surface. However, in a well 2 miles south of the Gila channel (2-1/4 S - 6-1/2 E), the Cl/SO_4 ratio in those years has remained between 5 and 6, comparable to that of waters under the Mesa farther south. If the coarse-gravel aquifer extends eastward up the Gila River channel, the water in it may be affected also, both in quantity and quality, by recharge from irrigation near Wellton. Such changes, however, doubtless would be slow to reach the Yuma area.

Changes in Mesa Wells

Of the 4 deep Mesa wells that were sampled in 1929 and resampled in 1947 and 1948, only one was within the area that was irrigated prior to 1947. In this well (near 10 S - 1 W) the Cl/SO_4 ratio dropped from 6.4 in 1929 to 0.7 in 1947. In the other 3 wells the change in Cl/SO_4 ratio was negligible.

In 1947 and again in 1948, water samples were collected and analyzed from about a dozen of the Bureau of Reclamation test wells on the Mesa, roughly along a north-south line south of Yuma. These wells are about 100 feet deep and penetrate only slightly below the pre-irrigation water-table positions. The results must be viewed with some caution, because the samples were collected from unused wells in which an open end provides the only access to ground water.

Changes in Drainage Wells

Wilcox and Scofield (1952) describe a deep drainage well in the northwest part of the Valley at 1 S - 5-3/4 W, and its use in quantitative and chemical-quality tests made in 1930. The casing in the well is perforated opposite the coarse-gravel aquifer and the overlying alluvium. In the course of a 60-day pumping test during which about 750 acre-feet of water was discharged, the total concentration of mineral matter, expressed as electrical conductivity, increased from 1,090 to 1,480 micromhos — rapidly at first and then leveling off. Percentage composition did not change appreciably, and the Cl/SO_4 ratio remained in the range from 1.3 to 1.8.

During the years 1947-51, water samples were collected periodically from 3 of the Valley drainage wells near the East Main Canal. As shown by the analyses of these samples (table 2), there has been a progressive decrease in concentration of mineral matter in the water pumped from all 3 wells during the period of sampling. As with the drainage well tested in 1930, a large change occurred in wells 4 and 6 in the first part of the period; and in all 3 wells there were appreciable progressive changes throughout the 4 years. In the northernmost well (No. 4), which is near the northern limit of the area irrigated on the Mesa, the concentrations of sodium, calcium, magnesium, sulfate, and chloride ions have all decreased during the period. In drainage well 7 the amount of chloride, in equivalents per million, increased during the 4 years, counter to the trend for the other ions included in the analyses. In well 6 the amount of chloride decreased, but at a rate less than that of the sulfate. Thus in both the wells 6 and 7, located in the Big Bend area, the Cl/SO_4 ratio has increased since pumping began. The implication from these data is that, as pumping continued over the years, wells 6 and 7 obtained a progressively greater proportion of water from the coarse-gravel aquifer, but well 4 did not.

Changes in Salt Balance

The problem of salt balance enters into this review because of the evidence, already presented, that the use of water for irrigation in the Valley is a controlling factor in the position of the water table. With more liberal applications, the water table rises unless the drainage system is able to drain off the excess. The use of irrigation water has demonstrably increased since Hoover Dam was completed. With fairly constant irrigated acreage since 1925, the net imports of water by the Valley have increased from about 200,000 acre-feet a year prior to 1935 to more than 300,000 acre-feet in recent years. Certainly this increased use contributes to the drainage problems.

In Yuma, with mean temperature exceeding 90°F during July and August, with average annual precipitation about 3-1/2 inches and evaporation more than 20 and perhaps more than 30 times as great, the Colorado River is a basic essential for agriculture. However, it carries an average of about a ton of salts in every acre-foot of water. If the water applied for irrigation in the Valley Division were limited to the consumptive use, these salts would accumulate in the soil at a rate of several tons per acre each year. Thus, the need for maintaining adequate records of the salt balance is evident.

Table 2 - Chemical analyses of water from Valley drainage wells
(Analyses by U. S. Salinity Laboratory, Riverside, Calif.)

Drainage Well No. 4 (U.S.B.R. No. 3)
SW$\frac{1}{4}$ SW$\frac{1}{4}$ Sec. 5, T. 9 S., R. 23 W.

Date	Conductivity (micromhos)	Total solids (tons per acre-foot)	Percent sodium (Na)	Chloride-sulfate ratio (Cl/SO_4)	Sodium (Na) (epm)*	Calcium (Ca) (epm)*	Magnesium (Mg) (epm)*	Sulfate (SO_4) (epm)*	Chloride (Cl) (epm)*
11/26/47	10,100	9.73	74	1.9	83.53	15.56	14.11	36.95	68.85
12/31/47	9,120	-	-	-	74.65	-	-	-	59.22
1/21/49	6,040	-	59	1.5	29.04	-	-	23.33	35.70
1/19/50	5,610	5.27	64	1.5	38.40	12.44	8.96	21.53	32.40

Drainage Well No. 7 (U.S.B.R. No. 1)
University of Arizona Farm SE$\frac{1}{4}$ NE$\frac{1}{4}$ Sec. 30, T. 9 S., R. 23 W.

3/25/47	2,930	2.8	52	.8	16.51	9.59	5.65	13.99	11.54
7/3/47	2,870	2.6	59	1.3	17.67	7.80	4.45	10.81	13.58
1/21/49	2,580	-	66	1.6	16.88	-	-	8.59	13.80
1/19/50	2,610	2.2	61	1.8	16.10	6.46	3.85	7.70	14.10
2/14/51	2,590	2.2	60	2.0	15.58	6.39	3.71	6.99	14.30

(*) - Equivalents per million.

Table 2 - Chemical analyses of water from Valley drainage wells--continued.
(Analyses by U. S. Salinity Laboratory, Riverside, Calif.)

Drainage Well No. 6 (U.S.B.R. No. 2)
DeWitt Ranch, SW$\frac{1}{4}$ SW$\frac{1}{4}$ Sec. 9, T. 9 S., R. 23 W.

Date	Conductivity (micromhos)	Total solids (tons per acre-foot)	Sodium (Na) (percent)	Chloride-sulfate ratio (Cl/SO_4)	Sodium (Na) (epm)*	Calcium (Ca) (epm)*	Magnesium (Mg) (epm)*	Sulfate (SO_4) (epm)*	Chloride (Cl) (epm)
3/25/47	3,640	3.19	62	2.0	23.23	9.06	5.21	10.93	21.51
7/3/47	3,290	2.83	60	2.1	19.79	8.57	4.73	9.14	19.49
10/23/47	3,110	2.71	59	2.1	18.89	8.21	4.71	8.65	18.39
11/26/47	3,090	2.70	58	2.1	18.43	8.43	4.72	8.67	18.20
12/31/47	3,060	-	-	-	18.54	-	-	-	18.13
4/16/48	2,990	2.58	60	2.1	18.13	7.50	4.52	8.25	17.70
7/20/48	2,940	2.54	60	2.2	17.66	7.29	4.39	8.03	17.30
1/20/49	2,860	-	61	2.2	17.35	-	-	7.60	16.50
1/19/50	2,700	2.29	62	2.4	16.49	6.31	3.89	6.74	16.05

Scofield (1929-44) in his annual report for 1935 concerning Yuma Valley, stated that " . . . the adverse salt balance condition in the Valley has continued throughout the past year [1935]. For the 7-year period [1929-35 inclusive] the aggregate adverse balance is 355,831 tons." More than 100,000 tons were left in the Valley in the single year 1934.

The graphs in figure 41 show the amounts of dissolved solids, and of chloride and sulfate, contained in the net inflow (table 1) and in the outflow as measured at the Boundary Pumping Plant. The curve showing dissolved solids in the imported irrigation water clearly demonstrates the stabilizing influence of Lake Mead on the chemical quality. Prior to 1935 the imported water, during the irrigation season, was erratic in quality and often was high in dissolved solids; after 1935 the quality has changed less and the proportion of dissolved solids has been moderately low. The basic data for these graphs are presented by Scofield (1929-44) and Wilcox (1945-51), except that their figures for inflow are based on "net deliveries to farms" rather than net inflow to the Valley. These graphs illustrate the conditions prior to 1935 as described by Scofield, for they show far greater inflow than outflow of dissolved matter, particularly in the drought years 1931 and 1934. Since 1935 the proportion of inflowing salts which have been carried on out of the Valley has increased significantly. The most significant change is in the chloride relationship. Since 1938 the quantity leaving the Valley has exceeded that entering the Valley. As pointed out by Scofield, the salts of sodium and of chloride are more soluble than the salts of the other constituents. Consequently they tend to remain in solution and thus are carried away in the drainage.

The residual salts in the Valley — the differences between inflowing and outflowing totals — are indicated by figure 42. Here is indication of a progressive though irregular decline in the amount of residual salts left each year since 1935. It appears that sufficient water is used to move out not only all the chloride brought in, but to leach and remove the accumulations of past years, when the salt balance was adverse. The question as to the need for such leaching would have to be answered by the present condition of the soils, which is beyond the scope of this review. But the graphs indicate that the use of water in recent years has been more than sufficient to maintain a satisfactory salt balance.

The accumulation of soluble material in the Valley since the salt-balance studies began in 1929 is shown in figure 43, which is a double mass plot of cumulative residual salts against the water consumed in the Valley since 1929. In this diagram chloride is taken as representative of the more soluble constituents, especially sodium chloride, which in high concentrations are toxic to plants and produce adverse soil reactions. The sulfate is taken as representative of the less soluble matter, such as calcium sulfate and calcium bicarbonate, which are generally harmless to crops and may be beneficial to the soil.

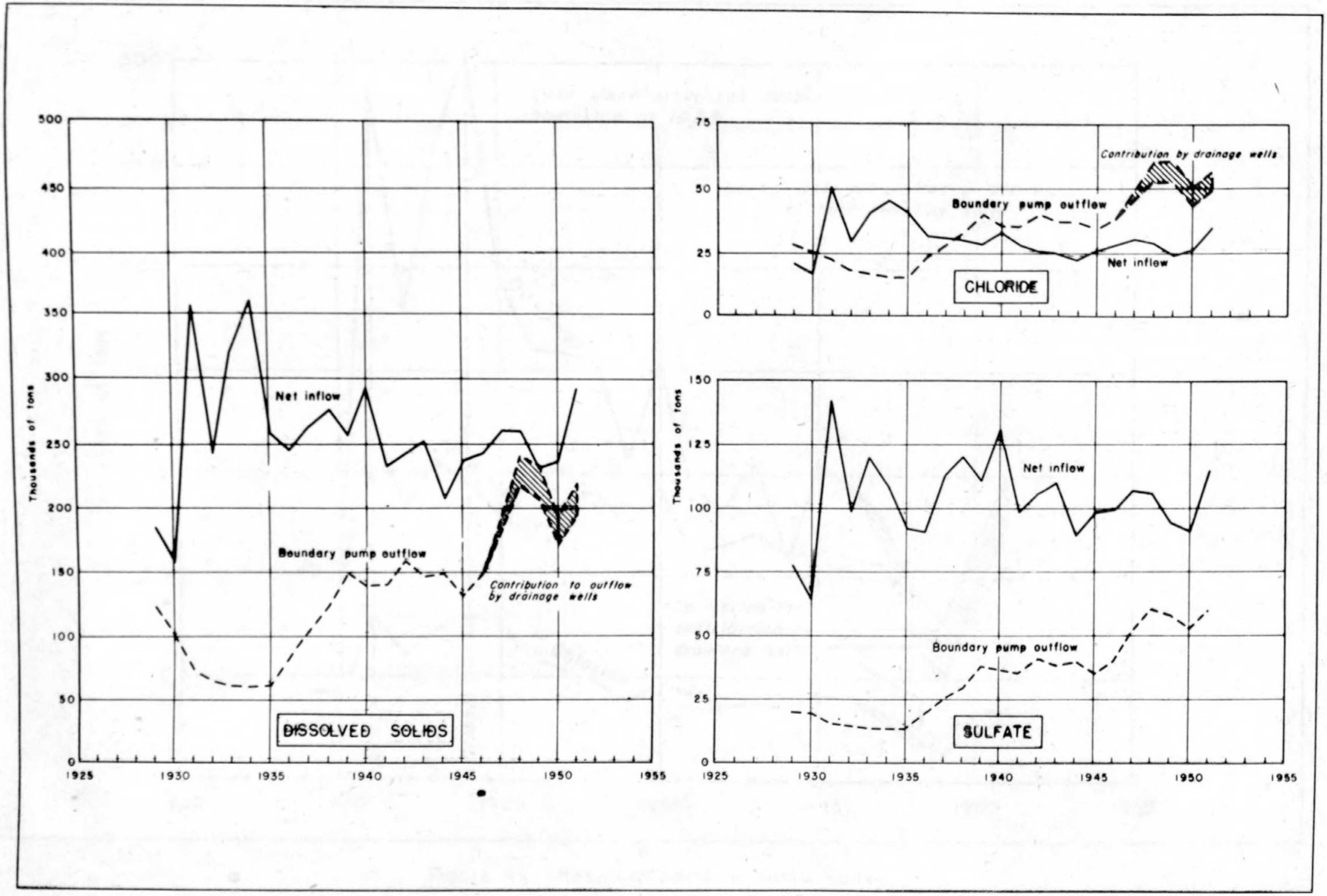

Figure 41--Dissolved solids, chloride, and sulfate in the net inflow to and outflow from the Yuma Valley.

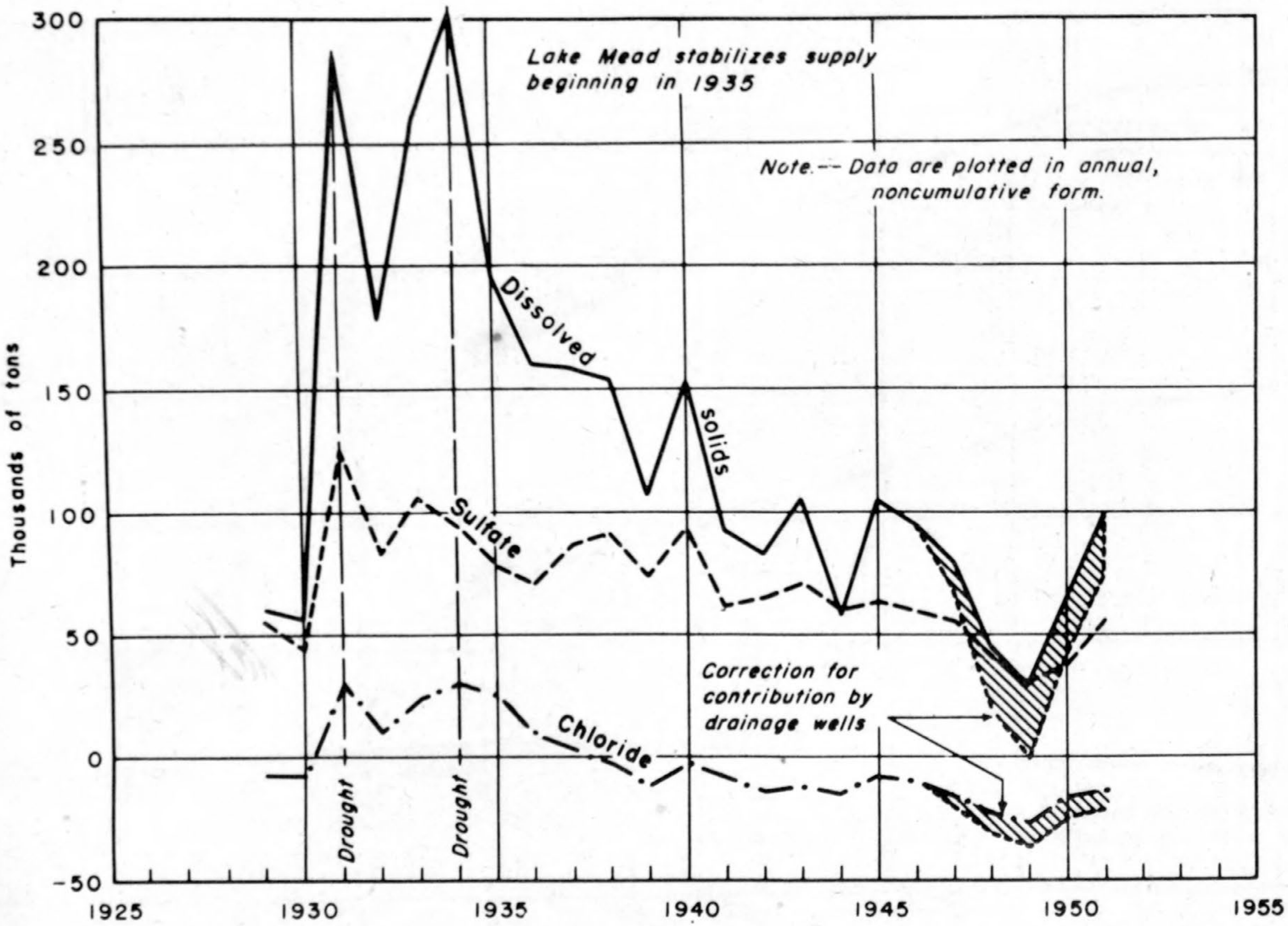

Figure 42.--Residual salts in Yuma Valley

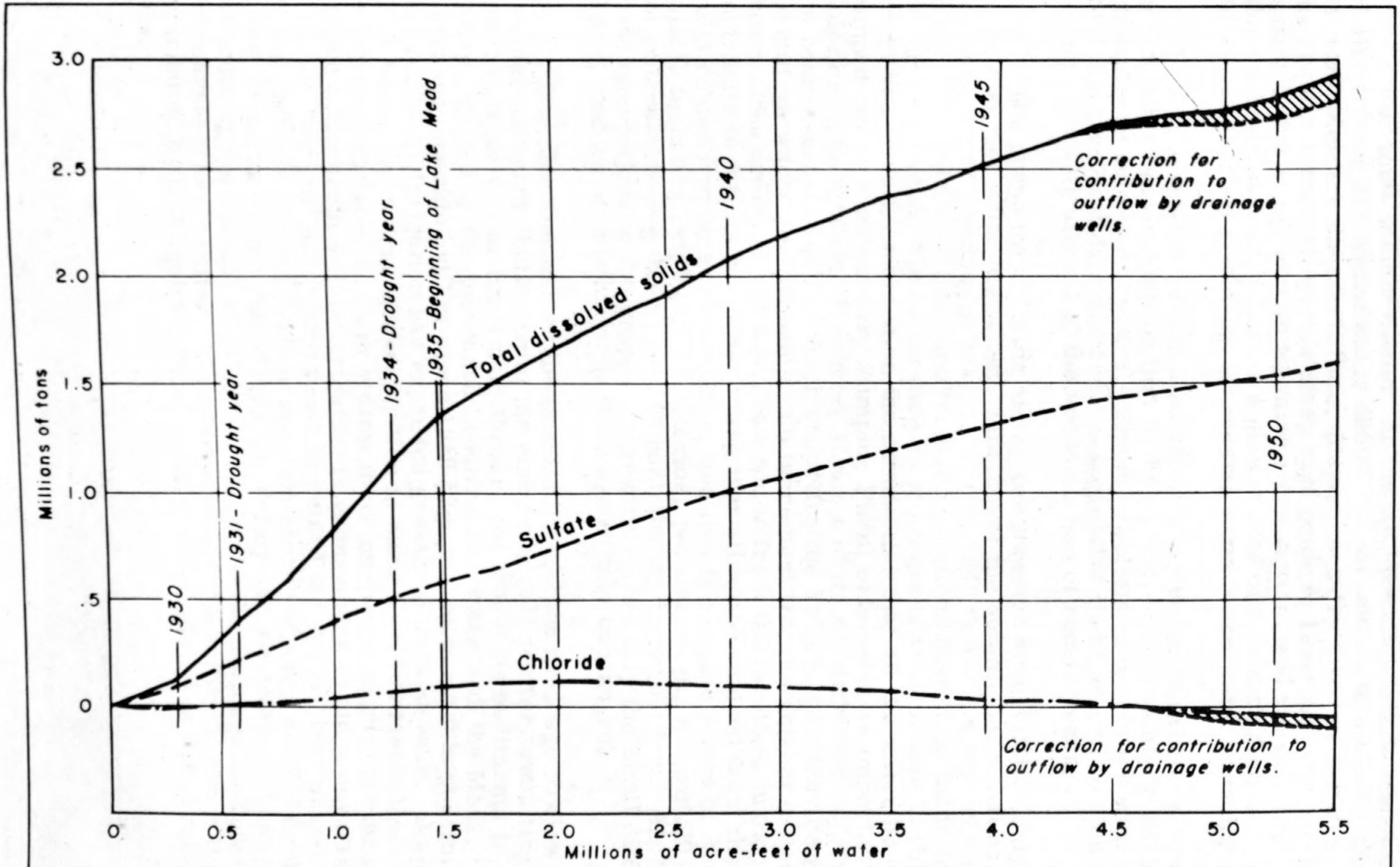

Figure 43. --Double mass plot of dissolved solids vs. water left in Yuma Valley, 1929-51.

For total soluble matter, an upward-trending line is characteristic of all arid regions where water can be evaporated from the soil, and typical examples are the alkali flats, playas, and dry lakes of the West. In the graph for the Valley, the steep rise prior to 1935 indicates rapid accumulation in proportion to water consumption, and the more gentle slope since that year indicates a slower rate of accumulation, with a fairly uniform but gradually decreasing ratio to the water consumption.

The graph for sulfate also shows a decrease in rate of accumulation in relation to water consumption in the period, most notably in 1935 and gradually in subsequent years. The parallelism of this graph with that for total dissolved solids since 1941 is suggestive that the less soluble salts comprise practically all of the accumulation of recent years.

The graph for chloride shows progressive accumulation only until 1937, and thereafter a gradual dwindling of the soluble salts that had accumulated in previous years, so that by 1948 there was less chloride in the Valley than in 1929, and further reductions have been made in subsequent years. This inference as to progressive decrease in chloride in Valley soils is based on the assumption that all the water being pumped out (at the Boundary Pumping Plant) originates as imported Colorado River water. However, if some of this outflow comes from the coarse-gravel aquifer which underlies the Valley, the chloride in the outflow would also include some increment from the higher-chloride water. The drainage wells do draw water from this aquifer, and do contribute to the outflow. Assuming that all water pumped from these wells comes from the deep aquifer, and that it contains 3 tons of dissolved solids, including 1-1/3 tons of chloride, per acre-foot, we probably are not underestimating their possible contribution to the outflow. Applying these corrections to the graphs, however, makes only the small differences shown, and leaves the major pattern essentially unchanged.

One should consider the possibility that the drainage outflow includes salt contribution from the coarse-gravel aquifer, resulting from upward ground-water movement through the overlying sediments in the Valley, caused by the increased head from irrigation on the Mesa. The increased chloride outflow since 1946 (fig. 41) supports this possibility, because Mesa irrigation has expanded greatly since that year. On the other hand, the coarse-gravel aquifer is more than 100 feet below the Valley land surface, beneath sediments of moderate to poor permeability, and the water from Valley irrigation is endeavoring to move downward from the land surface, which tends to retard the upward movement. Also, the soil zone is a much more accessible source of salts readily soluble in the irrigation water that leaves the Valley via the drain ditches. Thus determining the amount of salts contributed to the drainage outflow from the coarse-gravel aquifer, like determining the quantity of water itself contributed by that aquifer, must await the availability of more detailed data.

CONCLUSIONS AND RECOMMENDATIONS

The review of available basic data concerning ground water in the Yuma area has led to further proof of the generalization that, for any area, an adequate knowledge of the geology is essential to an understanding of the ground-water hydrology. This review has contributed to the great volume of basic data on the Yuma area through collection of deep-well logs from various sources, through brief geologic reconnaissance, and through interpretation of all these data to depict the geology of the area. One significant geologic feature has been recognized — a continuous and highly permeable coarse gravel, occurring approximately at sea level, underlying both Yuma Valley and Yuma Mesa and doubtless extending north into South Gila Valley and southwest into Mexico.

This coarse-gravel aquifer changes the whole concept of ground-water occurrence and movement in the Yuma area. If that aquifer is neglected, the ground-water flow is necessarily concluded to be chiefly through sand — greatest in the upper part of the zone of saturation and decreasing with increasing depth because of lesser permeability owing to the presence of clay and silt beds. If the coarse-gravel aquifer is recognized and incorporated into the interpretation of the flow pattern, all this is changed. For this review salient features of the ground-water flow pattern, with a highly permeable aquifer underlying sand and silt of varying but lesser permeability, have been developed theoretically by use of electric analogs, and confirmed by various items of observed data. However, these basic data are not sufficient to permit a general quantitative analysis of ground-water movement.

With reference to the specific problem that led to this review — whether water applied for irrigation on the Mesa aggravates materially the drainage problem in the Valley — the writers believe that there is sufficient evidence in the available data to support the conclusion that the Mesa irrigation does have such an effect. This evidence includes the theoretical studies using an electrical model, the effects of pumping wells that tap the coarse-gravel aquifer, the changes in form of the water table in the eastern part of the Valley since 1943, the history of water-level fluctuations in some wells in the Valley just west of the Mesa, and the absence of any indication in geologic studies of an effective barrier to ground-water movement from the Mesa to the Valley. The coarse-gravel aquifer is an important factor in this flow pattern, however, and because very few of the available data show the characteristics of that aquifer exclusively, it is impossible from present information to determine quantitatively the rate of ground-water flow from the Mesa toward the Valley.

It is also evident from the available data that the drainage problem in the Valley is aggravated by increasingly liberal applications of water for irrigation in the Valley. The data concerning salt-balance conditions indicate that the water applied is sufficiently in excess of consumptive use that the Valley is not only maintaining its salt balance, but is probably losing the more soluble salts (including sodium chloride) which had accumulated in the soil prior to 1935. In that year the Valley began to receive water of decreased average concentration of soluble salts from Lake Mead.

Determination of the exact degree to which Mesa irrigation and Valley irrigation respectively are responsible for the high water table in the Valley is not likely to be achieved. This three-dimensional problem involves questions of vertical movement of water beneath the Mesa and Valley, as well as lateral movement from one to another. Even if this problem could be solved satisfactorily, to solve it would require a great amount of additional basic data. The cost of such a study probably would be far greater than the cost of techniques for controlling ground water which have proved to be effective in areas of past distress.

In this review we have dealt with a relatively small part of a broad hydrologic unit which has as its common bond the lower Colorado and lower Gila Rivers as sources of ground water. The ground-water hydrology of this broad area — covering the entire apex of the Colorado delta below Imperial Dam and extending up the Gila for an unknown distance — is beyond the scope of the review, but is of importance to all inhabitants of the region. One specific feature that might be cited is the ground-water mound under Yuma Mesa, from which water is now moving outward in all directions. The movement northward toward the South Gila Valley pumping district, southward toward Mexico, and southeastward toward extensive lands owned by the State of Arizona may well bring about extensions of the hydrologic studies reviewed in this report. The beneficial or detrimental effects of this creation of man are of interest to local inhabitants, to the State, and to the Nation.

Our first recommendation is concerned with basic data. Abundant data are available on the water and sediments underlying the Valley and Mesa above mean sea level. Lacking, however, is adequate information on the extensive coarse-gravel aquifer which is approximately at sea level in the vicinity of Yuma Valley. Owing to this lack of data, the role of that aquifer in the area's hydrology has been underemphasized or even ignored in previous studies. Its importance may be overemphasized in the present review; whether this is so can be determined only by means of a more comprehensive evaluation of the hydrologic characteristics of the aquifer, which will require drilling wells for this express purpose in some parts of the region. Any study of the coarse-gravel aquifer should extend beyond the immediate areas where controversies have arisen over drainage problems. In fact, this aquifer may be extensive enough to become an item of common interest or controversy among those having special interests in the Wellton-Mohawk area, the South and North Gila Valleys, the Yuma Mesa and Valley, and the San Luis Mesa and lower delta in Mexico. However, the coarse-gravel aquifer is only one element in a recommended program of geologic studies, both detailed in areas of present or prospective interest in ground water, and comprehensive for the purpose of integrating the detailed data into a comprehensive understanding of the regional geology. The importance of this geologic research as a basis for understanding the hydrology has already been sufficiently stressed.

A second and general recommendation is in the form of a plea for a broader outlook on the part of all water users with respect to this important resource. It is recognized that, because of Yuma's hot desert climate, the rate of consumptive use of water for irrigation must be among the highest in the country; relatively liberal nonconsumptive use is essential also for maintaining a satisfactory salt balance and for maintaining water within reach of crops in pervious sandy soils. The total "use" of water in the Yuma area, however, may well exceed these consumptive and nonconsumptive needs, because of human factors: the psychology of scarcity which dictates that in arid lands one should attempt to "use" all the water he can obtain; and the conviction that "use" of water is essential to the proof and preservation of a water right. Unfortunately, use beyond the consumptive plus nonconsumptive requirements necessarily increases the nonconsumptively used water, and thus creates or aggravates drainage difficulties. A suggested alternative is effective management of the water resources in order to attain the greatest amount of use and reuse of water for beneficial purposes. For such management Yuma has, in surface-water diversions, shallow drains, and ground-water pumps, the tools for raising or lowering the water table, thereby regulating its position in accordance with agricultural needs. Such effective management would require expert hydrologic engineers, and they in turn would need an adequate foundation of hydrologic data as a basis upon which to operate. Furthermore, for effective regulation of the water resources to achieve the highest degree of beneficial use, their jurisdiction must extend beyond the limits of the individual project boundaries that have been set up in the past, and might well embrace the entire apex of the Colorado delta and possibly the lower part of the Gila River flood plain as a well-defined hydrologic unit.

APPENDIX

Table A.--Records of Yuma Mesa wells for which hydrographs are given

Well number[a]	Elevation of measuring point (feet)	Depth of well from land surface (feet)	Elevation of well bottom (feet)	Diameter of casing (inches)	Aquifer	Well record begins
Paired wells in area of perched-water mound:						
6-1/2 S - 1/2 E	197.24 198.94	103.4 60.5	93.5 136.4	2-1/2 3/8	Gravel-some large Fine sand-trace of clay	May 1947 March 1953
7 S - 0 W	194.2 195.78	119.0 70.1	74.2 123.1	2-1/2 3/8	Sand, some gravel Fine sand, trace of clay	February 1947 March 1953
7 S - 1/2 W	195.54 195.91	105.0 55.2	87.9 137.7	2-1/2 3/8	Sand, scattered gravel Sand	March 1947 January 1952
7-1/2 S - 0 W	193.52 194.72	102.0 73.8	91.0 119.2	2-1/2 3/8	Clay Fine sand	May 1947 March 1953
7-1/2 S - 1/2 W	194.2 197.31	97.9 50.0	95.0 142.9	2-1/2 3/8	Sand, some gravel Sand, trace of clay	February 1947 March 1953
8 S - 0 W	201.48 199.26	101.0 60.3	100.5 137.2	2-1/2 3/8	Clay Fine sand	May 1947 March 1953
8 S - 1/2 W	193.3 194.3	100.6 50.3	90.8 141.1	2-1/2 3/8	Gravel and sand Coarse sand	May 1947 March 1953
8 S - 1 W	189.6 191.47	101.1 50.1	88.1 139.1	2-1/2 3/8	Sand, some gravel Fine sand, trace of clay	May 1947 March 1953
8-1/2 S - 1-1/2 W	186.48 188.5	100.2 52.3	85.5 133.4	2-1/2 3/8	Sand	August 1947 January 1952
9 S - 1 W	191.06 192.02	101.0 37.2	80.1 152.9	2-1/2 3/8	Sand	June 1947 January 1952
10 S - 2 W	184.6 186.02	101.0 63.4	82.6 120.2	2-1/2 3/8	Sand, some gravel	April 1947 January 1952
10 S - 3 W	161.9 163.3	99.5 50.1	60.9 110.3	2-1/2 3/8	Sand Sand, clay binder	May 1947 January 1952

Table A.--Records of Yuma Mesa wells for which hydrographs are given--continued.

Well number a/	Elevation of measuring point (feet)	Depth of well from land surface (feet)	Elevation of well bottom (feet)	Diameter of casing (inches)	Aquifer	Well record begins
Single 100-foot wells at selected points on ground-water mound:						
5 S - 2 E	209.04	90.0	118.5	2-1/2	Gravel-large-medium	June 1947
7-1/2 S - 1 W	196.96	101.2	89.9	2-1/2	Sand	April 1947
8 S - 2 W	186.48	101.0	84.3	2-1/2	Tight sand	April 1947
8 S - 2-1/2 W	172.5	101.1	71.0	2-1/2	Sand	April 1947
9 S - 2 W	186.0	101.5	84.0	2-1/2	Sand, some gravel	April 1947
Deep wells tapping coarse-gravel aquifer:						
5-7/8 S - 4-5/8 E	210.5	195.0	13.9	16	Water, sand and gravel	May 1945
10-1/2 S - 4 E	223.5	250.0	-28.9	16	Sand and gravel	April 1947

a/ Well number is its grid location.

Table B.--Records of Yuma Valley wells for which hydrographs are given

Well number a/	Elevation of measuring point (feet)	Depth of well from land surface (feet)	Diameter of casing (inches)	Aquifer	Well record begins
1 S - 3 W	122.99	11.8	1-1/2		October 1911
3 S - 3 W	118.48	11.6	1-1/2		June 1916
4-1/2 S - 7 W	112.56	12.0	1-1/2	Sand	January 1942
5 S - 7 W	114.01	11.9	1-1/2		October 1911
5 S - 6 W	109.71 b/	10.5	1-1/2		June 1916
6 S - 4-1/2 W	115.01	11.59	1-1/4	Sand	June 1916
6 S - 3 W	111.89	10.9	1-1/2		October 1911
7 S - 3 W	110.57	14.2	1-1/4	Sand	June 1916
7-1/2 S - 3 W	110.27	12.0	1-1/4		June 1916
8 S - 3 W	111.81		1-1/4		July 1916
8 S - 3-1/8 W	112.84	12.0	1-1/4		January 1946
7 S - 2 W	113.89	18.5	1-1/2		June 1916
6 S - 1-1/2 W	117.92	13.28	1-1/2	Sand	October 1911
5 S - 1-1/2 W	116.35	16.05	1-1/2	Sand	June 1916
8 S - 8 W	113.41				October 1911
9 S - 6 W	102.95				October 1911
8 S - 5 W	108.02	10.8	2		October 1911
9 S - 3-3/4 W	111.10				October 1911
10 S - 4 W	105.08				June 1916
11 S - 6 W	101.58				October 1911
12 S - 9 W	97.42				October 1911

a/ Well number is its grid location.
b/ Approximate depth; casing bent.

Note: Most wells in the Valley are constructed as a 10 or 15-foot length of casing finished with a 2-foot well point.

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