PRELIMINARY REPORT

PR-235-77-2

September 15, 1977

LIMITED OFFICIAL USE

OVERVIEW REPORT OF HYDROLOGY AND WATER DEVELOPMENT COLORADO DELTA UNITED STATES AND MEXICO

Prepared For

INTERNATIONAL BOUNDARY AND WATER COMMISSION
UNITED STATES SECTION

Hon. J. F. Friedkin
Commissioner

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Hon. J. F. Friedkin
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INTERNATIONAL BOUNDARY AND WATER COMMISSION
UNITED STATES SECTION
P.O. Box 20003
El Paso, Texas 79998

Dear Commissioner Friedkin:

I am pleased to transmit herewith Preliminary Report (PR-235-77-2) "Overview Report of Hydrology and Water Development; Colorado Delta, United States and Mexico" dated September 15, 1977. This report was prepared in accordance with your request in letter dated July 2, 1976.

The overview report contains a preliminary review of the hydrologic conditions of the Colorado River Delta region in United States and Mexico as they pertain to the development, utilization, and management of the water resources. This overview includes pertinent information of the effects on hydrological components caused by various water management regimens. The principal effects and problem areas, which require consideration by United States authorities, are given in the "Summary of Findings".

We gratefully appreciate the splendid cooperation and provision of technical data by your staff for preparation of this report.

Sincerely yours,

John W. Harshbarger

John W. Harshbarger

Encl: PR-235-77-2 (40)

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OVERVIEW REPORT
OF
HYDROLOGY AND WATER DEVELOPMENT
COLORADO DELTA
UNITED STATES AND MEXICO

I. SUMMARY OF FINDINGS

The main purpose of this overview report is to assess the significant hydrologic conditions as they pertain to the development, utilization, and management of water resources in the Colorado River Delta region which lies within two countries; United States and Mexico, and four states; Arizona, California, Sonora, and Baja California (Figure 1). The several specific objectives comprise: 1) A review of the historic events of water works and development as they relate to changes imposed on the hydrological system; 2) the cause and effect relationships of hydrological components resulting from the various regimens of water management; 3) specific attention on the water balance budget of the groundwater flows in the several subsections of the delta and the amounts that flow across the international boundary; and 4) an outline of the pertinent effects and problem areas which require assessment for consideration by United States authorities of the desirability and terms of an international groundwater agreement between the two countries.

Salient features of the Colorado River Delta region, principal characteristics of the hydrological components, and major

elements of the water balance budget with especial attention to the distribution of groundwater flow which crosses the international boundary from United States to Mexico, are given herein.

HYDROLOGICAL FEATURES

1. The Colorado Delta region includes a complex sequence of alluvial sediments that form a vast groundwater reservoir. There are large extensive layers of sand and highly permeable gravels which accommodate high-yield wells in United States and Mexico. It has been estimated that the amount of recoverable groundwater is on the order of 200 million acre-feet (AF), about evenly divided between United States and Mexico (Table 2).

2. During its unregulated state, the Colorado River was the main source of recharge to the groundwater reservoir. Since the closure of Hoover Dam and completion of diversion structures and canals in United States and Mexico (1935-1950) nearly all the river flows are conveyed to agricultural lands.

3. Irrigation systems have caused a major change in groundwater conditions in the Colorado Delta region. a) Percolation of irrigation water and leakage from unlined canals now comprise the principal source of groundwater recharge. b) Groundwater mounds (rise in water levels) have been created beneath irrigated areas and unlined canals. c) By the mid-1950's to early 1960's, severe water-logging conditions occurred, which required construction of drainage canals and wells to lower groundwater levels for viable growth of crops. d) Nearly all of these drainage waters are delivered to water supply canals and/or the Colorado River channel for reuse as irrigation waters.

HISTORICAL WATER DEVELOPMENT EVENTS

Important water developments which have effected changes in the hydrologic regimen in the Colorado Delta region, are listed chronologically as follows:

1901 Diversion of Colorado River water via Alamo Canal, Mexico to Imperial Valley;

1904 Yuma Valley Irrigation Project was authorized, the first Bureau of Reclamation irrigation development project; first water delivered in 1912;

1935 Completion of construction of the Hoover Dam;

1938 Completion of the Imperial Dam. These structures comprised a major role in the change of the hydrologic regimen of the Colorado Delta;

1940 Delivery of water from Imperial Dam via All-American Canal to Yuma and Imperial Valleys began;

1943 Completion of Gila Gravity Main Canal to deliver water to North Gila Valley and Yuma Mesa;

1944 United States and Mexico adopted treaty allotting 1,500,000 AF/yr (acre-feet per year), "...of the waters of the Colorado River from any and all sources...The United States shall deliver all waters allotted to Mexico...in the bed of the limitrophe section of the Colorado River,...";

1945 Delivery of Colorado River water to Mesa Unit of Yuma Mesa Division began;

1950 Completion of Morelos Dam to divert water to Mexicali Valley via the Alamo Canal and 1944 Treaty provisions relating to Colorado River became effective;

1952 Completion of canals and pumping system for conveyance of Colorado River water to Wellton-Mohawk project;

1955 Mexican government authorized drilling of 281 deep wells in Mexicali Valley to augment surface water supply;

1961 Saline waters from drainage wells in Wellton-Mohawk project discharged into Colorado River; first drainage pumped from South Gila Valley discharged into Gila River upstream of the mouth; Mexico protested high salinity of waters delivered upstream of Morelos Dam;

1965 Minute No. 218, five-year agreement to resolve salinity problems adopted by the United States and Mexico;

1968 Construction of 12 drainage wells began on Yuma Mesa;

1971 Mexico began installation of San Luis wellfield;

1972 Minute No. 242 signed providing immediate improvement in the quality of Colorado River waters going to Mexico. Pumped waters from Yuma Mesa delivered to Colorado River above Morelos Dam. In December groundwater pumpage began at San Luis Mesa wellfield in Sonora, Mexico;

1973 Mnnute No. 242, agreement adopted to deliver about 1,360,000 AF/yr at Morelos Dam with an annual average salinity of no more than 115 ppm ± 30 ppm U.S. count (121 ppm ± 30 ppm Mexican count) over the average salinity of Colorado River waters which arrive at Imperial Dam. Additional 140,000 AF/yr to be part of 1,500,000 AF/yr to be delivered on land boundary at San Luis and in limitrophe section of Colorado River having customary qualities

Jan. 1976 The effects of pumpage from San Luis wellfield and 12 Yuma Mesa wells indicate a water level decline of about 12 feet at the international boundary and an increase of the hydraulic gradient of about 75 percent.

ELEMENTS OF THE WATER BUDGET

Major water components are summarized for the four subdivisions of the Colorado Delta region; Yuma area, Imperial Valley, and Mexican areas (Mexicali Valley and San Luis Mesa-Valley).

The validity, or accuracy, of the various budget components is related to the availability of adequate basic water data and quantitative analyses of the groundwater system for each of the four subdivisions. Information for the water budget was obtained from U.S. Geological Survey publications for the Yuma and Imperial Valley subdivisions. Only limited data are available for the Mexican areas, transmitted from the Mexican Section of International Boundary and Water Commission. Values for the water budget components are assumed to be representative of hydrologic conditions prevailing in the late 1960's, prior to the initiation of pumpage from the San Luis Mesa and Yuma Mesa wellfields.

WATER BUDGET SUMMARY

		Acre-feet per year
1. YUMA AREA[1] 1967-1969		
A. Inflow		
Colorado River Diversions and Groundwater Flows		666,900
B. Outflow		
Consumptive Use	354,100	
Drainage Waters	203,900	
Groundwater		
Colorado River (above NIB)	21,000	
Limitrophe Section	35,000	
Arizona-Sonora Border	49,000	663,000
C. Change in Groundwater Storage		+4,400
D. Imbalance		-500

[1] Includes Yuma Valley, Yuma Mesa, and South Gila Valley

		Acre-feet per year
II. IMPERIAL VALLEY AREA		
A. Inflow		
Surface Water (1971-1973)		
All-American Canal	3,444,000	
Alamo and New Rivers	113,300	
Groundwater		
Underflow from Mexico	7,000	
Infiltration of Runoff	10,000	3,574,300
B. Outflow		
Consumptive Use (1972)	1,831,300	
Surface Water		
Drainage to Salton Sea (1971-1973)	1,187,100	
Diversion reaching Coachella Valley (1971-1973)	359,900	
Groundwater		
Underflow to Salton Sea	2,000	
Canal Leakage to Mexico	90,000	3,470,300
C. Change In Storage[2]		
D. Imbalance		+104,000

[2] Data not available for computation but there is an increase from canal leakage.

		Acre-feet per year
III. MEXICAN AREAS[3]		
A. Inflow		
Surface Water (1967-1969)		
Colorado River at NIB	1,323,300	
Wellton-Mohawk Bypass	112,000	
Wasteways (Limitrophe)	6,700	
Flow Across Land Boundary Near San Luis	130,700	
Groundwater		
Arizona-Sonora Border	49,000	
Yuma Valley Across Limitrophe Section	35,000	
All-American Canal Leakage	90,000	1,746,700
B. Outflow		
Consumptive Use[4]	1,900,000	
Surface Water (1971-1973)		
Alamo and New Rivers	113,300	
Groundwater		
Underflow to Imperial Valley	7,000	
Underflow to Gulf of California[5]	81,100	2,101,400
C. Change In Storage[5]		-324,400
D. Imbalance		-30,300

[3] In recognition of differing estimates of groundwater flow across international boundaries, this summary is considered to be only the best present estimate.

[4] Estimate includes beneficial and non-beneficial water consumption.

[5] Estimate by Ministry of Hydraulic Resources, Mexico ca.1971 for eastern half of Mexican areas.

EFFECTS AND PROBLEMS

A resume of the principal effects and problems that are apparent is given, based on analysis of available information.

1. Surface Waters

a) Prior to 1956, Colorado River flows to Mexico exceeded the 1.5 million AF/yr guaranteed for delivery to Mexico. In 1954, Mexico diverted more than 2 million AF into Mexicali Valley and by 1957 constructed some 380 wells to supplement surface water supplies in anticipation that excess flow would not be available in future years. After 1963, upon completion of Glen Canyon Dam and reservoir, the river flows reaching the limitrophe section have been closely controlled to meet only the guaranteed allotment. Very little, if any, Colorado River water reaches the Gulf of California.

b) Significant changes have occurred in the flow regimen and salinity of the Colorado River waters. Irrigation developments have decreased the river flow but, at the same time, have increased the salinity of drainage return waters which are reused in the lower reach of the delta.

2. Groundwater

a) Infiltration of irrigation waters on Yuma Mesa created a groundwater mound which in turn caused water-logging conditions to occur in Yuma and South Gila Valleys.

b) Due to the steepening of the groundwater gradient on the mound, the rate of groundwater flow southward across the Arizona-Sonora boundary increased $2\frac{1}{2}$ times the virgin flow by 1969.

c) Infiltration of water leakage beneath the All-American Canal (Figure 2) along East Mesa has created another groundwater mound. It is estimated that more than 90,000 AF/yr of groundwater flows southward into Mexicali Valley from canal leakage.

d) Pumping of groundwater via wells in northeastern Mexicali Valley has caused the water levels to decline more than 30 feet, in places.

e) The San Luis Mesa wellfield in Mexico was completed in late 1972. Groundwater withdrawn by pumping from this wellfield averaged about 106,000 AF in 1975 and was conveyed into Mexicali and San Luis Valleys for irrigation in Mexico. Yuma Mesa drainage wells began pumping in mid-1972; these waters are discharged into the Colorado River above Morelos Dam (Figure 2) as part of the 1944 Treaty flows.

f) The effects of the Mexican San Luis wellfield groundwater pumpage have created a water level decline of 12 feet along the Arizona-Sonora boundary; an increase of the groundwater gradient from about 2.3 to about 4 feet per mile, in 1975. The combined effect of the San Luis Mesa pumping and the Yuma Mesa pumping has caused a reduction of flows from the Yuma Main Drain Canal from 124,975 AF in 1972 to 93,156 AF in 1975, for delivery at Southerly Boundary pumping plant and depletion of groundwater storage in United States.

g) The individual effect caused by each wellfield has not been determined. It was agreed under Minute No. 242 that each country shall limit pumping within 5 miles of the Arizona-Sonora boundary near San Luis to 160,000 AF/yr.

h) It has been estimated that the total groundwater flow from United States across the boundary to Mexico in 1976 was about 200,000 AF/yr.

3. Salinity Trends

Salinity of water at Morelos Dam remained nearly the same as the salinity at Imperial Dam prior to about 1960. In 1961, an influx of pumped irrigation drainage from the Wellton-Mohawk area caused the average annual salinity to increase to nearly 1,500 mg/l by 1962. Mitigation measures resulted in a gradual decline in salinity to about 1,250 mg/l by mid-1972; and operations under Minute No. 241 caused salinity reduction to about 1,140 mg/l. The bypass of all Wellton-Mohawk drainage flows below Morelos Dam, effected under Minute No. 242 in 1974, caused another significant reduction in the salinity above Morelos Dam to the 1976 average of about 965 mg/l.

4. Problem Areas

a) Pumping from the San Luis Mesa wellfield increased the flow of groundwater to about 75,000 AF/yr southward across the Arizona-Sonora border by 1976 and decreased the groundwater storage in United States. These pumping operations also have reduced the flow of drainage waters in the Yuma Main Drain. Protective pumping project for the United States' side of the boundary, opposite the Mexican San Luis Mesa wellfield, is to be undertaken early in 1977 with the installation of 6 wells, to be followed by an additional 19 wells in subsequent years.

b) About 300,000 AF/yr of water is lost from the All-American and Coachella Canals via leakage to the groundwater system in East Mesa and Sand Hills. About 90,000 AF/yr of groundwater flows into Mexicali Valley from the United States. The Bureau of Reclamation has been authorized to line 49 miles of the Coachella Canal which would reduce the total leakage by about 141,000 AF/yr.

c) There are discrepancies of the analyses of available data pertaining to the flow of groundwater across the international boundary. Estimates of All-American Canal leakage to Mexicali Valley range from 66,000 to 90,000 AF/yr. Estimates of underflow across the limitrophe section to Mexicali Valley range from 35,000 to 57,000 AF/yr.

d) The United States presently replaces the Wellton-Mohawk bypass water with Colorado River waters and groundwater pumped from Yuma Mesa. Wellton-Mohawk drainage water, bypassed to the Colorado River below Morelos Dam, has become a source of salinity, contaminating groundwater pumped for irrigation near the Colorado River. However, this problem was overcome in mid-1977, upon completion of the concrete lined canal extension to the Wellton-Mohawk drain, to convey drainage waters and brine waters from the desalting plant to the Gulf of California. The authorized project for desalting the Wellton-Mohawk drain waters is scheduled to be in operation by 1981.

e) Groundwater salinity in northeastern Mexicali Valley may be expected to continue to increase under the current irrigation pumping regime. Percolating irrigation water, after leaching salt accumulations from the soil, is recirculated by the wells and reapplied to the overlying fields.

ACKNOWLEDGEMENTS AND CREDITS

The writers wish to extend their grateful appreciation to personnel of the United States Section, International Boundary and Water Commission for their outstanding cooperation and provision of basic water records, maps, and internal documents for the preparation of this report. Special thanks are expressed to Commissioner J. F. Friedkin, Messrs. Thomas Wootton and Willard Ericson for their invaluable review and critique.

The writers made copious use of many previous studies and reports prepared by the U.S. Geological Survey, Bureau of Reclamation, United States and Mexican Sections of International Boundary and Water Commission, and Imperial Irrigation District. Much of this information was not included in published reports, but comprised internal documents. A list of data sources is given in the Appendix (Sources of Data Utilized for the Overview Report). The writers wish to express their thanks for the availability of this information, as many of the basic parts of this report were derived from these data.

In addition, certain groundwater budget analyses were obtained from previous reports and memoranda prepared by Harshbarger and Associates. Preparation of this overview report on the Colorado River Delta region has been a most interesting assignment, as this area comprises one of the most challenging hydrologic systems in the world.

SECTION II

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RESUME OF PHYSICAL FEATURES..... 2-1

II. RESUME OF PHYSICAL FEATURES

The Colorado River delta occupies an area of about 3,300 square miles which covers southeastern California and southwestern Arizona in the United States, and northeastern Baja California del Norte and northwestern Sonora in Mexico (Figure 1). From the apex, near the Laguna Mountains, Arizona, the axis of this low, wide, flat, fan-shaped delta extends southwestward, topographically separating the Gulf of California and the Salton Sea. Physiographically, the delta lies within the Sonoran Desert and Salton Trough sections of the Basin and Range physiographic province and is characterized geomorphically by low north-northwest trending mountains separated by more extensive desert plains which have been dissected by several cycles of degradation by the Colorado and Gila Rivers.

The apex of the delta is located where the Colorado and Gila Rivers have cut through the eastern-most range formed by the Chocolate, Laguna, Gila and Tinajas Altas Mountains. From the confluence with the Gila River, the Colorado River meanders southwestward across the delta area bounded on the west by the Sierra de los Cucapas, Santa Rosa and other mountains of the Peninsular Range. Near the Sierra de los Cucapas, the Colorado River flows southeastward toward the Gulf of California. North of the delta axis surface water flows toward the Salton Sea. Floods of the Colorado eroded part of the older, more extensive delta surface leaving mesas which border the modern floodplain. Sykes (1937) describes features of the Colorado River delta in greater detail.

The Salton Sea, the Colorado River Delta, and the Gulf of California are located within one continuous structural basin formed by the presently active San Andreas fault system. The lower and largest part of the basin is filled mostly with marine sediments containing saline water to depths of more than 17,000 feet in places. Alluvial sediments from the Colorado

and Gila Rivers occupy the upper 2,000 to 3,000 feet of the basin and form the deltaic features outlined in Figure 1. Fresh water-bearing sand and gravel layers in the deltaic sediments comprise the principal aquifer in the region. The groundwater reservoir is bounded by the nearly-impermeable mountain ranges bordering the trough.

For this report, the delta region is subdivided into four areas based principally on political and geographic delineation rather than hydrologic boundaries: Yuma Area, Imperial Valley, Mexicali Valley, and San Luis Mesa-Valley.

The Yuma area comprises the valley and mesas bordering the Colorado and Gila Rivers in Arizona and California southwest of the Gila and Laguna Mountains. The Yuma area includes the towns of Yuma, Somerton, and Gadsden. The limitrophe section, that reach of the Colorado River between Mexico and United States, bounds the Yuma area on the west. The international boundary between Arizona and Sonora represents the southern limit of the Yuma area. Within the Yuma area, subareas of principal hydrologic interest are the Yuma Valley, Yuma Mesa and South Gila Valley. Laguna, Bard and North Gila Valleys, which lie north of the confluence of the Colorado and Gila Rivers and south of Imperial Dam, are not seriously affected by groundwater developments and are not discussed herein (Figure 2). The Yuma Valley lies in the Colorado River floodplain in Arizona southwest of Yuma. It is about 19 miles long and ranges from 2 to 9 miles in width, the valley slopes southwestward from 125 feet above sea level west of Yuma to 90 feet above sea level at the southerly international boundary. Yuma Mesa, the first terrace level above the floodplain, lies about 70 to 80 feet above the east side of Yuma Valley. Yuma Mesa also forms the southern escarpment of south Gila Valley. The South Gila Valley, about 12 miles long and 2 miles wide, is the eastward extension of the floodplain south of the Gila and Colorado confluence, west of the Gila Mountains.

Imperial Valley lies in the Salton Trough between the Salton Sea and the international boundary. Imperial Valley region is divided into the eastern, central, and western areas. The eastern area includes the East Mesa and Sand Hills subareas, extends from the Cargo Muchacho and Chocolate Mountains and slopes gradually westward to the extensively irrigated central valley area (Figure 1). The central Imperial Valley includes nearly half a million acres of irrigated land, the principal cities of El Centro and Brawley, and several smaller towns. The central valley is an intermontane plain dissected by the Alamo and New Rivers which drain northward from Baja California del Norte to the Salton Sea. Nearly all the central area lies below sea level. The western area consists principally of the West Mesa and isolated mountain blocks related to the Peninsular Range which borders the area on the west.

The Mexican delta areas, consisting of Mexicali Valley and San Luis Mesa-Valley, embrace about 2,300 square miles of the lower Colorado River delta. These two areas extend southward from the United States-Mexico border to the Gulf of California. Except where the boundary shifts eastward about 25 miles north of the Gulf of California, Mexicali Valley lies west of the Colorado River in the state of Baja California del Norte, and San Luis Mesa-Valley lies east of the river in the state of Sonora. The principal cities within the respective areas are Mexicali and San Luis. Irrigated flatlands of the modern floodplain delta extending southwestward from the Yuma Valley occupy most of Mexicali and San Luis Valleys. Mesa Arenosa, an extension of East Mesa into northern Mexicali Valley, and San Luis Mesa, an extension of Yuma Mesa, lie 50 to 75 feet above the valleys.

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III. HISTORIC EVENTS OF DEVELOPMENT AND WATER WORKS

PRINCIPAL EVENTS

Diversions of Colorado River water for irrigation in the delta region began near the turn of the 20th Century. As a result of substantial rises in groundwater levels, the development of drainage systems was required to enable continued farming. As the irrigated lands expanded and the demand for a dependable water supply increased, the Boulder Canyon Project Act was passed by the United States Congress in 1928. One of the most important aspects of the act authorized the construction of Hoover Dam (completed in 1935) for water storage and power generation. Construction of the Imperial Dam and All-American Canal, completed in 1938, was also authorized to deliver waters to Imperial and Coachella Valleys in California. These structures played a major role in altering the hydrologic regime of the delta in subsequent years.

In 1944, the United States and Mexico adopted a treaty which allotted to Mexico 1,500,000 AF/yr (acre-feet per year) "...of the waters of the Colorado River from any and all sources..." (IBWC, 1974, p.1). In 1950, the Mexican government completed Morelos Dam one mile downstream from the Northerly International Boundary to divert water to Mexicali Valley via the Alamo Canal. In 1961, saline water was pumped from an aquifer underlying the Wellton-Mohawk Irrigation and Drainage District in Arizona to effect drainage needed and discharged into the Colorado River above Morelos Dam. As a result, the salinity of waters made available to Mexico at the Northerly International Boundary nearly doubled in 1962. During the years 1965 to 1973, agreements to resolve this problem were made between the United States and Mexico under Minute Nos. 218, 241, and 242 of the International Boundary and Water Commission (IBWC). Minute No. 218, a five-year agreement, basically called for improvement of the

quality of Colorado River waters delivered to Mexico by bypassing portions of the Wellton-Mohawk drainage to the Colorado River below Morelos Dam and by replacing such waters with released waters from United States storage works above Imperial Dam. Minute No. 241 called for further improvement by bypassing additional drainage waters and replacing them with water from both Imperial Dam and a drainage wellfield on Yuma Mesa. The agreement reached in Minute No. 242 for a "permanent and definitive solution" provides that the approximately 1,360,000 acre-feet of water delivered to Mexico upstream from Morelos Dam will have an annual average salinity of no more than 115 ppm $\pm$ 30 ppm (U.S. count) over the annual average salinity of the Colorado River waters which arrive at Imperial Dam. For the current interim period until the authorized desalting plant is built, the salinity is reduced by bypassing all Wellton-Mohawk drainage waters below Morelos Dam and replacing them with waters released from storage above Imperial Dam and Yuma Mesa wellfield.

To fulfill the Mexican allotment of the 1944 Treaty, the United States shall continue to deliver about 140,000 AF/yr on the land boundary at San Luis and in the limitrophe section of the Colorado River downstream from Morelos Dam; with the understanding that any decrease in such deliveries, will be made up by an equal increase in deliveries upstream from Morelos Dam. The salinity of the waters delivered at San Luis will be substantially the same as customarily delivered there.

In December of 1972, Mexico began operating a wellfield with the capacity to pump more than 160,000 AF/yr just south of the border on San Luis Mesa (Figure 2). Terms of Minute No. 242 of 1973 limit pumping for each country to 160,000 AF/yr within 5 miles of the Southerly International Border. Pumping from San Luis Mesa and Yuma Mesa wellfields has lowered water levels in Yuma Valley and reduced the flow of water across the land boundary. Plans have been prepared to replace these losses by pumping from wells to be located in the southern part of the Yuma area.

more discussion of Yuma area to Wellton-Mohawk

YUMA AREA

Surface Water

Irrigation began in Yuma Valley about 1897. By 1904 diversions from the Colorado River by pumps and gravity canals exceeded 10,000 AF. In the same year Congress authorized the Yuma Project, the first federal irrigation project on the main stem of the Colorado River. During these early years, flow from the Colorado and Gila Rivers ranged from about 8,000,000 to more than 25,000,000 AF in flood conditions. This large variability in river flow produced an undependable water supply and created problems in maintaining intake structures for irrigation. At the same time the natural high river flows often resulted in overflows, which provided the dominant source of recharge to groundwater in the delta.

The first major diversion work in the Yuma area was the Laguna Dam completed in 1909, which served part of the Yuma area until 1954. It is presently used only on a limited scale to control flow downstream from Imperial Dam. Diversions from Imperial Dam to the All-American Canal began in 1940, although small releases for priming the canal began in 1938. Several small diversions from both the All-American and a major branch, the Yuma Main Canal, serve the California part of the Yuma area. Most of the All-American Canal water is conveyed to Southern California, but Mexico receives some water which is diverted from the canal and returned to the river via the California Wasteway of the Yuma Main Canal and from the Pilot Knob power plant near the Northerly International Boundary. The Gila Gravity Main Canal, completed in 1943, delivers water from the east end of Imperial Dam to the North Gila Valley, the Wellton-Mohawk Canal system, the South Gila Valley and a pumping plant that lifts water to Yuma Mesa (Figure 2) (Olmsted and others, 1973).

During 1972, water diverted for irrigating the 104,500 acres in the Yuma area totaled about 767,300 AF. About 83 percent of this water was derived from the Colorado River, about 16 percent was pumped from groundwater, and the remainder from drains and off-stream ponds. About 236,400 AF of water was diverted from the All-American Canal to the Siphon Drop for irrigation of 47,800 acres in the Yuma Valley subarea. The East Main and West Main Canals convey the water to laterals in the Yuma Valley (Figure 2). Irrigation water from wells, direct diversion from the river, drains, and ponds amounted to nearly 29,300 AF. About 236,000 AF of the 277,700 AF of water supplied to irrigate 23,000 acres in Yuma Mesa is diverted from Imperial Dam via the Gila Gravity Main Canal. The Yuma Mesa Pumping Plant, located 9 miles east of Yuma, lifts the water to the mesa for distribution by the 'A' and 'B' Canals (Figure 2). In South Gila Valley 69,800 AF of water irrigated 10,700 acres. Prior to 1947 all irrigation water in South Gila Valley was supplied by groundwater pumpage. After water from the Gila Gravity Main Canal became available in 1965, use of groundwater for irrigation decreased. In 1972, more than 70 percent of the total water applied in South Gila Valley was from surface diversions via Gila Gravity Main Canal (USBR, 1974).

Regulation of the natural flows by man brought marked changes in the hydrologic system. Under natural conditions, the Gila River generally flowed year-round at Yuma. Following the construction of Roosevelt Dam in 1911 and increased irrigation in the Salt River valley, flow at the mouth of the Gila decreased so that after the late 1920's only occasional flood flows reached Yuma. Constructed between 1935 and 1963, Hoover, Imperial, Davis, and Glen Canyon Dams regulated the Colorado River for flood control, irrigation, municipal supply, power generation and recreation benefits. As a result, the irrigated lands are now generally free from damaging floods. Regulation has also brought a dependable supply of water for irrigation and municipal use in the Yuma area even though average annual

flow of the Colorado River at Imperial Dam is now only about half the river flow prior to controlled conditions. Although the flow was reduced, erosion of the river bottom increased because of a decrease in normal river sediment load due to silt retention in the reservoirs. The channel now lies 10 to 20 feet below the adjacent floodplain, from Laguna Dam to the Southerly International Boundary. The lowering of the channel bed, combined with low flows in the river and with the application of irrigation water on the floodplain, has reversed the direction of groundwater movement near the river. In most areas groundwater flows from the valley toward the Colorado River (Olmsted and others, 1973). Thus, regulation of the river's natural flows and irrigation of the lands has changed the river from a source of recharge to groundwater to a drain channel.

Groundwater

Due to the availability of large dependable surface water supply in the Yuma area, groundwater has not been extensively developed as a source of irrigation water. However, in South Gila Valley groundwater was the sole source of irrigation water from 1915 to 1947 and continued to exceed diversions from the Gila Gravity Main Canal until 1965. In 1972, 55 irrigation wells in South Gila Valley pumped nearly 20,000 AF. In Yuma Valley 17 wells, located mostly along the river, pumped more than 23,000 AF. Irrigation pumpage in 1972 from 21 private wells, located mainly in the southern part of Yuma Mesa, was nearly 41,700 AF (USBR, 1974). Irrigation well locations are shown in Figure 3. These irrigation pumpages, combined with that from other parts of the Yuma area, amount to only 16 percent of the total irrigation water used. In general, groundwater pumpage for irrigation has had little effect on water levels, except in the South Gila Valley where the water level declined 10 to 15 feet between 1915 and 1947 (Olmsted and others, 1973).

The huge applications of surface water have had a considerable effect on groundwater conditions throughout the Yuma area. Under natural conditions, based on data for 1925 and 1939 (Figure 4 and 5), the direction of groundwater movement was southward beneath the principal subareas and away from the Colorado and Gila River recharge areas. The overall effect of irrigation has been the rise of water levels in all subareas, and creation in some areas of water-logging conditions where the depth to water is less than 4 feet.

Irrigation on Yuma Mesa began in 1923, expanded during the 1940's, and stabilized by about 1939. It is estimated that two-thirds to three-fourths of more than 5 million acre-feet of water imported for irrigation on the mesa from 1922 through 1966 increased the groundwater storage and formed a widespread groundwater mound which enhanced groundwater movement toward the valley lands, west and north of the mesa (Olmsted and others, 1973). The original depth to water beneath the mesa lands was about 90 feet, but continued irrigation on the mesa produced a water table rise of nearly 80 feet near the crest of the mound when conditions stablized in about 1970.

Development of the mound on Yuma Mesa also caused water levels to rise in the valleys. After 1950 the normal southerly groundwater flow from South Gila Valley beneath Yuma Mesa was reversed (Figures 5 and 6) and water-logging problems developed near the edge of the mesa in South Gila. In Yuma Valley the outward flow from the Yuma Mesa mound shifted the groundwater flow southwestward and westward and caused the water table to rise near the land surface adjacent to the mesa escarpment. Drainage was accomplished by constructing 17 wells in Yuma Valley, 24 wells in South Gila Valley, and 12 wells on Yuma Mesa during the 1947 to 1972 period. The most successful drainage wells tapped the highly permeable coarse gravel aquifer.

Valley drainage wells reduced upward leakage from the coarse gravel aquifer to the shallow alluvial zone to prevent waterlogging conditions caused by the Yuma Mesa mound.

The 12 drainage wells on Yuma Mesa were constructed during 1967-1968 and began operations in June, 1972 at about 60,000 AF/yr. Drainage from the Yuma Mesa wellfield is conveyed via Yuma Mesa Conduit to the Colorado River to replace part of the Wellton-Mohawk bypass water (Figure 7). Water levels beneath the mesa declined several feet since operations began (Figure 8).

The application of irrigation water and groundwater pumping also altered the quantity of groundwater moving within and out of the Yuma area. Groundwater flow southward across the Arizona-Sonora border was about 20,000 AF/yr under virgin conditions (Olmsted and others, 1973). After the development of the Yuma Mesa mound and prior to pumping at San Luis Mesa, the underflow increased to about 49,000 AF/yr, due to an increase in hydraulic gradient (Moosburner, 1971). During 1939, groundwater flow westward toward Mexicali Valley from the limitrophe section of the Colorado River was about 100,000 AF/yr. During the period 1967-1969, flow across the limitrophe section, including flows from the limitrophe section, amounted to about 35,000 AF. This reduction could be attributed to lower river flows and the change in the Colorado from a losing to a gaining stream. Changes in the direction of groundwater flow, before and after closure of Hoover Dam, are demonstrated by water table contour maps of 1939 and 1960 (Figures 5 and 6).

The United States established a monitor well program in 1971 to determine the combined effects of irrigation pumping at San Luis Mesa and drainage pumping at Yuma Mesa. These data showed significant changes in groundwater elevations between 1972 and 1976 (Figures 8, 9, 10, 11, and 12).

Pumping at Yuma Mesa and San Luis wellfields caused a 10-foot decline in water levels one mile north of the boundary and a 5-foot decline seven miles north of the boundary since 1972. One of the principal effects of the lower water table was decreased yield from drainage wells in Yuma Valley which discharge into Yuma Main Drain. Irrigation return flows to the Main Drain have also decreased. As a result, the volume of water flows from the Yuma Main Drain to the Boundary Pumping Plant decreased nearly 37,000 AF from the 1962-1971 average (Figure 13) (IBWC, 1976a). The reduction in treaty water available at the southern land boundary is compensated by increased water flows at Morelos Dam.

Drainage Return Waters

As water levels rose very rapidly after the first irrigation diversions, farmers and ranchers recognized the need for adequate drainage. In Yuma Valley construction of gravity drainage ditches began in 1916. By 1972, the drainage network in the Yuma area included about 100 miles of open gravity drains, 52 drainage wells and a subsurface pipe drain field on Yuma Mesa. This system removed a total of more than 260,000 AF of drainage water in 1972 from the Yuma area (USBR, 1974).

The Main Drain extends southward through the center of Yuma Valley and is joined by other drains before reaching the Boundary Pumping Plant near San Luis, Mexico. Historically, the average annual flow of 125,000 AF delivered by the drain to Mexico, plus 15,000 AF of canal wasteway flow, was credited to the 1944 Treaty allotment. The components of flow in the Main Drain at the Boundary Pumping Plant are pumped water from Yuma Valley drainage wells, gravity return flow from the irrigated lands in the valley, and irrigation waste waters (IBWC, 1976a). Salinity of water in the Main Drain averages about 1,600 mg/l. The effectiveness of the Main Drain in controlling the flow of groundwater in Yuma Valley has been demonstrated

since 1925 (Figures 4, 5, 6, 9, and 10). In order to lower water levels in Yuma Valley, due to the Yuma Mesa groundwater mound, drainage wells were first constructed along the escarpment in 1947 and in South Gila Valley in 1961. During 1972, 16 drainage wells in Yuma Valley pumped about 68,000 AF of water and 24 drainage wells in South Gila Valley pumped over 62,000 AF. Most of the pumpage in Yuma Valley is diverted into the gravity drain system; in South Gila Valley pumped drainage water is conveyed directly to the Gila and Colorado Rivers. About 58,000 AF/yr of drainage from Yuma Mesa wellfield is conveyed in the Yuma Mesa Conduit and returned to the Colorado River 5 miles upstream from Morelos Dam (Figure 7).

The drainage flow to Mexico from the Main Drain and canals was reduced from about 140,000 AF to slightly more than 93,000 AF in 1975, due to a water table decline in Yuma Valley from the combined pumping effects of the Yuma Mesa and San Luis Mesa wellfield since 1972 (Figure 13). Such reductions in Treaty deliveries must be replaced by increased flows to Mexico above Morelos Dam. Pumpage from Yuma Mesa wellfield has been the source of replacement water (IBWC, 1975a).

Salinity Changes

During a 25-year period (1941-1965) salinity at Imperial Dam usually ranged between 700 and 800 mg/l. During the late sixties average salinity ranged from 850 to 900 mg/l, partly due to expanded irrigation upstream in Parker and Palo Verde Valleys (Irelan, 1971), and partly due to reduced river flows. Since 1971, salinity of water arriving at Imperial Dam has decreased to about 830 mg/l, Figure 14 (IBWC, 1976b).

Below Imperial Dam the chemical regimen of the Colorado River is complicated because the flow of the river is greatly depleted at the dam and because numerous drains and wasteways, having differing chemical characteristics, empty into it and the

tributary Gila River. The most significant change in water quality occurred in 1961 by the pumping of groundwater drainage from the Wellton-Mohawk area along the Gila River. These waters, initially averaging 6,000 mg/l salinity, were pumped at the rate of about 200,000 AF/yr into a wasteway channel that extended nearly to the mouth of the Gila River. Also, at this time almost all the Colorado River water was designated for use in the United States or Mexico so that no excess flow could be released below Imperial Dam to dilute the Wellton-Mohawk drainage. The effect of these developments was an increase in the salinity of Colorado River waters made available to Mexico at the Morelos Dam from about 800 mg/l to nearly 1,500 mg/l salinity in 1962 (USBR and IBWC, 1974).

Under the terms of the agreement reached in 1965 (Minute No. 218), a part of the Wellton-Mohawk drainage waters was bypassed. For this reason and because the salinity of the drainage waters was less, by mid-1972 the average annual salinity of the waters made available to Mexico above Morelos Dam was reduced to about 1,250 mg/l. Under terms of Minute No. 241, the volume of water bypassed again increased, causing a reduction in average annual salinity of the waters made available to Mexico above Morelos Dam to about 1,140 mg/l. After mid-1974, under terms of Minute No. 242, all Wellton-Mohawk drainage was bypassed below the dam and replaced with better quality water and salinity decreased to about 950 mg/l, Figure 14 (IBWC, 1976b).

IMPERIAL VALLEY

Surface Water

Diversion of Colorado River water for irrigation in Central Imperial Valley began in 1901. Prior to operation of the All-American Canal in 1940, water was diverted in Baja California through the Alamo Canal for use on both sides of the international boundary. During the 1920's, diversions in the Alamo Canal amounted to as much as 2,200,000 AF/yr; and about two-thirds

of the total was delivered to the Imperial Valley. The rapid increase in the amount of water diverted during the first part of the century was interrupted by the drought of 1931-1934, but after regulation of the Colorado River was accomplished by closure of Hoover Dam in 1935, the rate of increase was resumed. Since 1941, the All-American Canal has supplied all water used in Imperial Valley and since 1948, water has been diverted to Coachella Canal for the southerly part of Coachella Valley. In the 1960's, about 2,760,000 AF/yr irrigated more than 430,000 acres in Imperial Valley (Hely, 1969). In 1973, about 444,600 acres were irrigated in Imperial Valley (IBWC, 1973) and water deliveries totaled 2,671,600 AF/yr.

Groundwater

Wells in the agricultural Central Imperial Valley yield very little water, and it is generally of poor quality. In East Mesa and most parts of the West Mesa, irrigation agriculture has not been extensively developed; however, recent pump testing has indicated a potentially large source of good quality water in the East Mesa (Loeltz and others, 1975).

The application of large quantities of imported surface water has had significant effects on groundwater conditions. Under natural conditions, approximated by the 1939 water-table contours, groundwater recharge occurred by underflow northward from Mexicali Valley and westward through the alluvial section between the Cargo Muchacho Mountains and Pilot Knob (Figure 5). When the Colorado River flowed to the Salton Trough, from 1905 to 1907, a substantial amount of recharge also resulted from the infiltration of river water in the East Mesa area of Imperial Valley. Following 1901, recharge to the shallow part of the groundwater reservoir increased with the expansion of irrigation agriculture.

Prior to the completion of the All-American and Coachella Canals in the 1940's, groundwater flowed westward beneath East Mesa (Figure 5). However, after deliveries began, the water-table rose rapidly beneath the unlined canals forming distinct

groundwater mounds. A comparison of the 1939 and 1960 water-table contour maps shows that water levels rose more than 60 feet in areas just west of the Sand Hills (Figures 5 and 6). Water level data for 1972 and 1976 indicate that the mound has slowly continued to expand beneath East Mesa (Figures 9 and 10). Leakage from both canals constitutes a major part of the groundwater recharge to Imperial Valley. However, it is estimated that more than 90,000 AF/yr of groundwater flows southward to Mexicali Valley.

Drainage Return Waters

Most early irrigation in Imperial Valley was conducted without any drainage except that which occurred through natural channels. The irrigated lands soon became water-logged and drainage systems were installed beginning in 1922. At the end of 1970, the drainage system included about 1,500 miles of deep open drains and nearly 16,000 miles of tile lines (Imperial Irrigation District, 1971). Irrigation returns collected by the system flow into the Alamo and New Rivers which discharge into the Salton Sea. In 1970, the quantity of drainage from Central Imperial Valley was about 1.25 million AF/yr (Irelan, 1971).

Salinity Changes

The natural saline mineral content of soils in parts of Imperial Valley was high before irrigation began. Soils in some areas were too saline for successful irrigation until they were leached with low saline water (less than 900 mg/l) imported from the Colorado River.

After leaching salt accumulations from the soil, the water collected by the drainage system increases considerably in salinity. Irrigation returns mix with water in the Alamo and New Rivers which in part contain saline drainage from Mexicali Valley. Before entering the Salton Sea, salinity of water in

the Alamo and New Rivers ranges from about 2,600 mg/l to more than 4,300 mg/l (Irelan, 1971).

When the recent Salton Sea was formed by flood waters of the Colorado River in 1905, the salinity probably averaged less than 500 mg/l. However, large quantities of soluble minerals that had accumulated in the valley during previous centuries were dissolved by this fresh water, and after 1907, the rapid reduction in volume of the Salton Sea caused additional increases in salinity. By 1925, when the sea recession stablized because of the increased irrigation drainage, the salinity was near 40,000 mg/l which is somewhat greater than ocean water (about 35,000 mg/l). Between 1942 and 1965, salinity decreased, but fluctuated between 32,000 mg/l and 37,000 mg/l. This reduction was due to dilution from an increase in the volume of irrigation drainage water (Hely and others, 1966). In recent years, the salinity of water flowing into the Salton Sea from the Alamo and New Rivers has varied depending on the proportion of canal water and drainage water in each of the rivers.

MEXICAN AREAS

The irrigated lands which overlie the southwestern part of the Colorado delta are mainly in Mexicali and San Luis Valleys. Although these two valleys occupy separate states, both areas are underlain by the same aquifers and rely heavily on groundwater to augment surface waters. Groundwater pumped from a well field on San Luis Mesa is conveyed to Mexicali and San Luis Valleys for irrigation purposes.

Mexicali Valley

Surface Water

In about 1901, the Colorado River was first used for irrigation in Mexicali Valley within an arable area of about 700,000 acres. The irrigation acreage increased from

40,000 acres in 1915 to 200,000 acres in 1925, but decreased during the drought of 1932 to 70,000 acres. From this low acreage the irrigated area steadily increased to 330,000 acres in 1949 and attained a maximum of 540,000 in 1955. Due to Treaty restriction on the amount of surface water available for irrigation, the total irrigated acreage declined to about 415,000 in the early 1960's (Olmsted and others, 1973). During 1973-1974 about 467,700 acres were irrigated in San Luis and Mexicali Valleys (Table 1).

Prior to 1941, the Alamo Canal (originally known as Imperial Canal) conveyed Colorado River water to both Mexicali Valley, B.C. and Imperial Valley, California. The water was used principally for irrigation but also provided water for domestic use to Mexicali. Diversions controlled by head gates were made at several locations near the site of Morelos Dam. During these early years, diversions to Mexico via the Alamo Canal increased from 709,700 AF in 1908, to more than 3,800,000 AF in 1937. Approximately two-thirds of the water diverted was delivered to California until the first major delivery of Colorado River water to Imperial Valley via the All-American Canal in 1941. In 1942, downstream diversion via the Alamo Canal decreased sharply to about 955,800 AF, and since then all water diverted via the Alamo Canal has been used only in Mexico (Hely, 1969).

In 1944, the United States and Mexico signed a treaty which allots to Mexico "...a guaranteed annual quantity of 1,500,000 AF..."; when a surplus of Colorado River water is available, as determined by the United States Section, the United States will deliver to Mexico "...a total quantity not to exceed 1,700,000 AF/yr." (Hely, 1969). More than 90 percent of the treaty water is delivered to Mexico in the bed of the limitrophe section of the Colorado River and the remaining, less than 10 percent, is delivered across the land boundary at San Luis.

TABLE 1.--IRRIGATED ACREAGE AND WATER SOURCES IN MEXICALI AND SAN LUIS VALLEYS
(Colorado River Irrigation District No. 14)

	1959-60	1960-61	1961-62	1962-63	1963-64	1964-65	1965-66	1966-67	1967-68	1968-69	1969-70	1970-71	1971-72	1972-73	1973-74
IRRIGATED ACREAGE (x1000)	469.6	459.8	439.7	436.9	456.6	442.3	438.7	440.3	437.8	429.9	426.6	429.1	423.9	420.2	467.7
SOURCE OF WATER (x1000 AF)															
GRAVITY DIVERSION	1849.0	1697.9	1501.4	1639.8	1613.7	1518.1	1539.2	1442.3	1446.7	1437.1	1406.8	1442.5	1447.7	1337.5	1509.2
GROUNDWATER	698.4	865.1	846.1	845.1	935.2	938.4	915.8	826.3	877.2	840.2	784.2	771.6	772.0	724.4	841.9
RIVER PUMPAGE	2.3	2.5	2.0	3.6	4.6	3.7	0	0	0	0	0	0	0	0	0
TOTAL -	2549.7	2565.5	2349.5	2488.5	2553.5	2460.2	2455.0	2668.6	2323.9	2277.3	2191.0	2214.1	2219.7	2061.9	2351.1

From:
Ministry of Hydraulic Resources, Mexico
Dept. of Statistics, 1975

From 1941 to 1950, water was also delivered to the Alamo Canal from the All-American Canal via Pilot Knob Wasteway and a connecting canal that is now plugged. In 1950, the Mexican government completed the construction of Morelos Dam to control diversions to its lands without the use of facilities in the United States (Hely, 1969). Water deliveries to Mexico began in 1950 pursuant to the 1944 Treaty.

Diversions via the Alamo Canal generally increased between 1942 and 1961, and several times exceeded the minimum treaty requirement because of the excess waters reaching the Mexican points of diversion. In 1958, the diversions amounted to 1,962,000 AF (Hely, 1969). However, since the early 1960's excess flows reaching Mexico have been curtailed, and in recent years flows available for diversion by Mexico have averaged approximately 1,500,000 AF/yr including those delivered across the land boundary near San Luis, Arizona.

Prior to 1961, surface water leaving Mexicali Valley via the Alamo and New Rivers averaged 5,700 and 55,000 AF/yr, respectively (Ariel Construction Co., Inc., 1970). Between 1971-1973, discharge of the Alamo River at the international boundary averaged 1,440 AF/yr, consisting normally of groundwater seepage from the All-American Canal and drainage water from Mexicali Valley. During 1971-1973, the New River flow at the international boundary averaged 111,868 AF/yr (IBWC, 1971, 1972, 1973). Flow in the New River at the international boundary is derived from the following sources: approximately 78 percent from irrigation drainage, 18 percent from Mexicali municipal waste and 4 percent from irrigation waste water (IBWC, 1975b). Runoff in the New River resulting from infrequent but violent desert storms may cause crop and property damage during flood stages.

The canal system in Mexicali Valley was revised in the early 1970's. Canal Alimentador del Norte transports water from Morelos Dam across the northern portion to the valley and terminates near the city of Mexicali. Canal Alimentador Central branches from

Canal Alimentador del Norte south of Morelos Dam and conveys water to the central part of the valley. Canal Alimentador del Sur, lying along the right bank of the Colorado River, provides water to the southern part of Mexicali Valley and Canal Alimentador Margen Izquierda branches from Sifon Sanchez Mejorada and conveys water to the San Luis Valley (Figure 2). These main conduits deliver water to numerous smaller canals and laterals.

The Alamo Canal delivers domestic water for Mexicali B.C. to a water treatment plant built in 1963. In 1968, the plant produced approximately 20,000 AF of potable water (Ariel Construction Co., Inc., 1970).

Groundwater

Groundwater pumpage for irrigation in the northeastern portion of Mexicali Valley began in the 1930's but was relatively small until the late 1950's. Pumpage expanded rapidly because as river flows reaching the Mexican points of diversion decreased, the surface supply was not sufficient for the increased acreage of irrigated lands. Pumpage from all wells amounted to only several tens of thousands AF/yr by 1950. In 1955, the Mexican government authorized the drilling of 281 deep wells to augment the surface water supply and authorized construction of 100 additional wells in 1957 in the eastern part of Mexicali Valley. These wells were in addition to the 230 privately owned irrigation wells which had already been drilled by that time. As a result, total pumpage from government and private wells increased from 300,000 AF in 1956 to 635,000 AF in 1957. In 1957, the Ministry of Hydraulic Resources limited the number of pumped wells to 495 to avoid exploitation of the aquifer and concomitant salinity increases. However, irrigation pumpage in Mexicali and San Luis Valleys continued to increase steadily, and during 1965 totaled about

938,400 AF/yr. Following 1965, irrigation pumpage declined due to increased groundwater salinity. This apparently led to a detailed investigation of groundwater resources in the late 1960's when 51 wells were drilled, including 15 production wells. During 1972 to 1973, groundwater pumpage in Mexicali and San Luis Valleys totaled 724,400 AF (Table 1). In addition to about 8,500 AF/yr pumped by domestic wells, the city of San Luis, Sonora pumped about 2,400 AF/yr of groundwater for municipal use in 1968 (Ariel Construction Co., Inc., 1970). The location of irrigation wells is shown in Figure 3.

Since 1972, groundwater pumped from 63 wells along the international boundary on San Luis Mesa has supplied up to about 128,000 AF/yr of irrigation water to Mexicali Valley and San Luis Valley. This additional source of water allowed a reduction in the number of irrigation wells in the southern part of Mexicali Valley which pumped moderate amounts of saline water.

Throughout the northeastern part of Mexicali Valley, pumping has lowered the water table an average of about 20 feet between 1957 and 1975. Near several pumping centers, the water table decline has been more than 36 feet so that the flow of groundwater has shifted toward these pumping centers. A comparison of the 1960, 1972, and 1976 water table contour maps indicates that the water table has not attained a steady-state position (Figures 6, 9, and 10) and is still declining.

Prior to the extensive development of irrigation, groundwater generally flowed westward from the limitrophe section and then northwestward toward Imperial Valley. South of San Luis, the direction of groundwater movement was to the southwest (Figure 5). The principal sources of recharge to northern Mexicali Valley were the Colorado River and Alamo Canal leakage. Recharge from the Alamo Canal occurs mostly in the northeastern part of the valley where the soils are sandy. Water

level data, representing conditions prior to the use of the Alamo Canal, are not available. Small amounts of recharge may also occur along the front of the Sierra de los Cucapas.

Shortly after the transport of water in the All-American Canal in 1941, the water table began to rise in the Mesa Arenosa area which lies between the Northerly International Boundary and the Alamo Canal. Leakage from the All-American Canal southward into Mexicali Valley produced a sharp change in the direction of groundwater flow as shown on the 1960 Water Table Contour Map (Figure 6) which indicates a southwestward flow from the Yuma area and southerly flow from East Mesa toward the Alamo Canal.

Drainage Return Waters

In eastern Mexicali Valley the coarse sandy soils are effectively drained by the irrigation wells. In the western and southern irrigated areas where the surficial soils contain more clay and silt, water-logging developed in some of the irrigated areas. Construction of drainage facilities to alleviate water-logging conditions did not begin in Mexicali Valley until about 1955. Between 1955 and 1961, 900 miles of open drainage ditches were constructed. By 1961, discharge from major drains into the New River amounted to 94,560 AF/yr; but from 1966 to 1974 averaged only 83,050 AF/yr (IBWC, 1975b). Irrigation drainage comprises about 78 percent of the flow in New River at the international boundary. A part of the flow in the Alamo River also consists of drainage returns.

Salinity Changes

Before 1961, river waters diverted at Morelos Dam had a salinity only slightly greater than waters at Imperial Dam (about 800 mg/l). Under natural conditions the discharges and the salinity of the Colorado River at the Southerly International Boundary below San Luis were probably not materially

different from those at the Northerly International Boundary. As irrigation drainage water became part of the river flow, the salinity increased. Currently Wellton-Mohawk drainage (3,700 mg/l salinity) constitutes the principal source of water in the channel below Morelos Dam. Small amounts of seepage and wasteway returns dilute the Wellton-Mohawk drainage to about 3,400 mg/l near San Luis, Sonora. Salinity data for the Colorado River below San Luis are not available.

San Luis Mesa-Valley

Although a separate historical account of irrigation and drainage works in the San Luis Valley is not available, they probably closely parallel developments in Mexicali Valley and Yuma Valley which began in the early 1900's. In contrast to Yuma Mesa neighboring to the north, irrigated agriculture has not been developed on San Luis Mesa. Sources of irrigation water for San Luis Valley include treaty deliveries from the United States, groundwater pumped from San Luis Valley, and groundwater pumped from San Luis Mesa.

Minute No. 242 specifies approximately 140,000 AF/yr as treaty deliveries to Mexico at the land boundary near San Luis (Figure 2) and in the limitrophe section of the Colorado River. Deliveries across the land boundary are composed of flow from the Yuma Main Drain through the Boundary Pumping Plant plus flows from the East and West Main Canal Wasteways, which during the 1962-1971 period averaged 130,000 AF/yr and 10,000 AF/yr, respectively (IBWC, 1975a). In combination, the salinity of water arriving at the land boundary is less than 1,600 mg/l. These waters are then delivered to the Canal Sanchez Mejorada which conveys irrigation water to the southern part of San Luis Valley. Waters diverted at Morelos Dam may also be delivered to San Luis Valley via a siphon under the Colorado River west of San Luis.

Groundwater pumped from a large number of wells in the northern half of San Luis Valley is the second principal source of irrigation water (Figure 3). Groundwater is also pumped to canals to supplement surface water delivered to the southern area.

In the late 1960's, approximately one-third of the underflow crossing the Arizona-Sonora border flowed westward to Mexicali Valley and two-thirds flowed southward to the San Luis Valley.

Groundwater has been pumped on San Luis Mesa for use in Mexicali Valley, as well as San Luis Valley since December, 1972. Sixty-three wells, located just east of San Luis, were constructed to a depth of about 500 feet (Figure 3). Total production capacity is about 162,000 AF/yr; however, actual pumpage through 1975 averaged only about 107,000 AF/yr (IBWC, 1976a). At the wellfield, these waters are discharged into the Canal Principal de Conduccion. Water conveyed from the San Luis Mesa wellfield may be delivered to a main canal which crosses underneath the Colorado River at the Sifon Sanchez Mejorada just west of San Luis (Figure 2) for conveyance of irrigation waters into Mexicali Valley. On the east side of the river, the pumped waters may also be delivered to the Canal Alimentador Margen Izquierda.

Water levels beneath San Luis Mesa have declined since well field production began in 1972. The lowering of the water table, due to pumping at San Luis Mesa, has steepened the hydraulic gradient in the direction of the wellfield so that the flow of groundwater from the Yuma area across the land boundary has increased. As the San Luis Mesa wellfield intercepts much of the groundwater flow across the land boundary, less groundwater moves southwest from San Luis Mesa toward San Luis and Mexicali Valleys.

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IV. HYDROLOGIC CONDITIONS

GENERAL

The Colorado River, having a drainage area of about 246,000 square miles, originates in the snow-capped Rocky Mountains of Colorado and Wyoming and traverses 1,400 miles through vegetated montane slopes and desert terrain of the seven basin states to the Gulf of California in Mexico. Due to the system of storage reservoirs and controlled releases, streamflow at Imperial Dam, the diversion works for the Delta region generally vary only to meet irrigation demand and presently average about 6.0 million acre-feet per year. The Gila River drains about 58,200 square miles, mostly within the United States; but the present flows reaching the Colorado River near Yuma consist mainly of drainage and irrigation waste water. Due to irrigation diversions in the United States and Mexico, almost no flow enters the Gulf of California except effluent drainage from irrigated lands in the Mexicali Valley.

As the delta sediments were laid down during the past 10-14 million years, the Colorado River periodically shifted its course from southwestward into the Gulf of California to westward discharging into the Salton Sea by way of the Alamo and New Rivers. This area was a dry salt flat about 275 feet below sea level when early American explorers arrived in the 1800's. The present Salton Sea was formed during 1905-1907 when floodwaters of the Colorado River breached the Imperial Valley irrigation diversion intakes located near Yuma.

Following the flood, the water level of the Salton Sea declined rapidly. Since about 1920, however, water levels have gradually risen to the present elevation of about 230 feet below mean sea level due to increased inflows from irrigation drainage (Hely and others, 1966). Levees and storage reservoirs, constructed in the Colorado River basin, now restrict floodwaters from entering the Salton Trough.

Much of the delta region is irrigable by gravity diversions from the Colorado River. Northwest of the delta axis, rainfall runoff and irrigation drainage generally flow toward the closed Salton Sea trough; southwest of the axis surface, water drainage is toward the Colorado River and Gulf of California.

Prior to the formation of the delta, a deep trough-like depression formed by the San Andreas fault system extended from the Salton Sea into the Gulf of California. The trough is bounded by dense, nearly impermeable bedrock. Marine waters of the Gulf of California occupied the trough and extended as far north as Parker, Arizona. The marine sediments are mostly fine-grained and, along with volcanic and non-marine sedimentary rocks, fill the lower part of the trough. These sediments contain water generally of very poor quality and contain geothermal brines in parts of Mexicali and Imperial Valleys.

Overlying the poorly water-yielding rocks are mostly deltaic sediments derived from the Colorado and Gila Rivers. In general, the deltaic deposits thicken southwesterly from the delta apex and attain a thickness of about 2,500 feet in southwestern Arizona. The combined thickness of the deltaic and underlying sediments is as much as 20,000 feet in Imperial Valley.

Deltaic deposits comprise the principal fresh water aquifers in the region. Except in Imperial Valley, sediments overlying the poor water-yielding rocks are divided into the following stratigraphic units in ascending order: 1) older alluvium, 2) younger alluvium, and 3) windblown sand. For hydrologic convenience these sediments have been divided into the wedge zone, coarse gravel zone, and upper fine-grained zone. The principal groundwater reservoir lies within the older alluvium which is divided into two parts: the lower "wedge zone"

and the upper "coarse gravel zone". The coarse gravel zone interfingers with the lower part of the overlying younger alluvium. The upper fine-grained zone consists mainly of the floodplain alluvium and windblown sand (Olmsted and others, 1973). This three part aquifer system is well documented in the Yuma area and generally extends into Mexico. Due to the great lateral extent of the aquifers, there is hydraulic continuity in the groundwater reservoir across the political boundaries.

The top of the "wedge zone" ranges from about sea level (160 feet below land) near the delta apex to nearly 200 feet below sea level (300 feet below land) in southern Yuma Valley and consists dominantly of sand and gravel. The base of the "wedge zone" lies about 2,500 feet beneath the San Luis area but the zone pinches out to the north near the Gila and Laguna Mountains (Figure 2).

The highly permeable zone tapped by most wells in the Yuma and Mexicali Valleys is the "coarse gravel zone". This unit ranges from 0 to 100 feet thick, and lies 100 feet beneath Yuma Valley and 170-180 feet beneath Yuma Mesa.

The upper fine-grained zone contains the shallow aquifer system, a minor part of the groundwater reservoir. It receives return flow from irrigation water which constitutes the principle source of recharge in the delta region. The large areal extent of the deltaic aquifers is shown in cross-sections in Figure 15.

Although the deltaic sediments were deposited in marine water, fresh Colorado River water replaced more than two thousand feet of the salt water from the groundwater reservoir. An interface between fresh groundwater and saline water derived from the Gulf of California is located approximately along the 32-degree parallel in the southernmost part of the delta.

In gross aspect, the groundwater reservoir extends over an area of approximately 3,500 square miles: one-third in the United States and two-thirds in Mexico. Based on available data, it has been estimated there are more than 200 million AF of economically recoverable groundwater in the vast subterranean system; approximately 108 million AF in United States and 95 million AF in Mexico (Table 2). However, the amount of groundwater that would be useable would be dependent upon the chemical quality of the waters in the deeper parts of the aquifer.

YUMA AREA

Colorado River Flows and Diversions

The surface water supplies conveyed to the Yuma area are controlled at Imperial Dam where about 6 million AF/yr are diverted from the Colorado River. Approximately 80 percent of this flow is conveyed via the All-American Canal for distribution to Imperial Valley, Yuma Valley, and Mexicali Valley; about 15 percent is diverted by the Gila Gravity Main Canal to the Gila River valley including Wellton-Mohawk and Yuma Mesa, and about 5 percent is released downstream. In recent years, Colorado River discharge at Yuma averaged less than 600,000 AF/yr, which includes flow from the Gila River and upstream irrigation return flows. Morelos Dam, the diversion works for diversion of water by Mexico, is located on the Colorado River about one mile south of the international boundary (Figure 2). In 1973, about 1,272,300 AF was diverted to the Mexicali Valley via the Alamo Canal (IBWC, 1973). These consist of waters discharged to the river at Imperial Dam, and from the All-American Canal via the California Wasteway of Yuma Main Canal and Pilot Knob power plant, and irrigation return waters from the Yuma area. Most of the surface water flow in the limitrophe section downstream from Morelos Dam is derived from Wellton-Mohawk drainage water, irrigation returns from Yuma Valley and seepage. At the Southerly International Boundary near San Luis, flow in the

TABLE 2.--ESTIMATED ECONOMICALLY RECOVERABLE GROUNDWATER[1]
LOWER COLORADO RIVER DELTA REGION

	AREA[2] (Square Miles)		RECOVERABLE FROM STORAGE (Million Acre-Feet)	
UNITED STATES				
Arizona				
Yuma Mesa	425		35	
Valley Lands	110		10	
	535		45	
California				
West Mesa	465		22	
East Mesa	350		18	
Sand Hills	450		20	
Colorado River Valley	55		3	
	1,320		63	
		1,855		108
MEXICO				
Baja California				
Mexicali Valley	510		25	
Sonora				
San Luis Mesa	1,000		65	
San Luis Valley	100		5	
	1,100		70	
		1,610		95

[1] Based on 600-foot pumping lift independent of water quality

[2] Estimated area underlain by deltaic sand and gravel within 600 feet of land surface

Colorado River averaged 103,000 AF/yr from 1966 to 1972 and about 150,000 AF/yr in more recent years. Since about 1961, very little flow has entered the Gulf of California via the Colorado River, because the small flows below Morelos Dam were lost by seepage or evaporation before reaching the Gulf.

Groundwater

It is estimated that the total amount of economically recoverable groundwater within a depth of 600 feet is about 45 million AF in the Yuma area. Return irrigation water, most of which comes from diverted Colorado River water, is the present source of nearly all recharge to the reservoir. The infiltration of irrigation water on Yuma Mesa has created a groundwater mound in the upper fine-grained sediments where the depth to the water table is about 15 feet. The total estimated storage in the mound is on the order of 1.5 to 2.0 million AF. Groundwater flow from the Yuma Mesa mound radiates outward in all directions and constitutes a principal source of groundwater recharge to the Yuma area. Surface drains in the valley-floodplain and drainage wells along the Yuma Mesa escarpment intercept much of the groundwater flow derived from irrigation. Depth to groundwater in the valleys ranges from 4 to 20 feet and averages about 10 feet. The general direction of groundwater movement in South Gila and northern Yuma Valley is northwest toward the Gila and Colorado Rivers. Groundwater flows southwestward parallel to the Colorado River in central and southern Yuma Valley. Water level contours beneath Yuma Mesa show that the southward groundwater flow is markedly impeded by the northwest-trending Algodones fault of the San Andreas fault system (Figure 10).

Groundwater pumpage for irrigation accounts for about 16 percent of irrigation water in the Yuma area (USBR, 1974); however, large amounts of groundwater have been pumped to

maintain good drainage in Yuma and South Gila Valleys and Yuma Mesa. The valleys are irrigated by Colorado River water and also receive groundwater recharge from the Yuma Mesa mound. Most of the drainage wells are constructed in the permeable coarse-gravel aquifer to drain the overlying fine-grained zone. Wells located along the westerly and northerly edges of Yuma Mesa range from about 100 to 300 feet deep and yield as much as 4,000 gpm (gallons per minute). Pumpage from mesa wells, just north of the Sonora border, is about 26,000 AF/yr (USBR, 1974).

Water Budget

A water budget provides an account of the water resources of an area during a specific period of time. The budget balance is attained when inflow to the area equals outflow plus changes in storage. In general, most inflow is derived from percolating irrigation water, a portion of which is consumed by crops and natural vegetation. Outflow is principally the amount of water discharged from an area by evaporation, wells, drains, and wasteways and includes the quantity of groundwater which flows to adjacent areas. Outflow from one area may become the inflow to another area. Changes in storage are exhibited by rise or decline of water levels in the groundwater reservoir during the period of accounting.

A water budget for the Yuma subareas has been prepared for the period 1967-1969 (Moosburner, 1971) and is summarized in Table 3. In Yuma Mesa, for example, 283,300 AF of water was diverted to the mesa lands and about 188,600 AF percolated to the water-table. Of this amount, 6,200 AF contributed to a rise of the water-table. Discharge from the mesa is mostly groundwater outflow to adjacent lands; 52,000 AF to South Gila Valley, 87,000 AF to Yuma Valley, and 44,000 AF/yr flows across the international boundary into Sonora, Mexico (Figure 9).

The annual inflow to Yuma Valley consists of 309,500 AF of surface water mostly from the Yuma Main Canal and 87,000 AF

TABLE 3.--WATER BUDGET ANALYSIS FOR THE YUMA AREA, ARIZONA AND CALIFORNIA, 1967-69

SUBAREA (1)	INFLOW (2)	CONSUMPTIVE USE (3)	INFLOW MINUS CONSUMPTIVE USE (4)	CHANGE IN STORAGE (5)	OUTFLOW (6)	CHANGE IN STORAGE PLUS OUTFLOW (7)	IMBALANCE (Column 4 minus Column 7) (8)
Laguna Valley	34,400	29,400	5,000	0	5,000	5,000	0
Reservation and Bard	144,000	62,200	82,200	-500	78,900	78,400	+3,800
Island	26,400	25,000	1,400	0	2,000	2,000	-600
North Gila Valley	82,200	36,500	45,700	-200	51,700	51,500	-5,800
South Gila Valley	126,100	51,400	74,700	1,000	80,100	81,100	-6,400
Yuma Mesa	283,300	94,700	188,600	6,200	183,400	189,600	-1,000
Yuma Valley	396,500	208,000	188,500	-2,800	184,400	181,600	+6,900
TOTAL FOR SUBAREAS 1/	1,093,000	507,000	586,000	4,000	586,000	589,000	-3,000

1/ Totals are rounded to the nearest 1,000 acre-feet

FROM:
Moosburner, 1971

of groundwater seepage from Yuma Mesa. From the total inflow, 208,000 AF is discharged by evapotranspiration, 137,400 AF is collected by drains and wasteways and 47,000 AF leaves the subarea via groundwater flow. Groundwater outflow from Yuma Valley includes 35,000 AF across the limitrophe section, 7,000 AF to the Colorado River north of the limitrophe section, and 5,000 AF to San Luis Valley.

Inflow to South Gila Valley comprises 47,100 AF of surface water diversions, 52,000 AF of groundwater flow from Yuma Mesa, and about 27,000 AF from canal leakage and inflow from valleys to the north. After plants consume 51,400 AF/yr, 66,100 AF are collected as surface water and 14,000 AF return to the Colorado River and North Gila Valleys as groundwater.

Water Quality

Prior to the development of agriculture, the salinity of Colorado River water recharging the groundwater aquifer probably averaged less than 500 mg/l (Hely and others, 1966). Since then the source and quality of recharge waters has changed, and the salinity of Colorado River water diverted for irrigation has increased to the range of 800 to 900 mg/l. These waters infiltrate through the upper fine-grained soils to the underlying coarse-gravel and wedge aquifer zones. In this infiltration process, saline waters mix with fresher water and are altered by natural chemical reactions in the groundwater reservoir. The salinity concentration may vary with location and may be related to leakage from fresh water canals, saline water drains, depth to groundwater, groundwater circulation patterns, and proximity to natural recharge areas.

In general, fresh groundwater can be obtained from the wedge and coarse-gravel aquifer zones in the Yuma area. The chemical quality varies markedly with location, but generally improves at depth. The quality of water in the wedge zone is relatively good, as many wells yield water having less than 1,000 mg/l salinity. In the coarse-gravel zone the salinity

is usually less than 1,800 mg/l, but may range from 1,000 mg/l to 4,800 mg/l. Water in the upper fine-grained zone is generally more mineralized, but is as low as 900 mg/l along some parts of the Colorado River.

Variation of water quality in Yuma Valley is not well defined because of the lack of data. Generally the quality of water from drainage wells along the base of the Yuma Mesa escarpment ranges from 1,100 mg/l to 2,300 mg/l and is reasonably consistent for individual wells. Salinity of water in other sectors varies from several hundred to several thousand milligrams per liter (Olmsted and others, 1973).

Beneath the irrigated area on Yuma Mesa, groundwater quality has been affected by Colorado River water infiltration, which is concentrated by evapotranspiration. The salinity of this water is generally less than 1,800 mg/l. Salinity ranges from less than 800 mg/l in the southern sector to more than 3,500 mg/l near the city of Yuma (Olmsted and others, 1973).

In the South Gila Valley and on the southeastern part of North Gila Valley, dissolved solids generally exceeds 1,800 mg/l in the coarse gravel zone. In two areas of the South Gila Valley, near the east and west ends, total dissolved solids exceed 3,600 mg/l. Water in the wedge zone contains substantially less than 1,800 mg/l (Olmsted and others, 1973).

IMPERIAL VALLEY

Salton Sea Drainage

The natural drainage area of the Salton Sea includes about 8,360 square miles in California and part of Baja California, Mexico which lies north of the crest of the delta. Most of the Salton Sea area is extremely arid, and natural runoff is inadequate to maintain a permanent body of water in this closed basin. Return flows from irrigation sustained the level of the sea following the floods of 1905-1907.

Surface inflows to the Salton Sea totaled about 1,350,000 AF/yr in the early 1960's. More than 90 percent of this inflow was drainage water from the Imperial Valley, mostly from the Alamo and New Rivers; and about 10 percent of the inflow came from other areas including Coachella Valley north of the Salton Sea (Hely and others, 1966). At the international boundary, a very small part of the flow in the Alamo River and a much larger part of the flow in the New River is drainage water from Mexicali Valley. Flow in the New River of the international boundary between 1966 and 1974 averaged 106,250 AF/yr, or about 8 percent of the total discharge to the Salton Sea. New River discharge at the international boundary consisted of 83,050 AF/yr of drainage returns and storm runoff from Mexicali Valley, 19,310 AF/yr of municipal waste water from Mexicali, and 3,890 AF/yr of wasteway flow (IBWC, 1975b). During 1971-1973, the combined discharge from the Alamo and New Rivers at the international boundary averaged 113,300 AF/yr.

All-American Canal Flows and Losses

The All-American Canal diverts about 3,444,000 AF/yr from Imperial Dam for use in Imperial and Coachella Valleys of California. The Coachella Canal branches from the All-American Canal just west of the Sand Hills and extends 123 miles along the eastern side of the Salton Sea Basin. At the point of diversion, flow in the Coachella Canal averages 500,000 AF/yr. The East Highline, Central Main and West Side Main Canals convey All-American Canal water throughout the central Imperial Valley (Figure 2).

There is considerable leakage from the unlined section of All-American and Coachella Canals, particularly in East Mesa and the southern Sand Hills subareas where the soils are sandy. Losses from the All-American Canal, between Pilot Knob west of Yuma and the East Highline Canal, averaged 140,000 AF/yr from 1950 through 1967 (Loeltz and others, 1975). Losses between Pilot Knob and West Side Main Canal averaged 132,000 AF/yr

from 1966 through 1975 (USBR, 1976). Along the 86-mile unlined section of the Coachella Canal, approximately 160,000 AF/yr, or about one-third of the initial diversion, is lost by leakage. In the first 49 miles, estimated leakage averages 141,000 AF/yr (USBR and IBWC, 1974). Estimated total volume of canal leakage through 1967 amounted to 2.7 million AF from the Coachella Canal and 4.5 million AF from the All-American Canal between Pilot Knob and the East Highline Canal (Loeltz and others, 1975). Canal losses within the irrigated valley lands averaged 145,600 AF/yr from 1973 to 1974. These losses represent only 5 percent of the total water delivery (Imperial Irrigation District, 1973, 1974).

Groundwater

Saturated valley-fill sediments in the Salton Trough are nearly four miles thick in places. For this report these sediments are grouped into two broad catagories: 1) a lower sequence of marine and non-marine rocks below a depth of about 3,000 feet; and 2) an upper sequence of lacustrine and deltaic deposits which constitutes the principal groundwater reservoir. The lower zone is in poor hydraulic connection with the upper part of the reservoir and generally contains saline or geothermal waters which are unsuitable for irrigation purposes. The upper zone sediments consist of a fine-grained mixture of sand, silt, and clay underlying the central valley which grades into coarse sand and gravel deposits toward the East and West Mesas. Most hydrologic data pertain to the upper water-bearing sequence, although some test wells have been drilled to depths exceeding 13,000 feet.

The total volume of "useable and recoverable" geothermal fluids from water-bearing sediments in Imperial Valley was estimated to be 1.1 billion AF (Dutcher and others, 1972). In California delta lands, the estimated volume of economically recoverable groundwater within a 600-foot pumping lift is about 63 million AF, Table 2. This estimate assumed all delta lands

in California, except those in central Imperial Valley, are underlain by sand and gravel. Because variation of groundwater salinity with location and depth is not well known, an accurate estimate of useable and recoverable groundwater is not available.

The major sources of recharge to the groundwater reservoir are infiltration of irrigation water and leakage from canals, although some natural recharge occurs via the coarse sediments along the mountain fronts. In the central valley approximately 400,000 AF of irrigation water is applied in excess of crop requirements to guard against salt accumulations in the soil. Most of this recharge is collected by drains before reaching deeper aquifers (Loeltz and others, 1975). In the East Mesa the total recharge from canal leakage is about 300,000 AF/yr. Of this amount approximately 90,000 AF/yr flows across the border to Mexicali Valley due to the steep southerly slope of the groundwater mound which parallels the All-American Canal (Figure 10). According to the Ministry of Hydraulic Resources (ca.1971) underflow of leakage to Mexico is about 85,000 AF/yr; the USBR (1976) estimates that about 66,000 AF/yr flows to Mexico.

From the eastern and western areas of the Imperial Valley, groundwater generally moves toward the New and Alamo Rivers and the major axis of the valley and then northwestward toward the Salton Sea. Groundwater inflow to the Salton Sea is estimated to be only 2,000 AF/yr, because of the low permeability of the fine-grained sediments underlying the central valley (Hely and others, 1966). In addition to the large amounts of discharge by evaporation and plant transpiration, small quantities of groundwater are discharged by springs and wells.

Groundwater is not used for large scale irrigation in the Central Imperial Valley due to the poor water quality and low well yield. Fresh water for domestic purposes is available in some areas, and many domestic wells flow at the surface east of the Alamo River. These wells range from 350 to 1,300 feet

deep and yield 10 to 100 gpm (Dutcher and others, 1972). Several hundred to more than 1,500 gpm can be obtained from many wells in the eastern and western areas. Pumping tests indicate a potentially large and undeveloped source of fresh groundwater in highly permeable sediments near the Coachella Canal Turnout (Loeltz and others, 1975).

Water levels in the eastern area range from 150 to 180 feet below land surface in the Sand Hills subarea and about 30 to 50 feet below land surface on East Mesa. In the Central Imperial Valley the average depth to water is 10 feet. The water table is less than 100 feet below land surface in much of the western area.

Water Budget

Although a comprehensive water budget for Imperial Valley has not been published, available data discussed previously in this report indicate the relative magnitudes of the principal water budget components during the early 1970's. Inflow to Imperial Valley consists principally of irrigation diversions, canal leakage, and surface runoff. Below Pilot Knob, flow in the All-American Canal averages 3,444,000 AF/yr. Streamflow in the Alamo and New Rivers at the international boundary averages 113,300 AF. Groundwater underflow from Mexicali Valley west of Calexico amounts to 7,000 AF/yr. Recharge from runoff is less than 10,000 AF/yr. In summation, inflow to Imperial Valley is about 3,574,300 AF/yr.

The quantity of water discharged from Central Imperial Valley totals about 3,470,300 AF/yr. Approximately 1,831,300 AF/yr of this amount comprises evapotranspiration by crops. Nearly 1,187,100 AF/yr of irrigation drainage flows from Imperial Valley to the Salton Sea mainly via the Alamo and New Rivers (Imperial Irrigation District, 1971-1974). In addition, discharge by groundwater underflow to the Salton Sea is estimated to be 2,000 AF (Hely and others, 1966). Diversions reaching Coachella Valley averaged 359,900 AF/yr. Leakage from All-American Canal to Mexicali Valley is about 90,000 AF/yr.

These estimates indicate that hydrologic conditions in Imperial Valley area are in a quasi-state of equilibrium. A comparison of the 1960 and 1976 water table contour maps shows groundwater mounds in the East Mesa and Sand Hills continue to expand; whereas, water levels in other subareas remain steady (Figures 6 and 10). The area affected by canal leakage is limited to within several miles of the canals and the rate of water level rise is generally less than one foot per year; thus, the annual increase in groundwater storage is probably only a few thousand acre-feet per year.

Geothermal Fluids

In parts of Imperial Valley the saturated sediments are heated by buried chambers of molten rock. These "hot spots", or areas of high heat flow from the earth, are located at the southeastern end of the Salton Sea, between El Centro and Calexico, and in the East Mesa area. This hydrothermal system consists principally of deep sandstone aquifers capped by about 3,000 feet of fine-grained sediments of very low permeability. Water circulates in the deep aquifers due to convection above the heat source. Temperatures within the deep aquifers usually exceed 150°C and some shallow domestic wells tap water sufficiently hot to provide home heating. Recharge to the system totals about 500 gpm, due to percolation from the overlying shallow aquifer mainly near the margins of the valley (Dutcher and others, 1972). An equal amount of fluid is discharged by the movement of vapor upward along fractures into the shallow aquifer. Thus, dissolved minerals in the recharge water accumulate in the deep aquifers. Extremely high salinity of the water, as much as 260,000 mg/l, prohibits commercial production in the geothermal fields at the present time (Dutcher and others, 1972). A relationship between these geothermal brines and the poor quality of groundwater in the overlying shallow aquifer has not been established.

Water Quality

Imported irrigation waters entering Imperial Valley have about the same salinity (830 mg/l, 1976) as the Colorado River at Imperial Dam. Salinity of the Alamo and New Rivers varies but typically ranges from about 2,000 mg/l to more than 5,000 mg/l. The New River is considerably more saline than the Alamo River. All drainage from Central Imperial Valley is toward the Salton Sea which has a salinity of more than 32,000 mg/l.

Groundwater quality differs greatly throughout Imperial Valley region, but generally water quality decreases toward the Central Valley. Much of the groundwater contains high salt concentrations which develop due to concentration by evaporation, leaching of salt accumulations in irrigated areas, redissolution of buried evaporite deposits, and mixing with connate water of marine origin. Most fresh water is probably derived from recharge from the Colorado River, canal leakage, and local infiltration of rainfall runoff.

In the eastern area, salinity ranges from 360 to 7,280 mg/l but most groundwater contains less than 2,000 mg/l. East of the Sand Hills, water quality improves toward the Chocolate Mountains. Pumping tests in the southeast corner of East Mesa indicate that a large supply of fresh water similar in composition to the Colorado River occurs to a depth of at least 2,519 feet. However, farther to the northwest, brackish water occurs at a depth of 250 feet (Loeltz and others, 1975).

In the Central Imperial Valley water-bearing deposits generally have a low vertical permeability and the contained groundwater may be highly mineralized in some zones and fresh in others. Although the extent to which useable groundwater occurs in the central valley is unknown, the occurrence of such water

certainly must be limited. The only two large capacity wells are drainage wells adjacent to major canals. Test wells drilled 500 to 1,000 feet deep in the southern and western parts of the central valley yielded waters having a salinity of 5,000 to 10,000 mg/l. In general, wells west of the Alamo River are not likely to produce artesian flow and have water of very poor quality. Salinity of water from the artesian wells east of the Alamo River commonly yield water ranging from 1,000 to 2,000 mg/l; however, these waters often contain high concentrations of fluoride, sodium and boron. In non-flowing wells less than 150 feet deep, salinity may exceed 9,000 mg/l in places (Loeltz and others, 1975).

In the western area, groundwater salinity is variable but usually decreases with depth and increases eastward toward the valley. In Coyote Valley irrigation wells yield water having salinity less than 400 mg/l. In most other areas salinity typically exceeds 1,500 mg/l and is as much as 13,000 mg/l (Loeltz and others, 1975).

MEXICAN AREAS

Mexicali Valley

Colorado River Flows and Diversions

As a result of increased releases from Imperial Dam which replaced the remaining portion of Wellton-Mohawk bypass waters after September 1974, the average flow in the Colorado River at the Northerly International Boundary increased to about 1,422,700 AF/yr for years 1975 and 1976. Diversions to Mexicali Valley at Morelos Dam via the Alamo Canal* averaged 1,383,050 AF/yr for years 1975 and 1976 (IBWC, 1975, 1976).

*Revised and designated as Canal Alimentador del Norte

In 1967 and 1968, canal losses in Colorado Irrigation District No. 14, which includes nearly all of Mexicali and San Luis Valleys, totaled more than 600,000 AF/yr. These losses represent about 48 percent of all surface water received. The greatest rates of leakage occur in irrigation districts located along the Colorado River just south of San Luis, where approximately 60 percent of the water received infiltrates through canal channels before reaching the field. The western half of Mexicali Valley (irrigation units 1, 2, and 3) received about 55 percent of the surface water diversion and lost more than 52 percent of the diversion received due to canal leakage (Ariel Construction Co., Inc., 1970).

Water in the channel of the Colorado River below Morelos Dam currently (1975) consists of more than 200,000 AF/yr of saline groundwater drainage from the Wellton-Mohawk Valley, leakage from Morelos Dam, relatively small quantities of canal wasteway water, and groundwater seepage from Yuma Valley. In the limitrophe section, the Colorado River loses about 31,000 AF/yr to the shallow groundwater aquifer. Most of the streamflow depletion in the limitrophe section is probably caused by groundwater pumping in Mexicali Valley. Very little, if any, Colorado River water reaches the Gulf of California.

Drainage Waters

There are two principal surface water drainage systems in Mexicali Valley which are separated by the axis of the Colorado River Delta. This drainage divide lies roughly along a line extending southwestward from Morelos Dam to just north of Rio Hardy and toward the central part of the Sierra de Los Cucapas (Figure 2). The Alamo and New Rivers drain the valley north of this line and flow via Imperial Valley to the Salton Sea. At the international boundary, flow in these rivers is perennial and, in 1973 was about 118,500 AF/yr. South of the delta

axis, surface water drainage flows either directly to the Colorado River or to the river by way of Rio Hardy in the western part of Mexicali Valley. Numerous ephemeral washes throughout the valley also discharge small amounts of rainfall-runoff to these principal rivers. Some of the southerly flowing drainage is diverted to the Laguna Salada.

Groundwater

Highly permeable sediments in the coarse gravel aquifer and wedge zone extend from the Yuma area and underlie approximately 500 square miles of northeastern Mexicali Valley. In some wells along the limitrophe section and along the Arizona-Sonora border, gravel and sand extend to depths exceeding 1,500 feet. Toward the west and south, fine sand, silt and clay layers interfinger with these coarse sediments; in the western and southern parts of the valley, the first several hundred feet consist dominantly of low-permeable, fine-grained sediments (Figure 15). An extensive drilling and testing program, conducted during the mid-1950's and 1960's, provided data to document the hydrogeologic characteristics and areal extent of the aquifers shown in Figure 15.

More than 1,000 wells located mostly in northeastern Mexicali Valley (Figure 3) produce from 1,600 gpm to more than 5,000 gpm (IBWC, 1962). The highly productive zone occurs at a depth of about 100 to 325 feet and is covered by fine-grained sediments of lower permeability (Paredes, 1963). The water level depth averages 10 to 15 feet in most of Mexicali Valley, but in northeastern Mexicali Valley, the depth to water ranges from 30 feet to as much as 100 feet near pumped wells. Flowing artesian conditions occur in wells along the western edge of Mesa Arenosa. The groundwater reservoir in Mexicali Valley contains an estimated 25 million AF of economically recoverable water (Table 2).

According to the Ministry of Hydraulic Resources (M.H.R., Mexico, ca.1971) a total groundwater flow of 263,575 AF/yr crossed into Mexico from the United States in the mid-1960's. The components of underflow included 85,155 AF/yr across the California-Baja California border east of Mexicali; 56,770 AF/yr across the limitrophe section; and 121,650 AF/yr across the Arizona-Sonora border. About 60 percent of the total underflow moved toward the heavily pumped northeastern part of Mexicali Valley. Although these estimates of underflow across the international land boundaries differ from estimates discussed in other sections of this report, they are in the same order of magnitude.

Discharge from the groundwater reservoir occurs mostly by pumping from wells, evapotranspiration, seepage into drainage ditches, groundwater underflow to the Colorado River and Gulf of California in southern Mexicali Valley, and underflow to Imperial Valley. Irrigation pumpage in 1973-1974 amounted to about 841,900 AF/yr, in addition to domestic and municipal pumpage which is estimated to total more than 11,000 AF/yr. It is also estimated that evapotranspiration consumes about 1,900,000 AF/yr in Colorado River Irrigation District No. 14. Only about 250,000 AF/yr of the total evapotranspiration loss comprises non-beneficial consumptive use. Alamo and New River drainage into Imperial Valley was 118,500 AF/yr in 1973. Approximately 81,100 AF/yr of groundwater flowing southward across the Arizona-Sonora border seeps into the Gulf of California; and about 20,275 AF/yr of underflow crosses into California near Mexicali B.C. Quantities of discharge estimated for other components are not available.

Data collected during the 1960's showed groundwater pumpage averaged 892,100 AF/yr in Mexicali Valley. This pumpage comprised approximately 162,200 AF/yr of underflow from the United States, 486,600 AF/yr from infiltration of irrigation waters, and 243,300 AF/yr from groundwater storage (Ariel Construction

Co., Inc., 1970). The latter two quantities differ from those in a report by Ministry of Hydraulic Resources (ca.1971) which indicated 405,500 AF/yr of groundwater recharge by infiltration and 324,400 AF/yr from depletion of groundwater storage. Since the 1960's, pumping has declined slightly; however, water levels have continued to decline and groundwater overdraft conditions persist.

Water Budget

Previous investigations did not include a complete water budget analysis for Mexicali Valley. However, available data indicate that estimates of inflow to Mexicali Valley consist predominantly of diversions from the Colorado River, surface waters discharged to the limitrophe section below Morelos Dam, drainage and wasteway flow reaching the land boundary near San Luis, and groundwater underflows from Arizona and California. In preparation of a water budget for this report, wherever possible, surface water data have been summarized for the period 1967-1969 to be compatible with the comprehensive water budget for Yuma Valley. Groundwater flows from Arizona into Mexicali Valley in the Moosburner (1970) investigation are considerably less than flows computed during approximately the same period by the Ministry of Hydraulic Resources (ca.1971) and Ariel Construction Co., Inc. (1970). The latter sources indicate underflows from All-American Canal leakage comparable to estimates given in the present (1977) report but larger than the leakage reported by United States Bureau of Reclamation (1976). Groundwater data prepared by Mexican sources will be presented in this section. However, there are differing estimates of groundwater flow across international boundaries and the best estimates are given as a composite water budget for Mexicali Valley in the summary (page 1-7).

Diversions from the Colorado River at Morelos Dam, approximated by flows at the Northerly International Boundary, averaged about 1,323,300 AF/yr during the period 1967-1969 (USGS, 1967, 1968, and 1969). United States' discharges to the limitrophe zone below Morelos Dam during 1967-1969 consisted of 112,000 AF/yr from Wellton-Mohawk drainage and 6,700 AF/yr from wasteways. Wasteway water and drainage delivered at the land boundary near San Luis averaged 130,700 AF/yr. Underflow across the limitrophe section was about 56,770 AF/yr. Leakage from the All-American Canal which flows into Mexicali Valley from California was estimated to be 85,155 AF/yr and prior to 1972, about 121,650 AF/yr entered Mexico from the Arizona-Sonora border (M.H.R., Mexico, ca.1971). Inflow from precipitation and other sources is presumed to be relatively small. Therefore, the total inflow to Mexicali Valley from these principal sources is about 1,836,275 AF/yr.

Discharge by evapotranspiration, the largest component of water outflow from Mexicali and San Luis Valleys, is roughly estimated to be more than 1,900,000 AF/yr from beneficial and non-beneficial sources. In 1971-1973, the combined flow of the Alamo and New Rivers to Imperial Valley averaged 113,300 AF/yr. Discharge from Rio Hardy to the Colorado River is not known at present. About 81,100 AF/yr of the flow which crossed the Arizona-Sonora border was discharged to the Gulf of California; and underflow to Imperial Valley west of Mexicali was about 20,275 AF/yr (M.H.R., Mexico, ca.1971). During 1967-1969, the incomplete water outflow from Mexicali Valley and San Luis Valley was about 2,114,675 AF/yr but data are not available on drainage water, runoff, and groundwater underflow to the Gulf of California from the western half of Mexicali Valley.

As a result of continuous water level declines due to pumping, groundwater storage is depleted at the rate of about 324,400 AF/yr (M.H.R., Mexico, ca.1971). A summation of inflow, outflow and change in groundwater storage components indicates an imbalance of about +46,000 AF/yr. This value differs from the -30,300 AF/yr presented in the water budget on page 1-7.

Geothermal Fluids

A geothermal field has been developed for generating electricity from steam near Cerro Prieto, about 25 miles southeast of Mexicali (Figure 2). As in Imperial Valley, the heat source is from a deeply buried magma chamber which heats water in a sandy aquifer at a depth greater than about 7,000 feet (Dutcher and others, 1972). In a conceptual model, heating occurs by convection in a deep cell which is capped by a fine-grained clayey layer above a depth of about 2,400 feet. The deep convection cell is recharged at the rate of 500 gpm by water in the overlying 2,400-foot zone which was assumed to have an average salinity of 1,500-2,000 mg/l during the development of the cell. Natural steam discharge along fractures from the convection cell is nearly salt-free and as a result salts have been left in the deep convection cell where salinity is about 15,000 to 20,000 mg/l (Dutcher and others, 1972).

Pumping from deep wells in the geothermal field has induced measurable land subsidence 7 miles outside the wellfield (Dutcher and others, 1972). Other effects of operating the geothermal field, with particular reference to water resources, have not been ascertained.

Water Quality

Surface water diverted for irrigation from the Colorado River at Morelos Dam had an average salinity of 960 mg/l since about mid-1974 (Figure 14). The salinity of this water is about 130 mg/l greater than water arriving at Imperial Dam. Below Morelos Dam, water in the channel of the Colorado River consists mostly of saline groundwater drainage (about 3,600 mg/l) from the Wellton-Mohawk Irrigation District. Since almost no Colorado River water reaches the Gulf of California, most of the flow below Morelos Dam seeps into the groundwater reservoir and may become part of the water pumped from wells along the river banks.

By June 1977, all Wellton-Mohawk drain waters will be conveyed by the new concrete lined extension channel to the Gulf.

Water in the Alamo and New Rivers consists largely of irrigation drainage and canal wastewater. In 1973, the salinity of the Alamo River at the international boundary ranged from about 1,800 mg/l to 2,300 mg/l. Salinity of the New River measured during 1973 ranged approximately between 3,500 and 5,100 mg/l.

Groundwater quality varies in Mexicali Valley, but generally useable water is obtained from the large number of wells in the eastern half of the valley. A newspaper article in El Mexicano (1973) stated that excess pumpage caused an increase in groundwater salinity to levels ranging from 950 to 1,250 mg/l. In the early 1970's, groundwater salinities were slightly less than the salinity of diverted Colorado River water. In 1975, salinity in most of northeastern Mexicali Valley exceeded 1,400 mg/l and, near many pumping centers, it exceeded 2,200 mg/l (Secretaria de Recursos Hidraulicos, 1975).

West of the heavily pumped area near Cerro Prieta, groundwater salinities in wells, several hundred feet deep, increase to about 14,000 mg/l. Ariel Construction Co., Inc. (1970) indicated that the contrast in salinity between the eastern and western parts of Mexicali Valley may be due to contamination by brines from the Cerro Prieta geothermal area. Salinity also increases gradually southward from the pumped area toward the marine saline-water interface, which is estimated to occur along the 32-degree parallel.

San Luis Mesa-Valley

In 1974, surface water resources in the San Luis area comprised 106,950 AF of flow from Yuma Valley delivered to the land boundary near San Luis and about 148,000 AF/yr of drainage, wasteway water and Wellton-Mohawk water bypassed to the Colorado

River below Morelos Dam which has not infiltrated into the subsurface along the limitrophe section. Rainfall-runoff discharged into ephemeral streambeds flows southwestward toward the Colorado River or Santa Clara Slough which empty into the Gulf of California.

The high yield aquifers comprise the coarse gravel beds and the wedge zone, which extend southward from the Yuma area and underlie the San Luis Valley and Mesa. Most irrigation wells in San Luis Valley tap the coarse gravel aquifer and wells in the San Luis Mesa wellfield penetrate both the coarse gravel aquifer and the wedge zone. Pumping tests at the San Luis Mesa wellfield indicate yields of nearly 5,000 gpm as reported by IBWC, 1973. During 1975, pumpage from the wellfield totaled about 106,000 AF (IBWC, 1976a). Salinity of water from the wellfield averages 890 mg/l (IBWC, 1975a).

Along the Arizona-Sonora border the depth to the groundwater table increases from about 100 feet beneath the western part of San Luis Mesa and to more than 270 feet beneath the upper mesa. The depth to groundwater is about 10 feet in the San Luis Valley. The 1972 water level contour map shows that groundwater flows southwest from Yuma Mesa across the Arizona-Sonora boundary and then, in general, flows west-southwest beneath San Luis Mesa and Valley toward the Colorado River (Figure 9). A similar direction of groundwater movement is shown for 1976 in the San Luis Valley and Mesa (Figure 10) even though production of groundwater from the San Luis Mesa wellfield began in December 1972, and the average was about 107,000 AF/yr. Hydrographs of water levels in wells along the Arizona-Sonora boundary are shown in Figure 12.

The 1976 water table contours on Yuma Mesa just north of the international boundary show a dominant southerly flow toward the San Luis Mesa wellfield (Figure 10). The bend in the contours around the wellfield shows the expected effects of pumpage on

the direction of groundwater movement in southern Yuma area. Water levels along the boundary declined as much as 12 feet since pumping began in 1972. A comparison of the 1972 and 1976 water table contour maps demonstrates that north of the international boundary the slope of the water table has increased about 70 percent toward the San Luis Mesa wellfield; therefore, since 1972 the quantity of groundwater moving from the United States to Mexico has also increased by approximately a proportionate amount.

According to Mexico Ministry of Hydraulic Resources (ca.1971), prior to 1972, groundwater underflow to Mexico along Arizona-Sonora border was about 121,650 AF/yr. Of this amount 40,550 AF/yr flowed to Mexicali Valley and 81,100 AF/yr flowed to the Gulf of California. Beneficial and non-beneficial consumptive use in the San Luis Valley was estimated to be about 380,000 AF/yr for the purpose of this (1977) report. The water budget for San Luis Valley and San Luis Mesa is included in the Mexican areas budget (page 1-7).

SECTION V

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V. EFFECTS AND POTENTIAL PROBLEMS

SURFACE WATER

During the first half of the twentieth century, an abundant supply of Colorado River water supported a rapid growth of irrigated agriculture in the semi-arid Colorado Delta region. During this period, river flows exceeded the demand for irrigation water and unused water flowed into the Gulf of California. Upstream from the delta, depletion and storage of Colorado River water caused a gradual reduction in river flows available for irrigation in the delta. By the time the 1944 Treaty with Mexico was signed, limits had been set on the volumes of Colorado water intended for use in the United States and Mexico. The amount allocated to the United States was then considered sufficient to sustain the growth of agriculture; and pending construction of storage works planned above Imperial Dam, flows to Mexico far exceeded the guaranteed minimum of 1.5 million AF/yr.

In 1956, discharges of the Colorado River were unusually low and flow to Mexico only slightly exceeded the minimum requirement as set forth in the 1944 Treaty. Prior to this period of reduced flow, the expanding irrigated acreage in Mexicali Valley depended on flows substantially greater than the guaranteed 1.5 million AF/yr. In 1954, Mexico diverted more than 2 million AF for irrigation in Mexicali Valley. Anticipating that excess flows would not be available in future years, the Mexican government constructed 381 wells in the northeastern part of Mexicali Valley to supplement surface water deliveries. Thus, Mexico's use of more river flows than guaranteed treaty allotment, coupled with the later decreased river flows led Mexico to rely on groundwater to sustain its level of agricultural production in the Mexicali Valley.

After 1956, discharge of the Colorado River reaching the limitrophe section again increased. Mexico again received

Colorado River water substantially in excess of the minimum treaty requirement until 1963 when storage began in Glen Canyon Reservoir. Since then river discharges reaching the limitrophe section have been closely controlled to guaranteed treaty allotment. The control of deliveries was further refined by the operation at Senator Wash Dam beginning in 1966 (Figure 16). As a result, controlled flows and diversions of Colorado River waters delivered to Mexico are limited closely to the Treaty allotment of 1,500,000 AF/yr. Practically no Colorado River water reaches the Gulf of California.

Significant changes have occurred in the regimen of the flows and salinity of the Colorado River due to the use of waters for irrigation. Portions of Colorado River water diverted for irrigation are consumed by crops, evaporate, percolate to the groundwater reservoir, and/or return to the river. Irrigation water returned to the river includes leached salt deposits which accumulated in the soil by evapotranspiration. In and upstream from the delta region, a large part of the natural flow of the river is replaced by irrigation drainage waters. Thus, irrigation decreases the flow of the Colorado River but increases salinity of the water.

Losses of several hundred thousand AF/yr also occur where water is diverted from the river via unlined canals. In the delta region, the greatest of these losses occurs along the All-American and Coachella Canals where an estimated 300,000 AF/yr seeps to the groundwater reservoir beneath the United States and Mexico. Construction of impervious lined canals in areas where leakage losses are large could conserve significant quantities of water, as has been authorized by the Congress for the Coachella Canal.

GROUNDWATER

Man's first attempts to develop irrigation verified the close relationship between surface water and groundwater. The application of large quantities of irrigation water caused a rise

in groundwater levels which created severe water-logging problems. Where the water table is close to the land surface, crop productivity decreases, large volumes of groundwater are lost by evaporation, and salts accumulate in the soil. In order to lower the water table, thousands of miles of drainage ditches and tile fields have been constructed and drainage wells have been placed in operation in much of the delta region.

Infiltration of irrigation water on Yuma Mesa produced a large groundwater mound having a total storage of 1.5 to 2.0 million AF. Although the development of the mound provides the benefit of additional groundwater storage in the United States, radial flow outward from the mound caused waterlogging conditions in Yuma and South Gila Valleys. A total of 52 wells were constructed near the Yuma Mesa escarpment to intercept the groundwater flow and lower the water level. Part of the pumped drainage water flows into the Yuma Main Drain and part into the Colorado and Gila Rivers and is eventually delivered to Mexico as part of the 1944 Treaty allotment. Due to the steep gradient imposed by the groundwater mound, the rate of groundwater flow increased about $2\frac{1}{2}$ times the virgin flow rate southward across the Arizona-Sonora border into Mexico by 1969.

Similar conditions occur along the All-American Canal in the East Mesa area. Leakage from the unlined canal produced a groundwater ridge beneath the canal just north of the international boundary. The quantity of leakage which moves southward into Mexicali Valley has not been accurately determined although estimates range from about 66,000 to more than 90,000 AF/yr. This quantity represents a loss of Colorado River water to United States. Movement of canal leakage southward into Mexicali Valley also shifted the northwesterly direction of groundwater flow to the west and southwest so that much less groundwater flows into Imperial Valley from Mexico. In Mexicali Valley, a large part of the increased groundwater supply from the canal leakage is pumped for irrigation and collected by surface drains.

Pumping from wells in northeastern Mexicali Valley has caused a water table decline of several tens of feet, and as pumping has continued the groundwater salinity has increased in some areas. Mexico began operations of its San Luis Mesa wellfield near the end of 1972, delivering an average of 107,000 AF/yr of groundwater for irrigation of its lands. Shortly thereafter, water levels began to decline in southern Yuma Mesa over a large area surrounding San Luis Mesa wellfield, and the slope of the water table steepened southward toward the wells. These conditions indicate that groundwater storage in Arizona is being depleted and that the rate of groundwater flow across the Arizona-Sonora border has increased. Based on the 1976 hydraulic gradient (Figure 10) east of San Luis the groundwater flow across the Arizona-Sonora border is about 75,000 AF/yr. Pumpage of San Luis Mesa wellfield has also depleted storage in Mexico and decreased the quantity of groundwater moving southwestward to San Luis and Mexicali Valleys. Under Minute No. 242 each country shall limit pumping within 5 miles of the Arizona-Sonora border near San Luis to 160,000 AF/yr. At present, the United States pumps only about 26,100 AF/yr of groundwater in this border area.

About six months prior to the start of pumping operations by Mexico in San Luis Mesa, the United States wellfield on Yuma Mesa, having a capacity of 50,000 AF/yr, began pumping operations. The Yuma Mesa wellfield was intended to intercept water from the mound and the waters pumped replace a part of the saline Wellton-Mohawk drainage waters bypassed below Morelos Dam. The positive impact of the Yuma Mesa wellfield has been to improve drainage conditions in the Yuma Valley and increase the water supply available for delivery to Mexico as part of the 1944 Treaty. However, pumping in Yuma Mesa has lowered water levels in Yuma Valley to the extent that yields of Yuma Valley drainage wells which discharge into the Main Drain have decreased, and less irrigation drainage flows into the Yuma Main Drain. Part of the water table decline and resulting reduction in flow of the Yuma Main Drain can be attributed to pumping from the San Luis Mesa wellfield. Because the flow in the Main Drain at the Boundary

Pumping Plant near San Luis comprises part of the water delivery guaranteed to Mexico, the reduced deliveries at San Luis must be replaced by increased water deliveries by the United States above Morelos Dam.

The source of replacement water has been considered to be part of the discharge from Yuma Mesa wellfield, so that part of the water which previously entered the Main Drain is diverted back to Mexico via Morelos Dam. A significant effect, caused by operation of Yuma Mesa wellfield is that replacing the reduced flows at San Luis means that less wellfield water is available to replace Wellton-Mohawk bypass water as originally intended. Therefore, additional water is released from Imperial Dam to replace Wellton-Mohawk bypass water to fulfill the salinity agreement with Mexico. In addition, a large quantity of groundwater flow, about 90,000 AF/yr, derived from leakage in the All-American Canal, moves into Mexicali Valley which comprises a significant loss to United States. Furthermore, a large quantity of groundwater from the Yuma Valley (about 35,000 AF/yr) flows westward across the limitrophe section of the Colorado River to Mexicali Valley.

SALINITY TRENDS

Prior to the closure of Hoover Dam, the salinity of Colorado River water above Imperial Dam fluctuated seasonally and annually probably averaging about 600 mg/l. Because upstream storage and uses, including diversions from the basin, caused a reduction in river flows, a lesser amount of Colorado River water was available to dilute increasing quantities of irrigation drainage return flow. As a result, the salinity of water arriving at Imperial Dam gradually increased to about 900 mg/l in 1970. Thereafter, the salinity declined slightly to the 1976 level of about 825 mg/l.

Salinity of water at Morelos Dam remained nearly the same as the salinity at Imperial Dam prior to about 1960 when relatively small quantities of saline groundwater drained from the

irrigated areas and discharged into the Colorado and Gila Rivers. Beginning in 1961, a marked decrease in the natural Colorado River flow and a large influx of pumped irrigation drainage from the Wellton-Mohawk area and South Gila Valley caused the average annual Colorado River salinity above Morelos Dam to increase sharply to nearly 1,500 mg/l by 1962. Measures under IBWC Minute No. 218 to mitigate the effects of the Wellton-Mohawk drainage resulted in a gradual decline in the salinity of the waters made available to Mexico to about 1,250 mg/l by mid-1972; and operations under Minute No. 241 caused a sharp salinity reduction to about 1,140 mg/l. The bypass of all Wellton-Mohawk drainage flows below Morelos Dam, in accordance with Minute No. 242 in 1974, caused another significant reduction in the salinity above Morelos Dam to the 1976 average of about 955 mg/l. Salinity at Morelos Dam is about 130 mg/l greater than that at Imperial Dam. This is due, in part, to pumped groundwater drainage from Yuma Mesa and South Gila Valley which enters the Colorado River above the Northerly Boundary.

The salinity trend of the Colorado River below Morelos Dam probably followed a pattern similar to that above Morelos Dam until 1965 when saline Wellton-Mohawk drainage water was first bypassed below Morelos Dam. The quantity of bypass water increased during operations of the Minutes of the IBWC; but, during this period, the salinity gradually decreased from about 5,500 mg/l to 3,700 mg/l. As the bypass flows have mixed with small amounts of water from other sources, which presumably have had stable salinity levels, salinity of the Colorado River below Morelos Dam probably has decreased since 1965.

As percolation from irrigation waters replaced the Colorado River as the principal source of groundwater recharge, groundwater quality also changed. Under virgin conditions, the shallow alluvial aquifer contained highly saline water due to the high rate of evapotranspiration where the water table was close to the land

surface. Originally salinity generally decreased with depth in the coarse gravel aquifer and the wedge zone. Application of fresh irrigation water from the Colorado River generally improved groundwater quality in the shallow aquifer by leaching salts from the soil and diluting the native saline water. In some areas, salinity of the coarse gravel aquifer may have increased due to the augmented recharge from the slightly saline irrigation water. Where groundwater is pumped from wells located near canals, salinity is generally similar to the canal water.

In South Gila Valley, groundwater pumpage for irrigation and the presence of the Yuma Mesa mound also contributed to salinity increases. Water quality progressively declined where pumped irrigation water was recirculated by wells between the irrigated fields and the groundwater reservoir (USBR, 1970).

In Mexicali Valley groundwater pumpage for irrigation caused an increase in salinity of the groundwater in heavily pumped areas. In the northeastern part of the valley, the salinity increase probably is due to recirculation of groundwater pumped for irrigation. In the southern part of the valley the source of this salinity may be due to the encroachment of marine water saturating the aquifer near the Gulf of California.

The influence of pumping at San Luis Mesa and Yuma Mesa wellfields on groundwater quality is not yet determined from data collected in the monitor well program, established in 1971.

PROBLEM AREAS

As all of the Colorado River waters have been allocated between United States and Mexico, by the Treaty of 1944, expansion of agricultural developments in the delta region will increasingly utilize groundwater resources. The total water supply in the delta must be viewed in terms of the interrelationship of surface and groundwater resources. Within this context, the main problem is focused on optimum and efficient

use of the total water supply within the established legal framework. The existing international legal structure does not include the consideration of groundwater flow across international borders.

According to published data, it is generally agreed that groundwater flow across the California-Baja California border increased substantially following completion of the All-American Canal. However, the quantity of flows which seeps into Mexicali Valley, has not been accurately determined. Estimates range from about 66,000 to more than 90,000 AF/yr. The underflow from the limitrophe section to Mexicali Valley has declined since about 1939, and the most recent quantitative estimates of underflow across the limitrophe range from 35,000 AF/yr to nearly 57,000 AF/yr.

Groundwater developments along the Arizona-Sonora border near San Luis have had an impact on surface water deliveries to Mexico and have led to the international agreement on groundwater pumping for that area in Minute 242, which reads as follows:

> "5. Pending the conclusion by the Governments of the United States and Mexico of a comprehensive agreement on groundwater in the border areas, each country shall limit pumping of groundwaters in its territory within 5 miles (eight kilometers) of the Arizona-Sonora boundary near San Luis to 160,000 acre-feet (197,358,000 cubic meters) annually. "

The southerly rate of groundwater movement has increased along with water table declines near the San Luis Mesa wellfield. About 30 percent of the wellfield pumpage is estimated to have been derived from groundwater stored in United States. This pumpage also reduces flows in the Yuma Main Drain delivered to Mexico as part of the treaty deliveries which is replaced by the United States with groundwaters pumped from Yuma Mesa and discharged to the Colorado River above Morelos Dam. A quantitative analysis of the current reduction of all water resources

in United States, due to San Luis Mesa wellfield operations, cannot be made until data from the IBWC monitor program have been collected over a longer period.

Plans have been prepared and construction will begin in 1977 on a wellfield producing up to 160,000 AF/yr in United States within 5 miles of the Arizona-Sonora border in accord with Minute No. 242. The United States wellfield near the border will decrease the portion of San Luis Mesa wellfield discharge derived from groundwater stored in Arizona and salvage a part of the available water supply within United States.

Another water supply problem in United States is the replacement of Wellton-Mohawk bypass water with Colorado River waters amounting to about 210,000 AF/yr. However, this problem will be largely remedied upon completion of the authorized project for desalting the Wellton-Mohawk drain waters to be in operation in 1981. There will be the remaining problem of replacing the brine waters and operational wastes from the desalting plant.

The problem of the Wellton-Mohawk drainage being bypassed into the Colorado River below Morelos Dam to become a source of salinity contaminating groundwater pumped for irrigation near the Colorado River, was overcome in late 1977. At that time concrete lined extension to the Wellton-Mohawk drain was completed, it conveys drainage waters and will convey brine waters from the desalting plant to the Gulf.

The loss of some 300,000 AF annually of water from the unlined All-American and Coachella Canals continues to present a water supply problem for the United States. Almost none of the leakage which flows west and northwestward across East Mesa is recovered by pumping from wells. Presently most of the leakage percolates to great depths and into low-permeable sediments in Central Imperial Valley. However, the United States is planning to line the first 49 miles of the Coachella Canal to conserve

about 141,000 AF/yr. About one-third of the leakage is likely to continue to move into Mexico where it is pumped for irrigation purposes and creates drainage problems in some areas. The effects of lining the Coachella Canal on the rate of leakage from the All-American Canal have not been calculated.

Groundwater salinity in northeastern Mexicali Valley must be expected to continue to slowly increase with continued pumping. In the vicinity of pumping wells the water table continues to decline. As a result, irrigation water applied in the vicinity of the well infiltrates to the water table and then moves toward the well where it is pumped again for irrigation. During the infiltration cycle more salts are leached from the surficial soils causing the groundwater salinity to increase. Unless pumpage is reduced further, or the pumping schedule modified, salinity in Mexicali Valley will probably continue to be a problem. Mexico may then be expected to look for other groundwater sources to maintain its agricultural economy.

Summation: Estimates of 1976 total groundwater flows from the United States to Mexico are as follows:

Boundary Segment	Acre-feet/year
1) Arizona - Sonora	75,000
2) Limitrophe of Colorado River	35,000
3) California - Baja California	90,000
TOTAL -	200,000

The protective pumping project for the United States' side of the boundary opposite the Mexican San Luis Mesa wellfield, authorized by the Congress P.L. 93-320, will be undertaken early in 1977 with the installation of 6 wells, to be followed by an additional 19 wells in subsequent years. The pumping effects from the total of 25 wells will be to reduce the groundwater flow across this segment of the boundary. In addition, significant

large amounts of groundwater are lost to United States which flow into Mexicali Valley; about 35,000 AF/yr flow westward across the limitrophe section of the Colorado River; plus an estimated 90,000 AF/yr of leakage flows southward from the All-American Canal.

The above losses of United States groundwaters constitute the current international groundwater problem in the Colorado River Delta region.

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_____ 1976, Tabulation of All-American Canal losses for the reach from Pilot Knob to the Imperial West Side Main over the years 1966 through 1975: written communication.

APPENDIX

SOURCES OF DATA UTILIZED FOR THE OVERVIEW REPORT

IMPERIAL VALLEY IRRIGATION DISTRICT

Well Hydrographs - East Mesa Area Near International Border.

INTERNATIONAL BOUNDARY AND WATER COMMISSION: UNITED STATES SECTION

1976a, Effects of pumping wells on the San Luis Mesa and Yuma Mesa on the groundwater regimen in Yuma Mesa and Yuma Valley through December 31, 1975: Western Boundary Regional Office, Yuma, Arizona Report.

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1976, Configuracion tentativa de niveles estaticos referidos al nivel del mar: Map.

1976, Gerencia de obras de rehabilitacion Planeacion General: Map.

1976, Jefatura de irrigacion y control de rios dirreccion general de aguas subterraneas distrito de riego del rio Colorado, B.C. residencia general de aguas subterraneas

1975, Curvas de igual contenido de sales y % de na. en el ano de 1975: Open-file data.

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1973, San Luis Mesa well field drilling logs and pump test data: Open-file report.

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1973, Olmsted, F. H., Loeltz, O. J., and Irelan, B., Geohydrology of the Yuma area, Arizona and California: U.S. Geol. Survey Prof. Paper 486-H.

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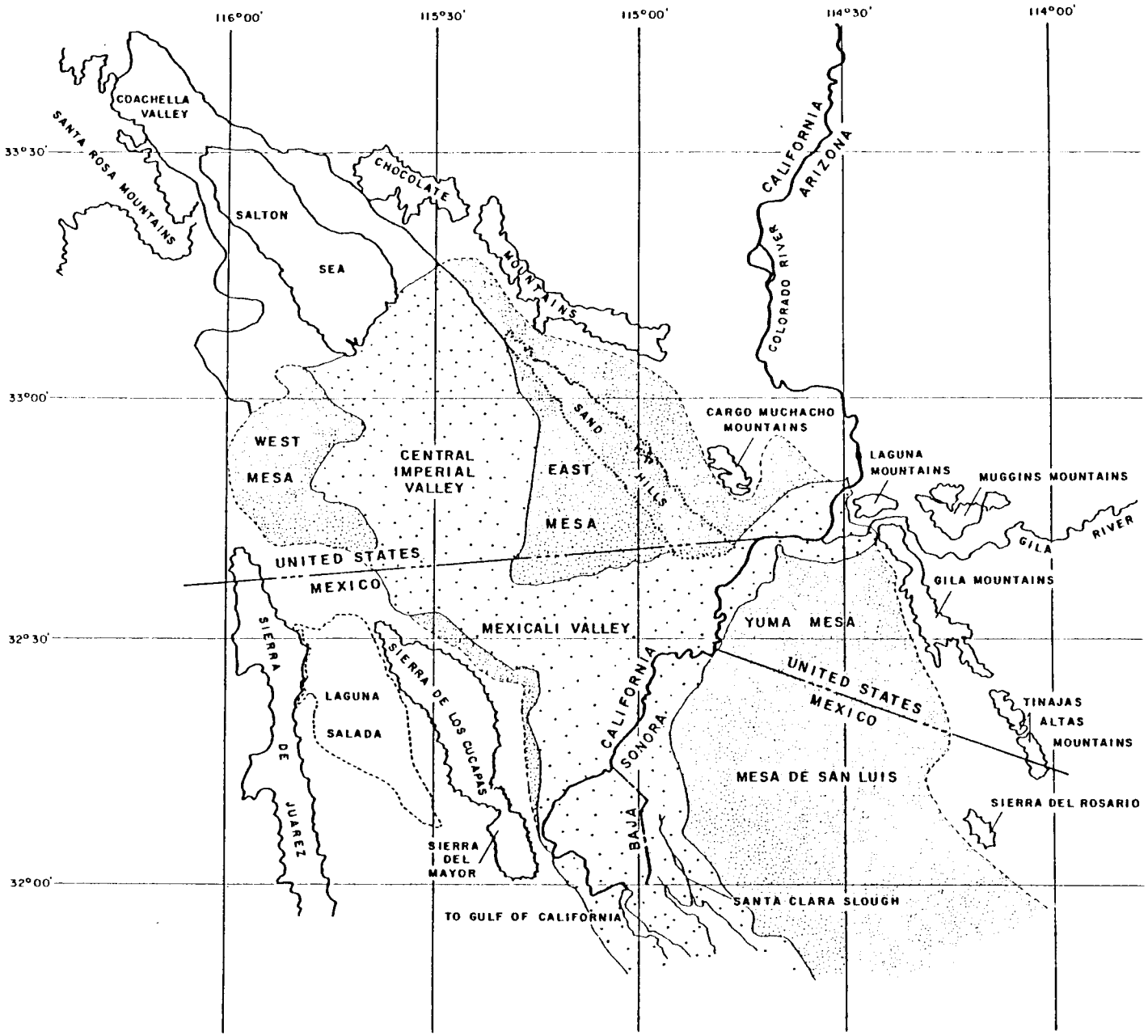


EXPLANATION

APPROXIMATE AREA OF DELTA DEPOSITS

MODERN FLOOD-PLAIN AREA

APPROXIMATE LIMIT OF ALLUVIAL BASIN

(Modified from Sykes, 1937)

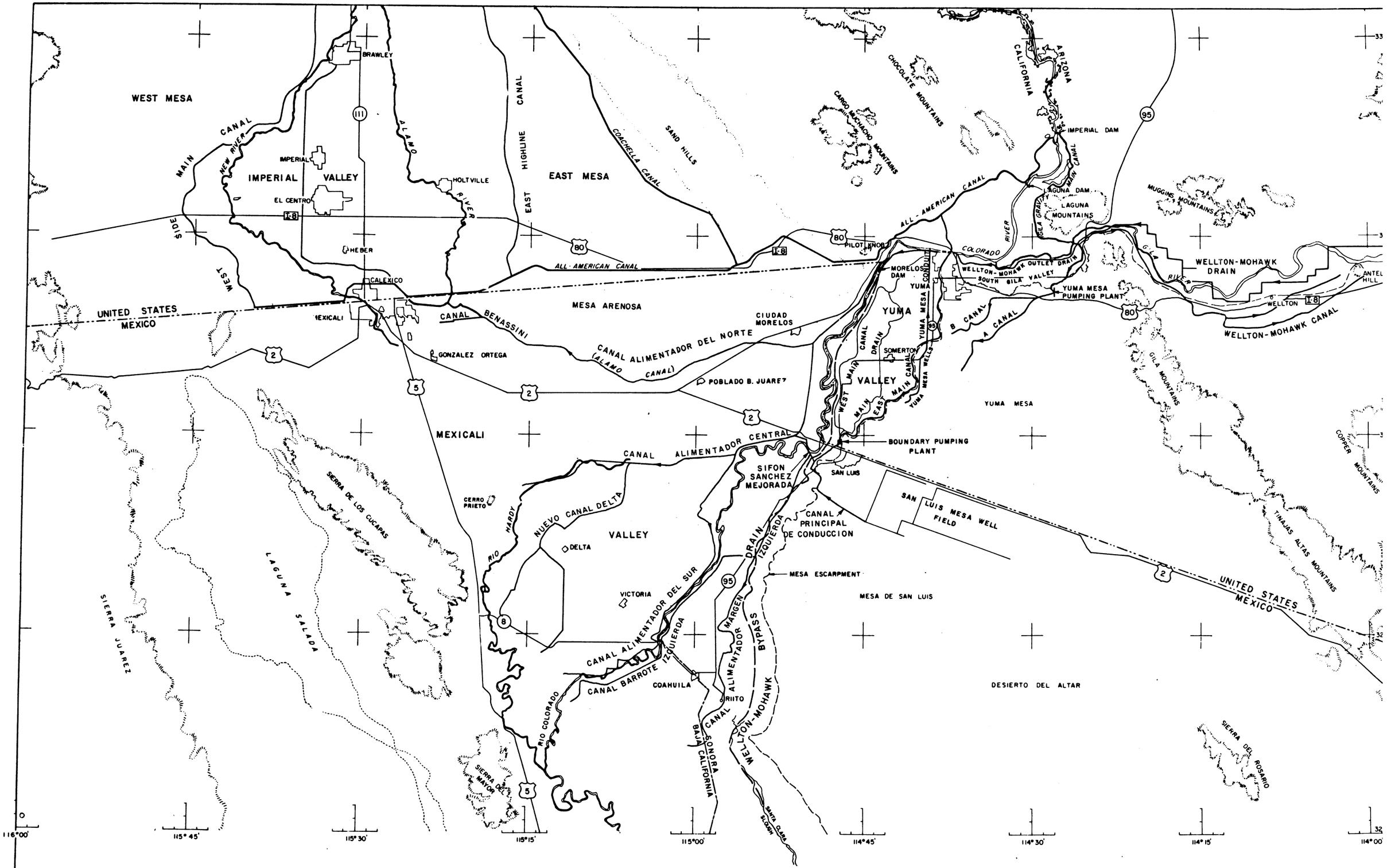
N

0 5 10 15 20 25
MILES

MAJOR PHYSICAL FEATURES OF THE COLORADO DELTA AREA

HARSHBARGER AND ASSOCIATES
TUCSON, ARIZONA 1976

FIGURE I



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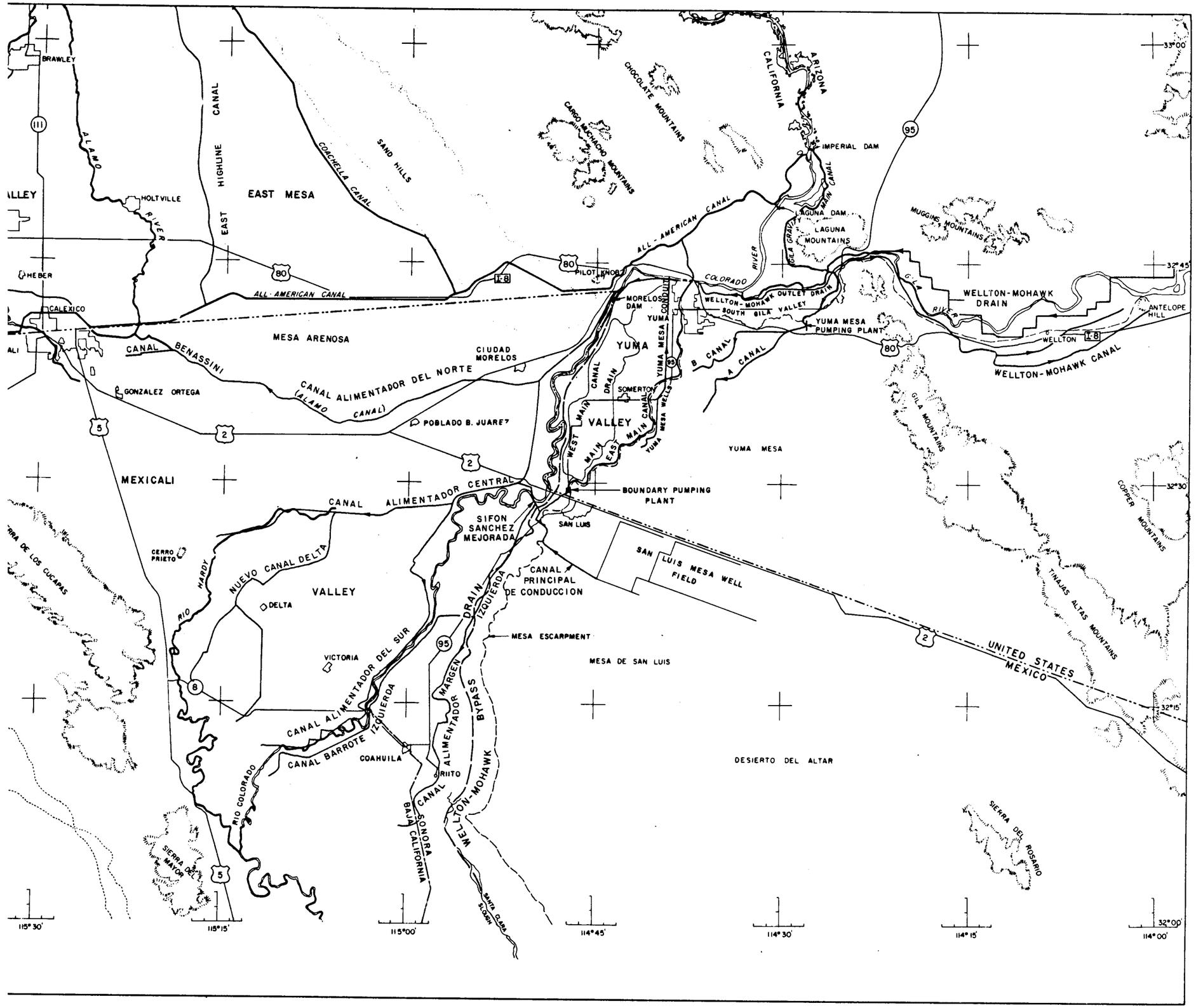


EXPLANATION

EAST MAIN CANAL

PRINCIPAL IRRIGATION AND DRAINAGE CANALS
ARROW INDICATES FLOW DIRECTION

HIGHWAYS

I-8 INTERSTATE

2 FEDERAL

8 STATE

N

5 0 5 10
MILES

5 0 5 10 15
KILOMETERS

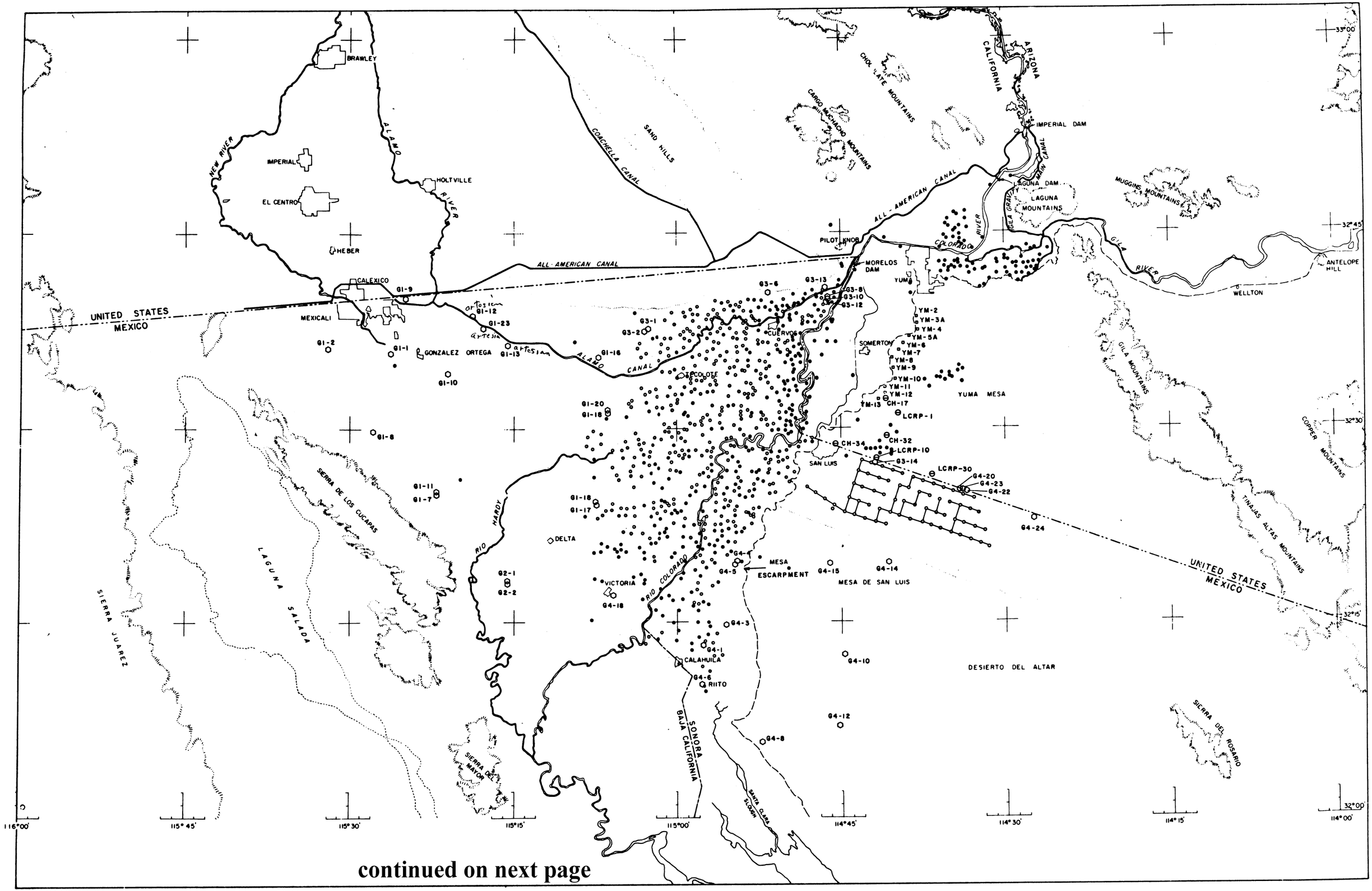
INTERNATIONAL BOUNDARY AND WATER COMMISSION
UNITED STATES AND MEXICO

COLORADO DELTA

PRINCIPAL IRRIGATION AND DRAINAGE WORKS

HARSHBARGER AND ASSOCIATES
TUCSON, ARIZONA 1976

FIGURE 2



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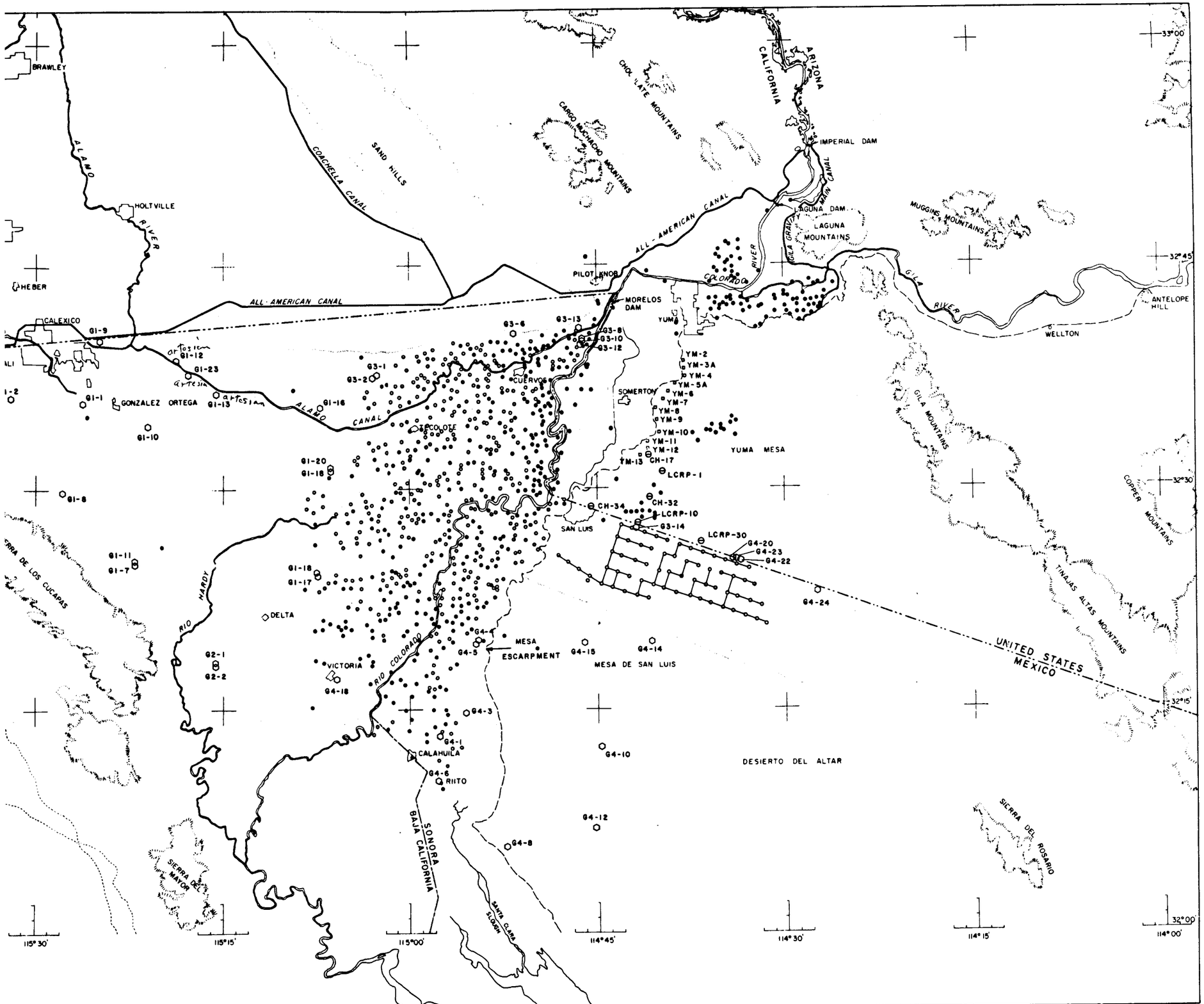


EXPLANATION

WELLS

IRRIGATION
- ● PRIVATE
- ○ GOVERNMENT

DRAINAGE
- YM-5 □ YUMA MESA

MONITOR
- CH-32 ⊖ IDENTIFIER

TEST
- G4-5 ○ IDENTIFIER

N

5 0 5 10
MILES

5 0 5 10 15
KILOMETERS

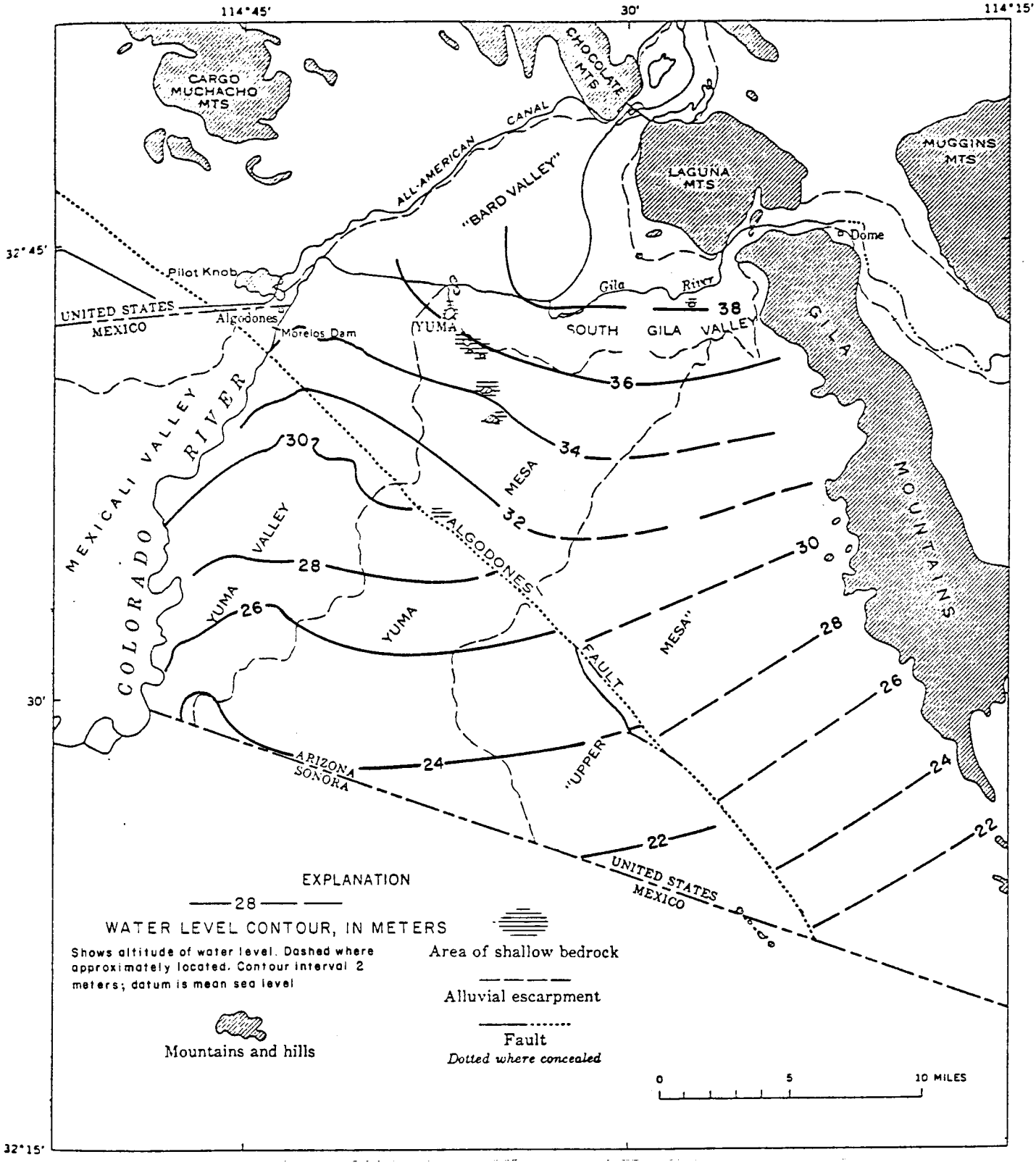
INTERNATIONAL BOUNDARY AND WATER COMMISSION
UNITED STATES AND MEXICO

COLORADO DELTA

WELL LOCATIONS

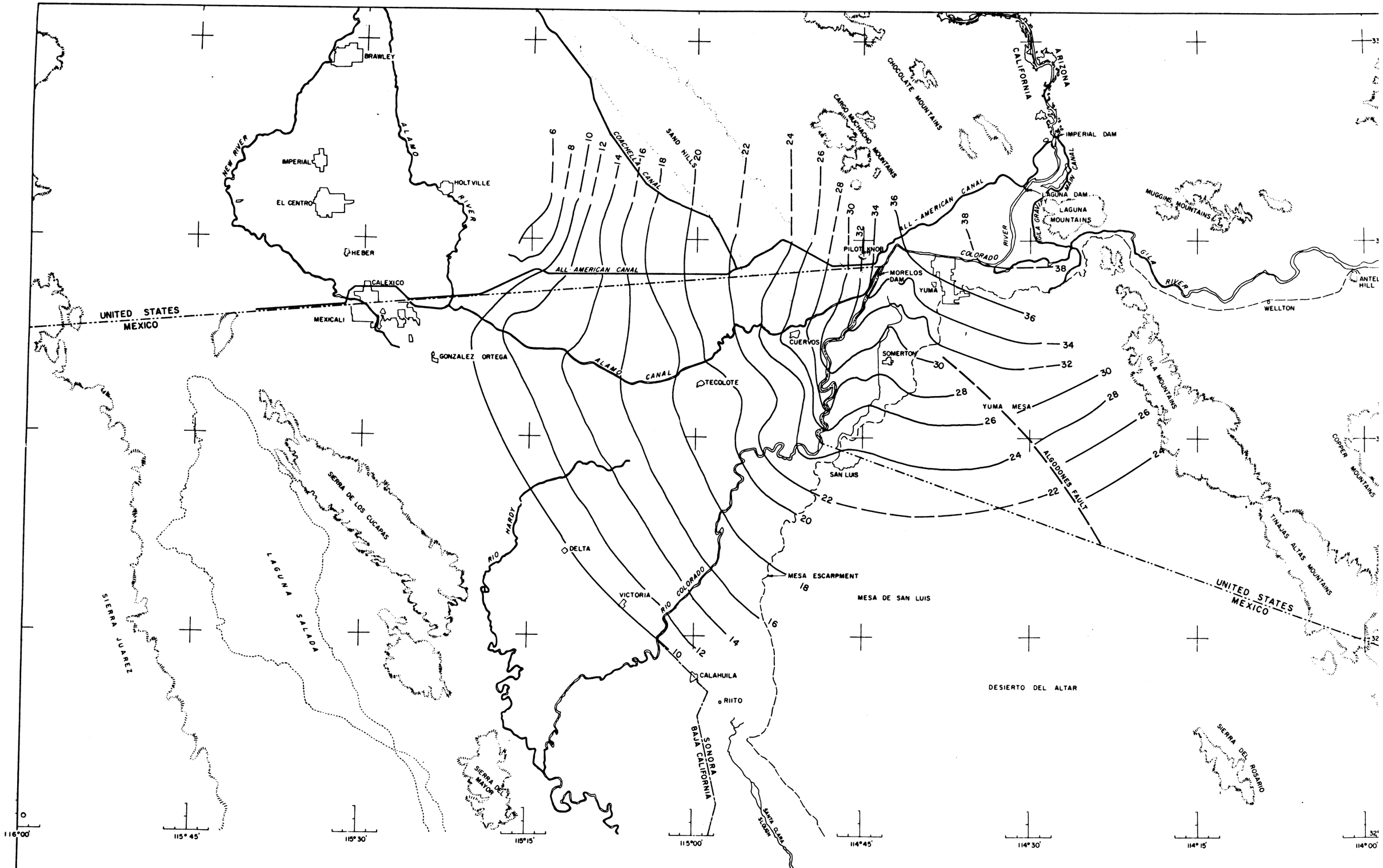
HARSHBARGER AND ASSOCIATES
TUCSON, ARIZONA 1976

FIGURE 3



(Modified from: Figure 29; Prof. Paper 486-H; U.S. Geological Survey)

FIGURE 4.--AVERAGE WATER-LEVEL CONTOURS IN 1925



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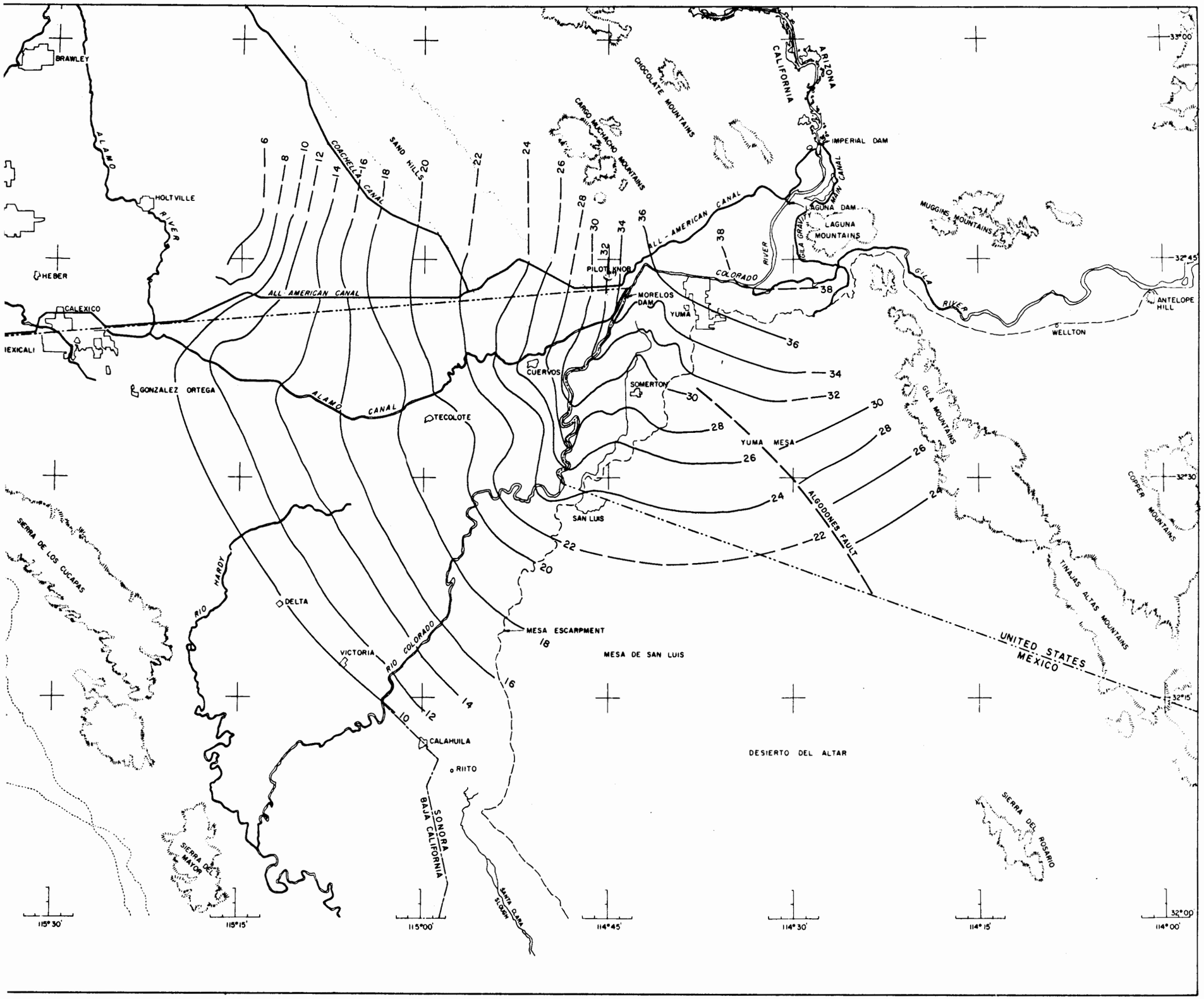


EXPLANATION

20

WATER-LEVEL CONTOURS
IN METERS ABOVE MEAN SEA LEVEL
DASHED WHERE APPROXIMATE

N

5 0 5 10
MILES

5 0 5 10 15
KILOMETERS

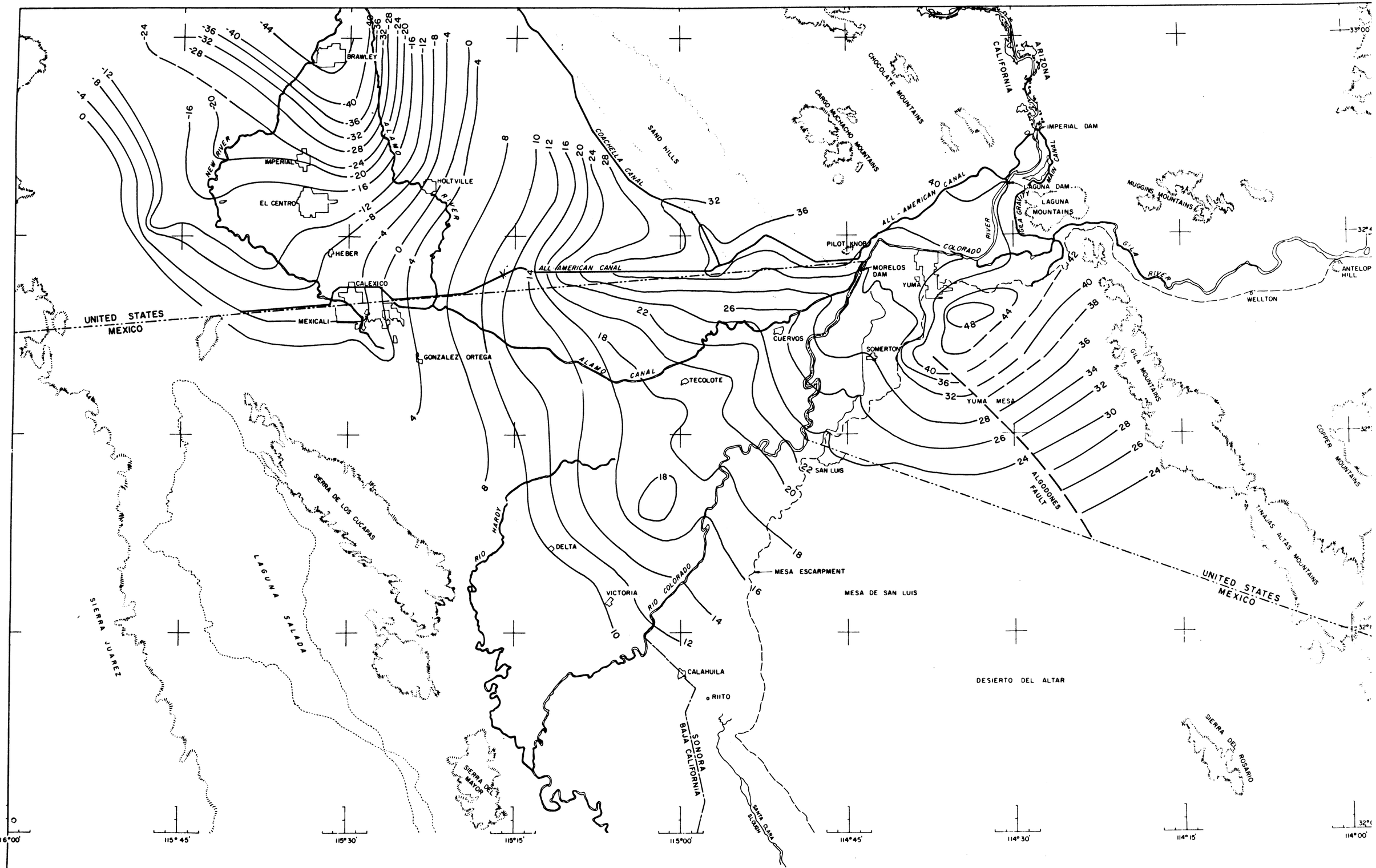
INTERNATIONAL BOUNDARY AND WATER COMMISSION
UNITED STATES AND MEXICO

COLORADO DELTA

WATER-LEVEL CONTOURS IN 1939

HARSHBARGER AND ASSOCIATES
TUCSON, ARIZONA 1976

FIGURE 5



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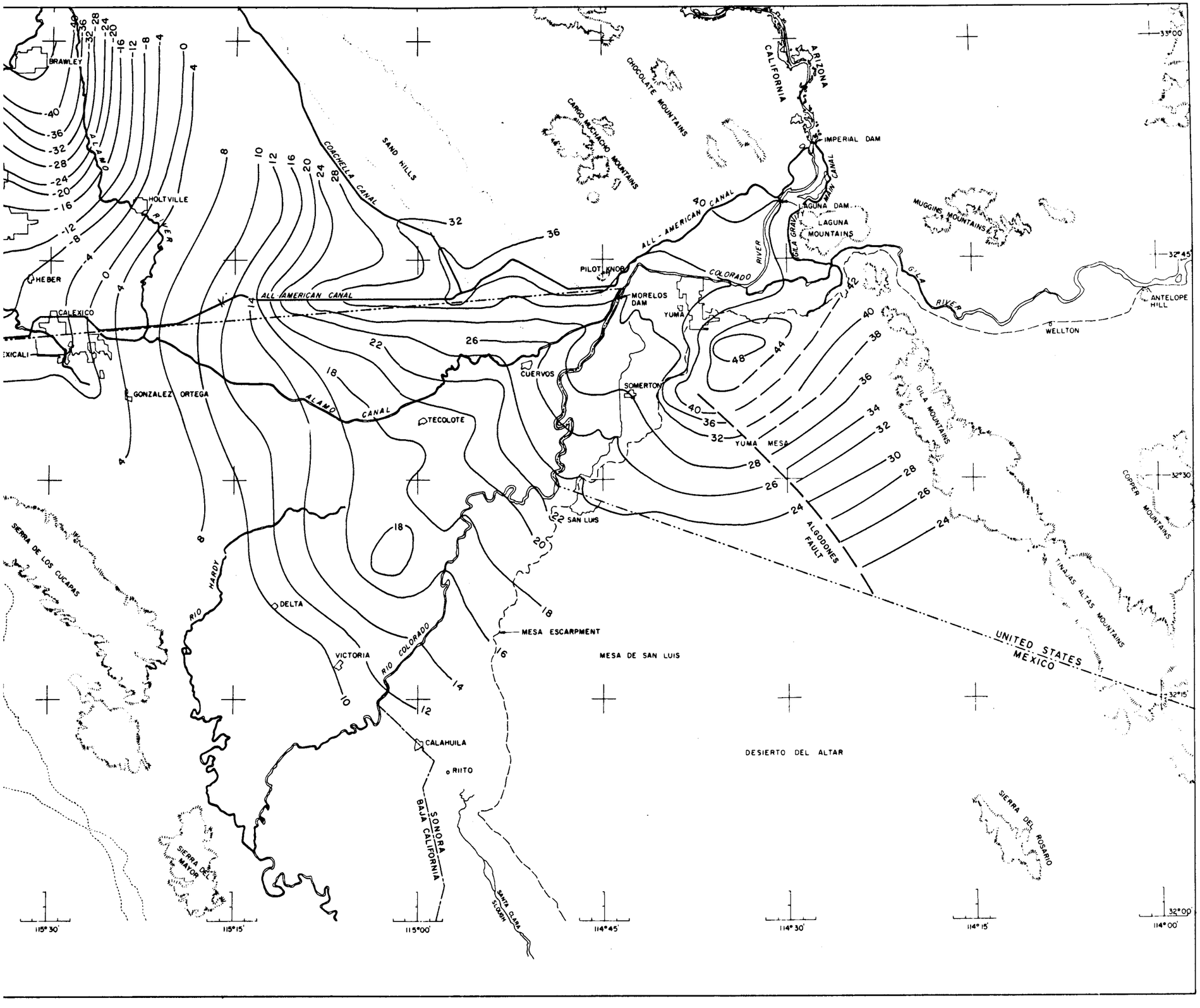


EXPLANATION

——20— — —

WATER-LEVEL CONTOURS
IN METERS ABOVE MEAN SEA LEVEL
DASHED WHERE APPROXIMATE

N

5 0 5 10
MILES

5 0 5 10 15
KILOMETERS

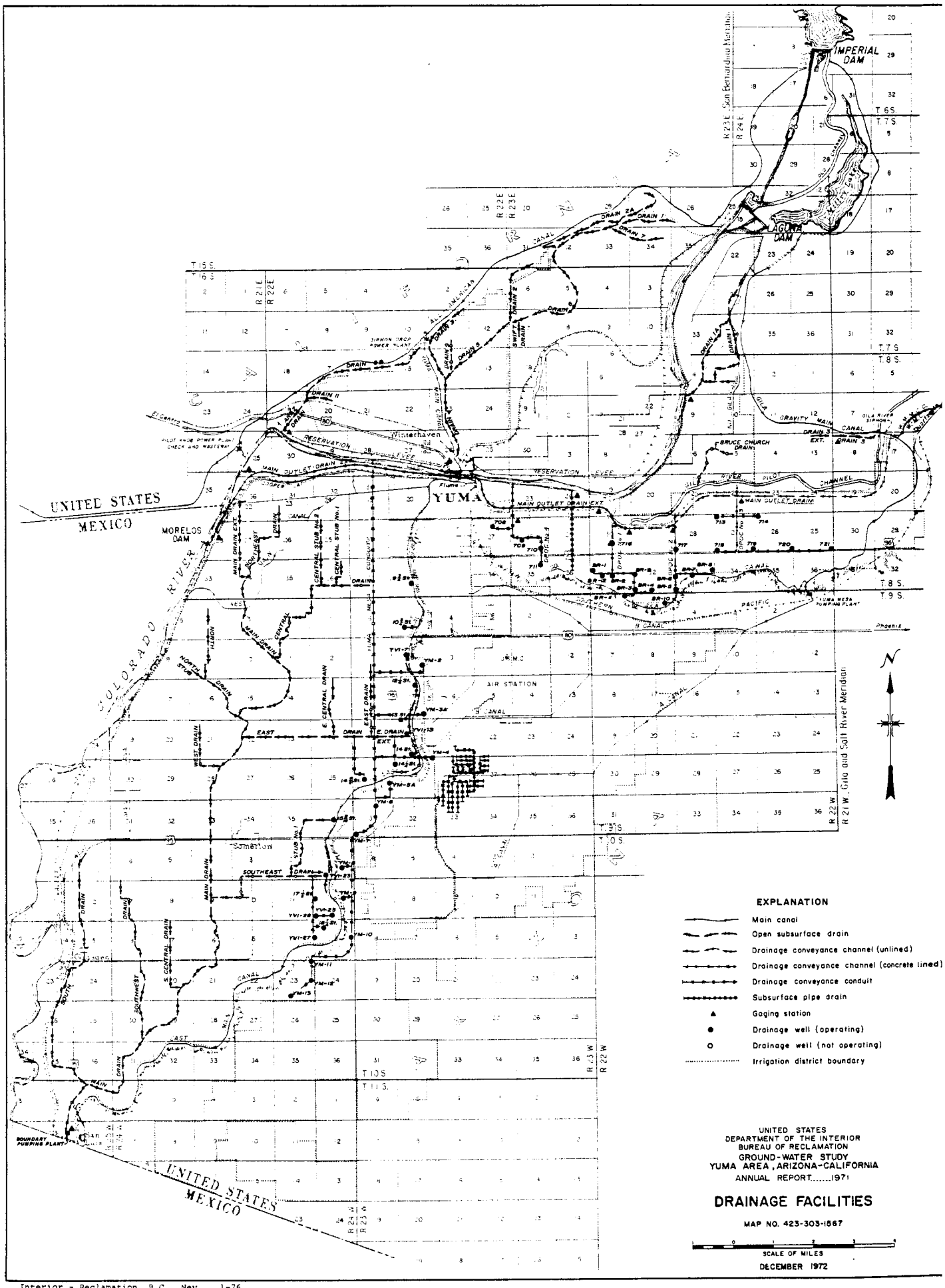
INTERNATIONAL BOUNDARY AND WATER COMMISSION
UNITED STATES AND MEXICO

COLORADO DELTA

WATER-LEVEL CONTOURS IN 1960

HARSHBARGER AND ASSOCIATES
TUCSON, ARIZONA 1976

FIGURE 6



Interior - Reclamation, R.C., Nev. 1-76

FIGURE 7

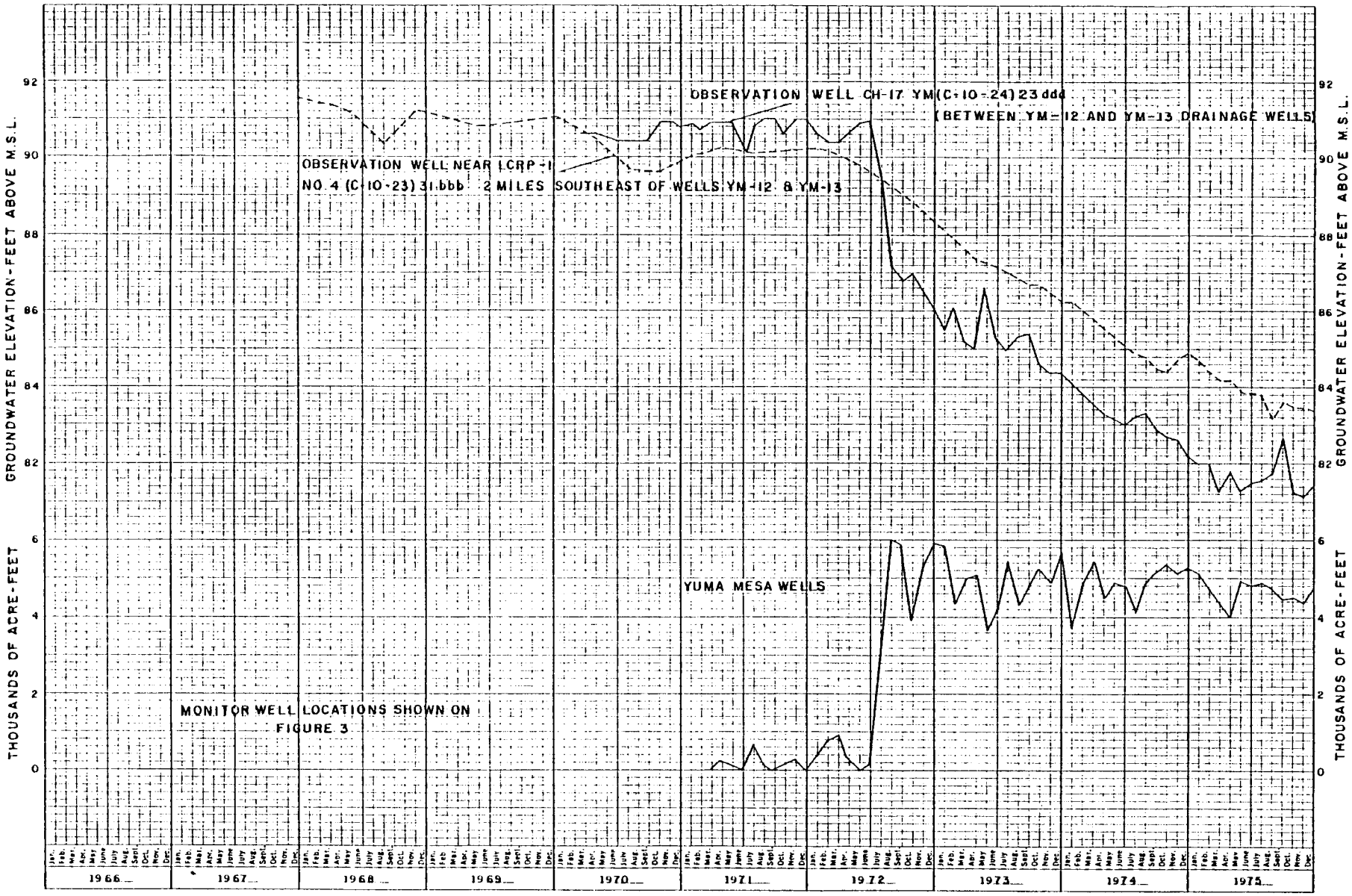
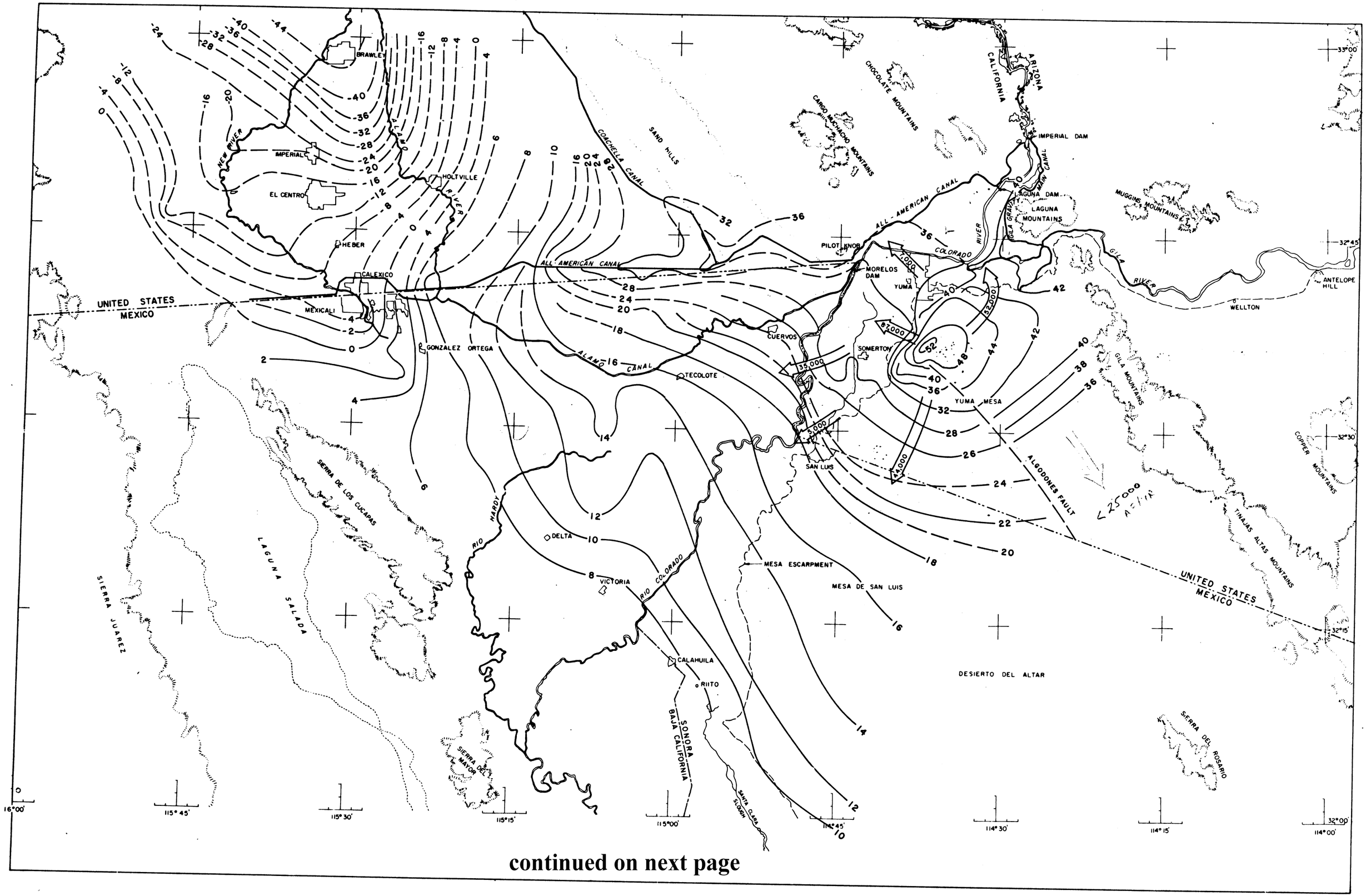


FIGURE 8 --HYDROGRAPHS OF WATER LEVELS IN MONITOR WELLS AND YUMA MESA WELLFIELD PUMPAGE



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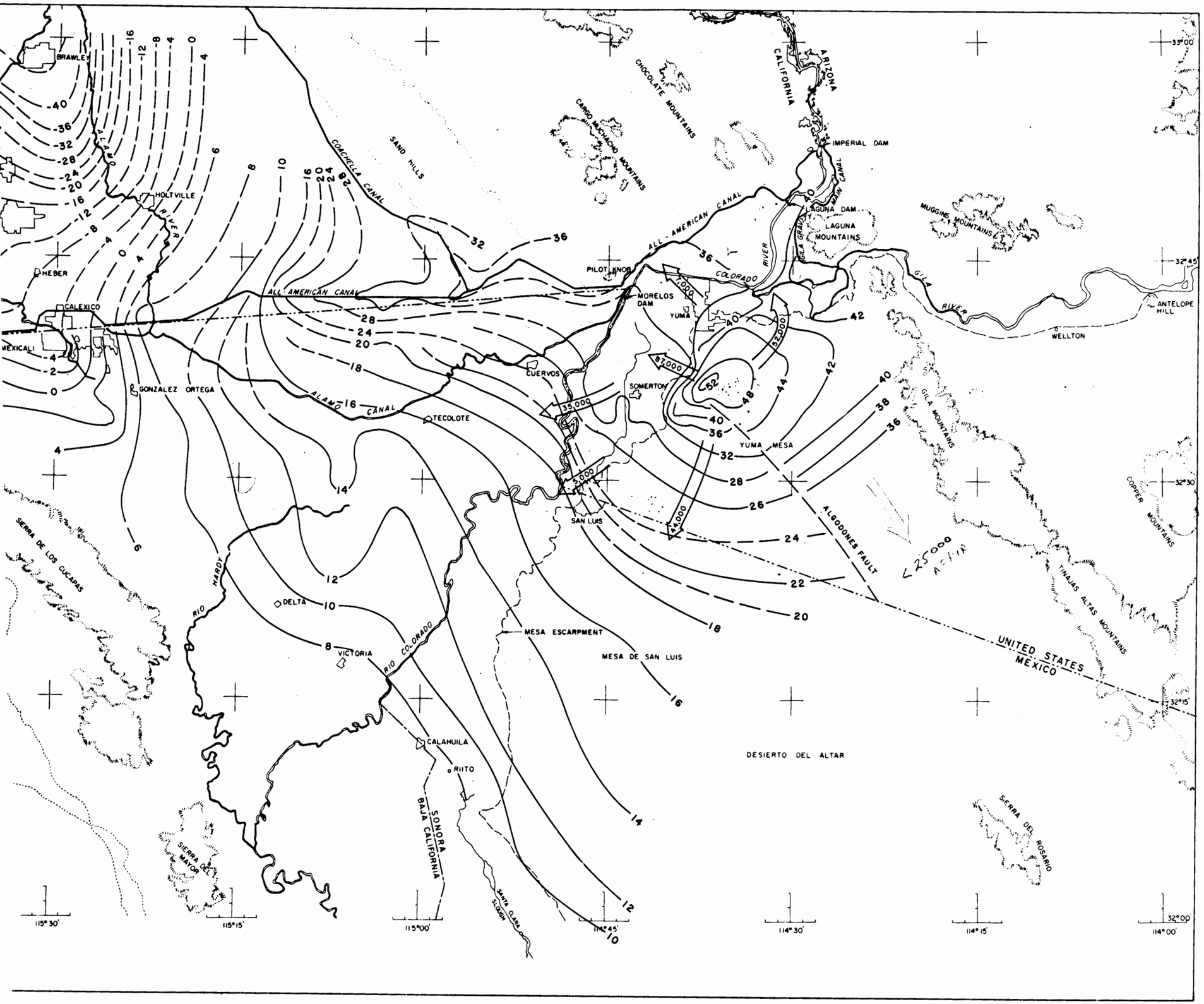


EXPLANATION

20

WATER-LEVEL CONTOURS
IN METERS ABOVE MEAN SEA LEVEL
DASHED WHERE APPROXIMATE

7,000

DIRECTION OF GROUNDWATER FLOW; 7,000
INDICATES ACRE-FEET PER YEAR

N

5 0 5 10
MILES

5 0 5 10 15
KILOMETERS

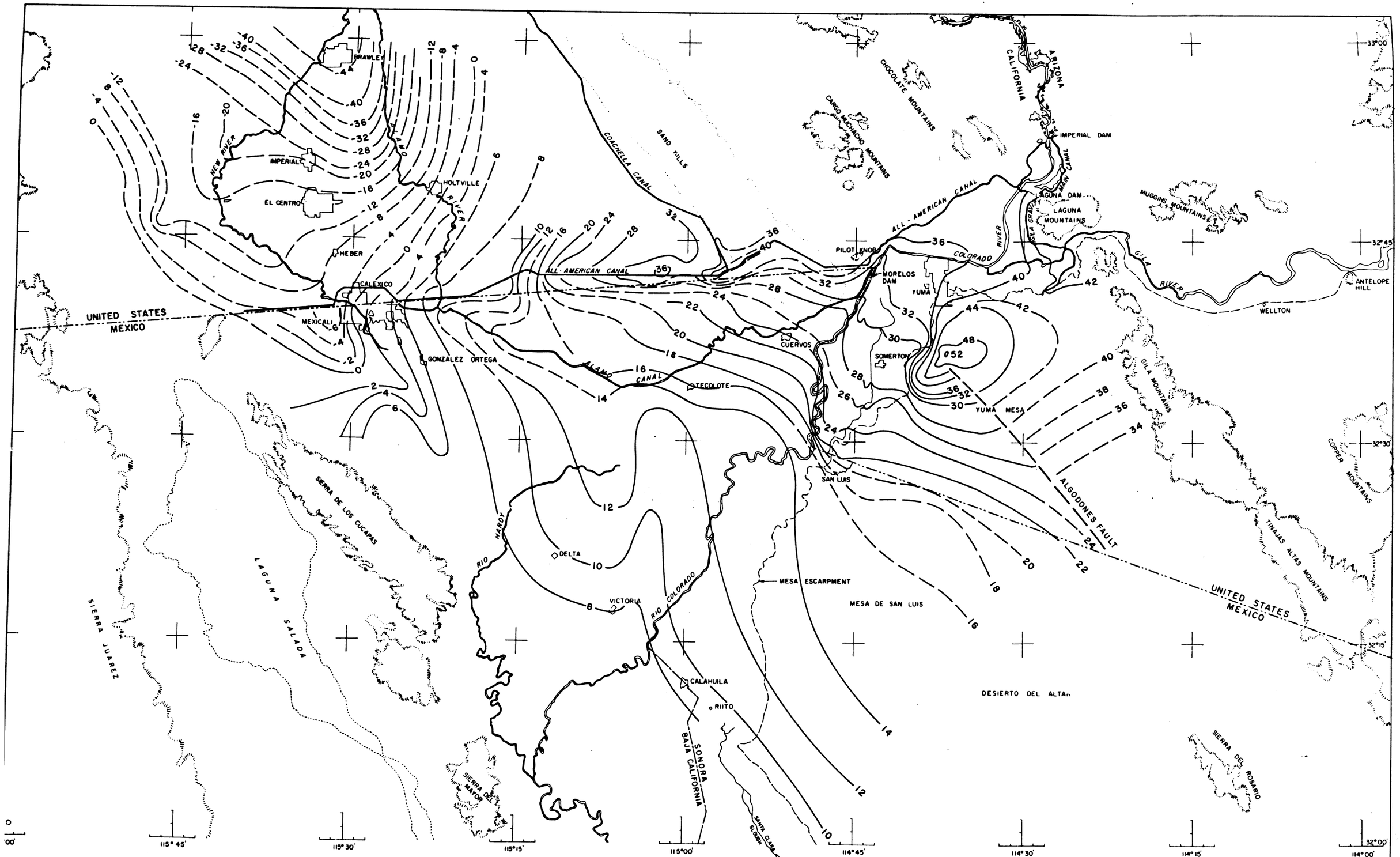
INTERNATIONAL BOUNDARY AND WATER COMMISSION
UNITED STATES AND MEXICO

COLORADO DELTA

WATER-LEVEL CONTOURS IN 1972

HARSHBARGER AND ASSOCIATES
TUCSON, ARIZONA 1976

FIGURE 9



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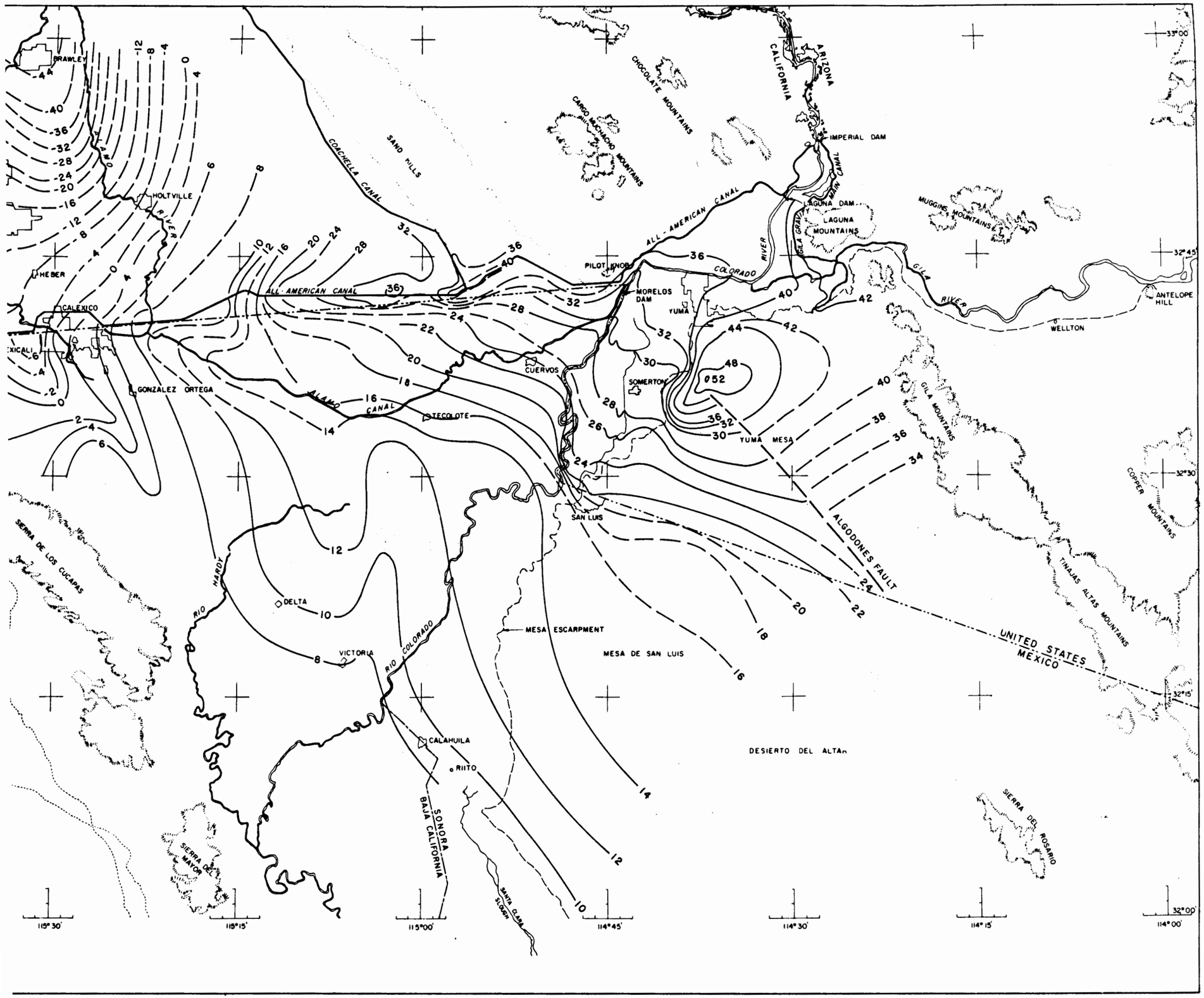
INTE

WA



EXPLANATION

20

WATER-LEVEL CONTOURS
IN METERS ABOVE MEAN SEA LEVEL
DASHED WHERE APPROXIMATE

N

5 0 5 10
MILES

5 0 5 10 15
KILOMETERS

INTERNATIONAL BOUNDARY AND WATER COMMISSION
UNITED STATES AND MEXICO

COLORADO DELTA

WATER-LEVEL CONTOURS IN 1976

HARSHBARGER AND ASSOCIATES
TUCSON, ARIZONA 1976

FIGURE 10

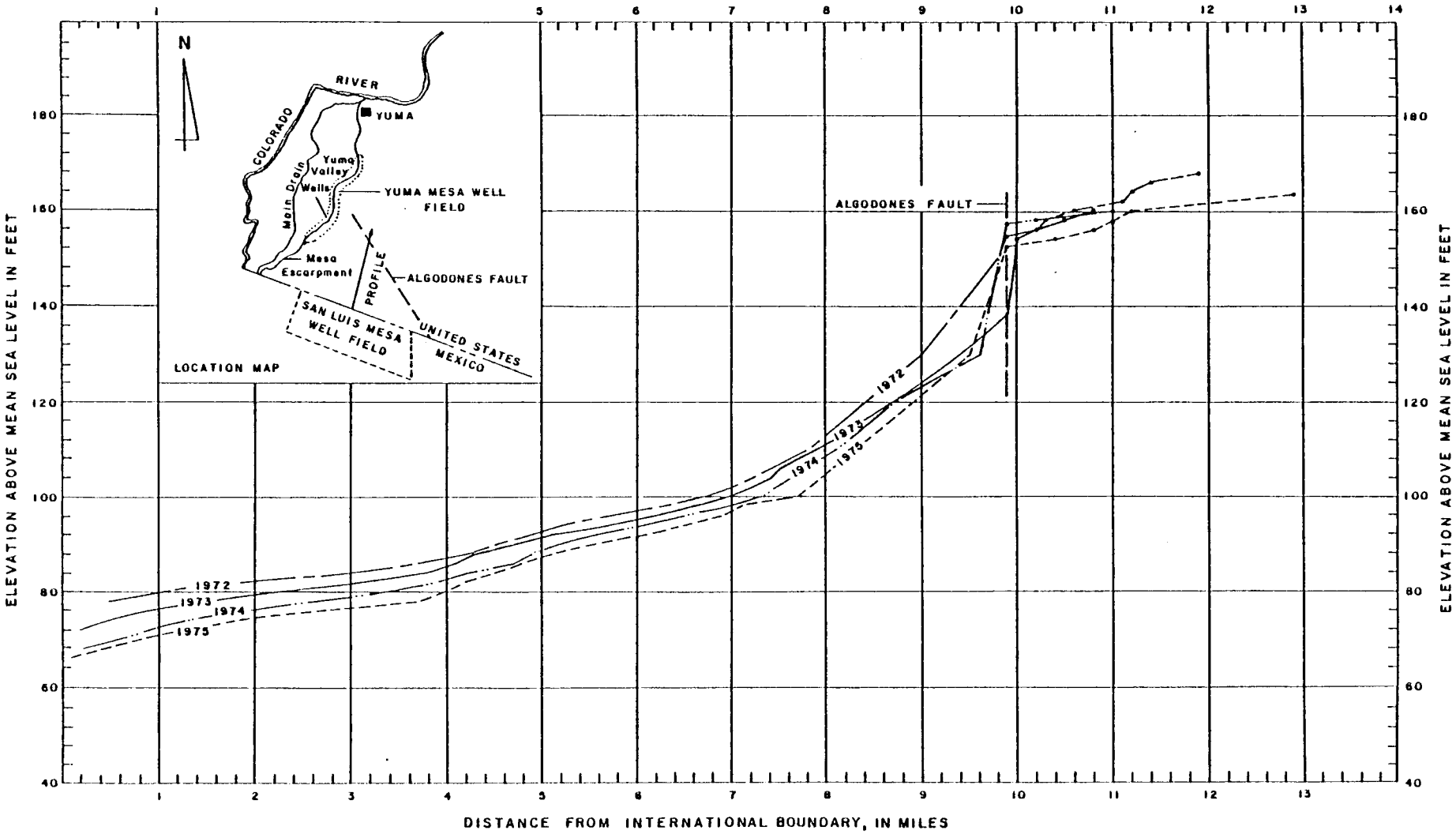


FIGURE 11--COMPARISON OF GROUNDWATER PROFILES, DECEMBER 1972-1975, IN SOUTHERN YUMA MESA

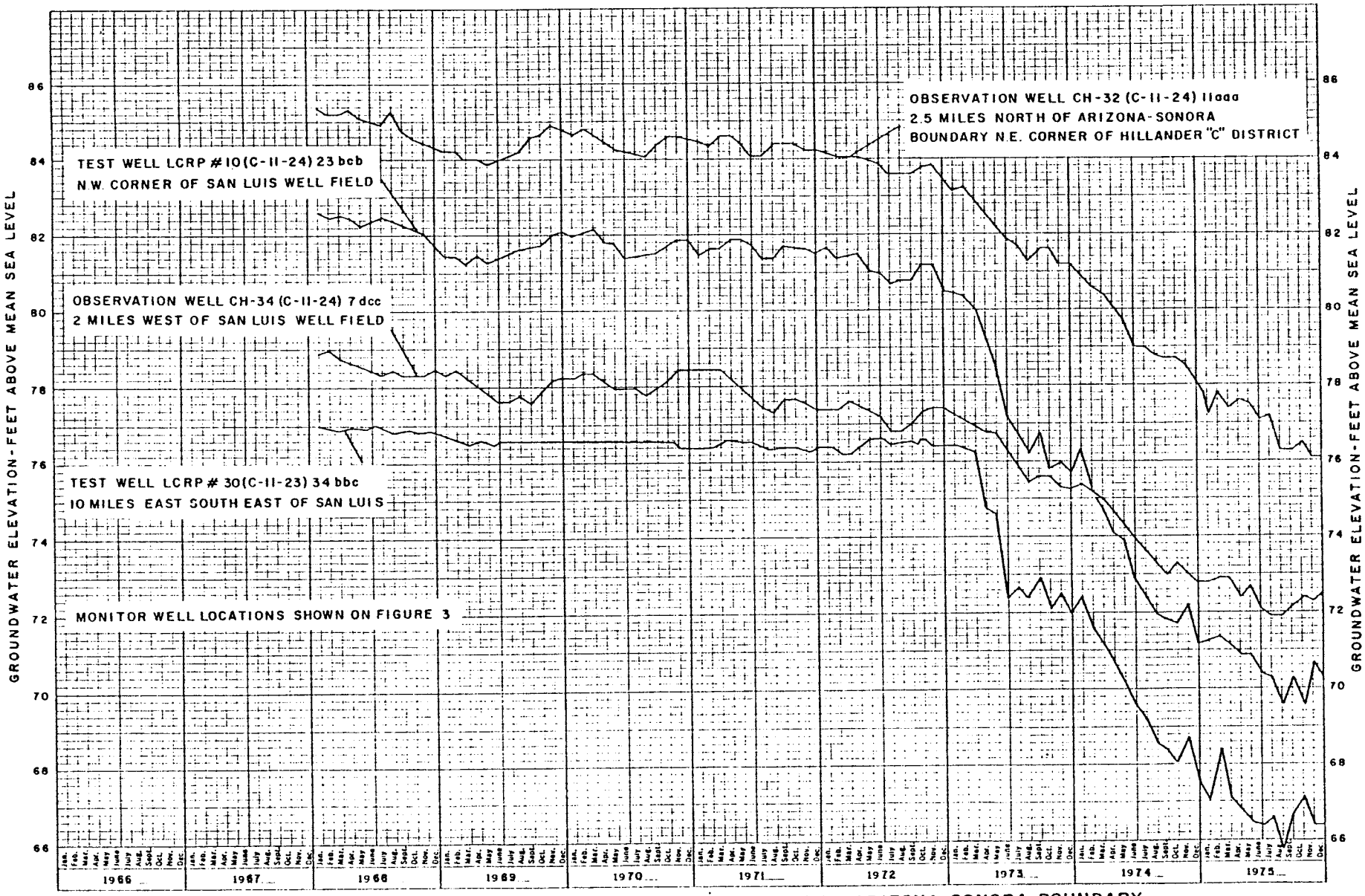


FIGURE 12--HYDROGRAPHS OF WATER LEVELS IN WELLS ALONG ARIZONA-SONORA BOUNDARY

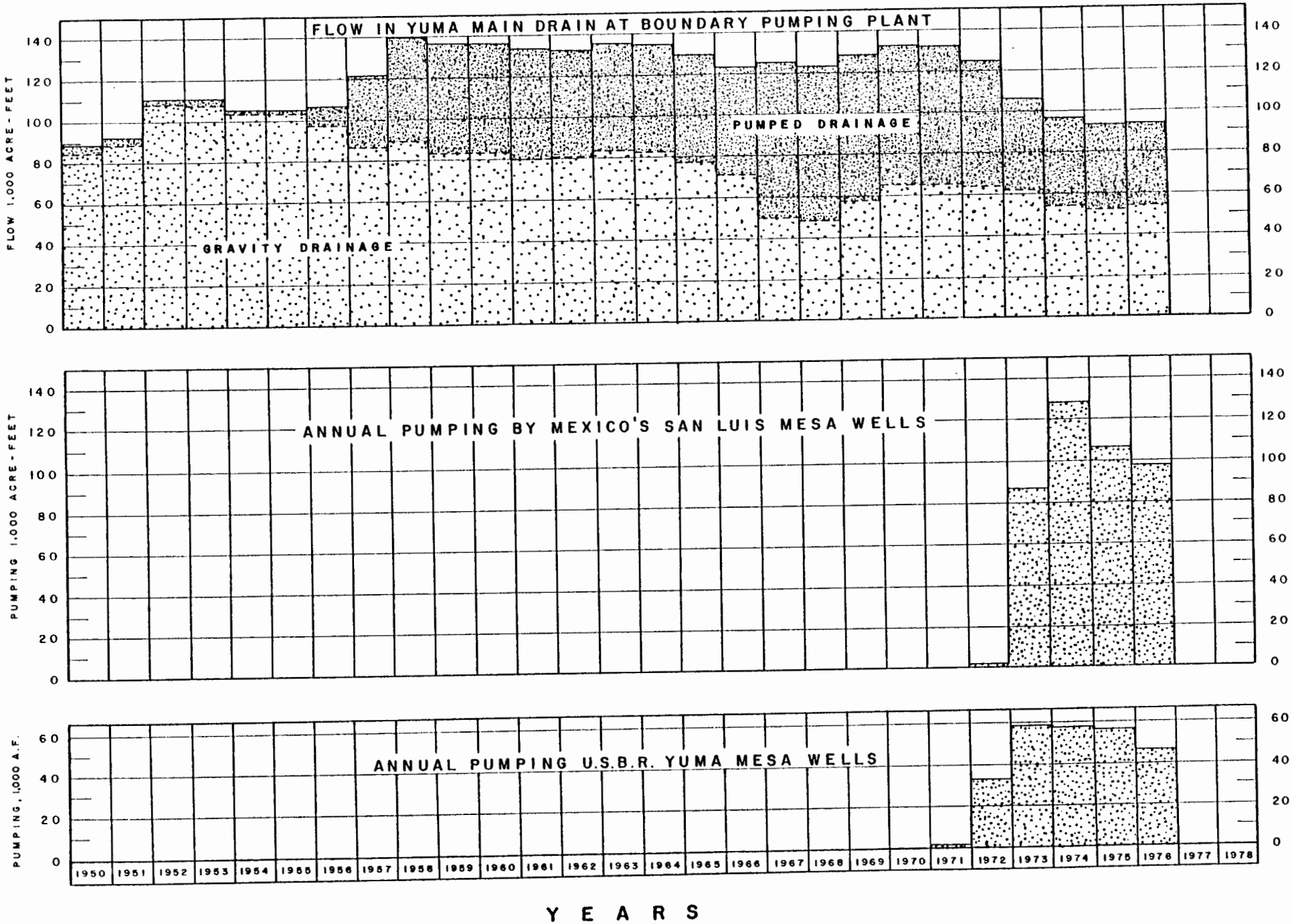


FIGURE 13.--STUDY OF EFFECTS OF YUMA MESA AND SAN LUIS MESA PUMPING ON FLOW IN YUMA MAIN DRAIN

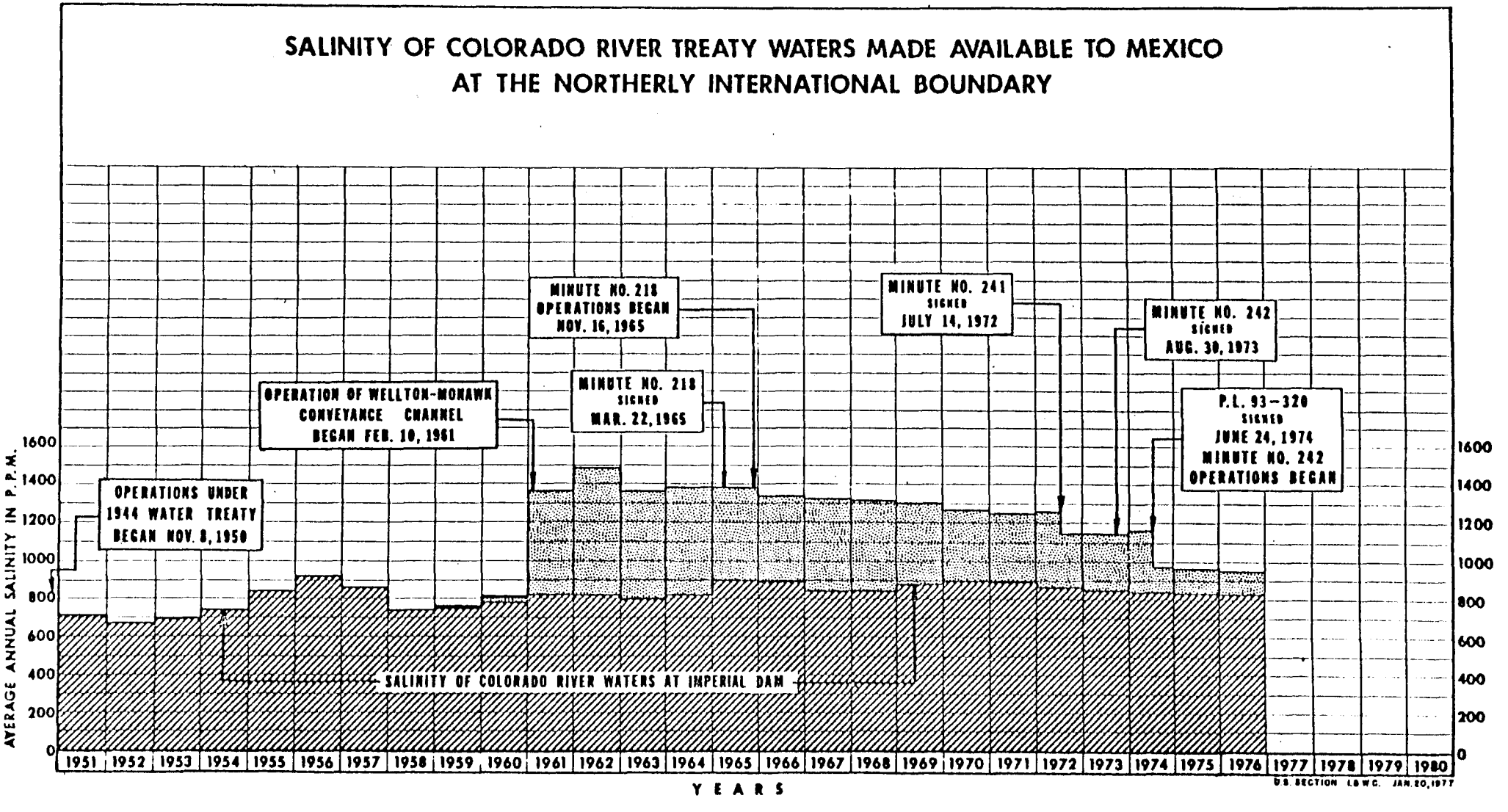

SALINITY OF COLORADO RIVER TREATY WATERS MADE AVAILABLE TO MEXICO
AT THE NORTHERLY INTERNATIONAL BOUNDARY
OPERATIONS UNDER 1944 WATER TREATY BEGAN NOV. 8, 1950
OPERATION OF WELLTON-MOHAWK CONVEYANCE CHANNEL BEGAN FEB. 10, 1961
MINUTE NO. 218 OPERATIONS BEGAN NOV. 16, 1965
MINUTE NO. 218 SIGNED MAR. 22, 1965
MINUTE NO. 241 SIGNED JULY 14, 1972
MINUTE NO. 242 SIGNED AUG. 30, 1973
P.L. 93-320 SIGNED JUNE 24, 1974
MINUTE NO. 242 OPERATIONS BEGAN
SALINITY OF COLORADO RIVER WATERS AT IMPERIAL DAM
AVERAGE ANNUAL SALINITY IN P.P.M.
0
200
400
600
800
1000
1200
1400
1600
1951 1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980
YEARS
U.S. SECTION I.B.W.C. JAN. 20, 1977

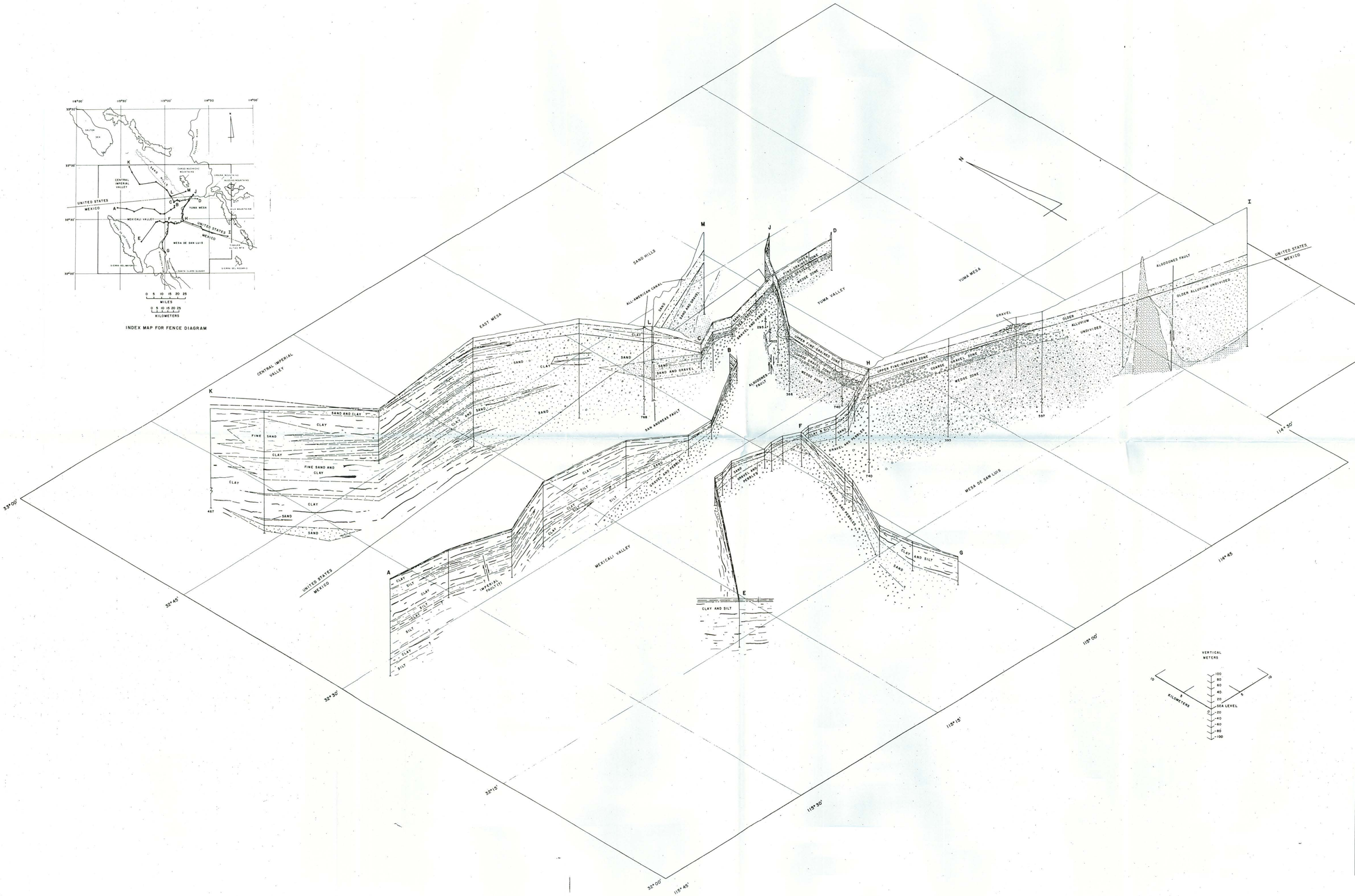
FIGURE 14

FIGURE 15

HYDROGEOLOGICAL FENCE DIAGRAM

(In Pocket)

INDEX MAP FOR FENCE DIAGRAM



EXPLANATION

AQUIFERS

MOST WELLS YIELD 1,000 TO MORE THAN 3,000 GPM*
Coarse gravel, pea gravel, wedge zone, and sand-gravel zones

MOST WELLS YIELD ABOUT 500 GPM*
Upper fine-grained zone, sands, and interbedded sequences of sand and clay

Saturated sediments; low-permeable sand, silt, and clay

*GPM-GALLONS PER MINUTE

SYMBOLS

TERTIARY SEDIMENTARY ROCKS

PRE-TERTIARY CRYSTALINE ROCKS

CONTACT, DASHED WHERE INDEFINITE

POTENTIOMETRIC SURFACE

SEA LEVEL DATUM PLANE

FAULT, ARROW INDICATES RELATIVE DIRECTION OF MOVEMENT

Break in scale

716
TOTAL DEPTH, IN METERS
WELLS, LOCATION PLOTTED ON SEA LEVEL PLANE

INTERNATIONAL BOUNDARY AND WATER COMMISSION
UNITED STATES AND MEXICO

COLORADO DELTA

HYDROGEOLOGICAL FENCE DIAGRAM

HARSHBARGER AND ASSOCIATES
TUCSON, ARIZONA 1976

FIGURE 15

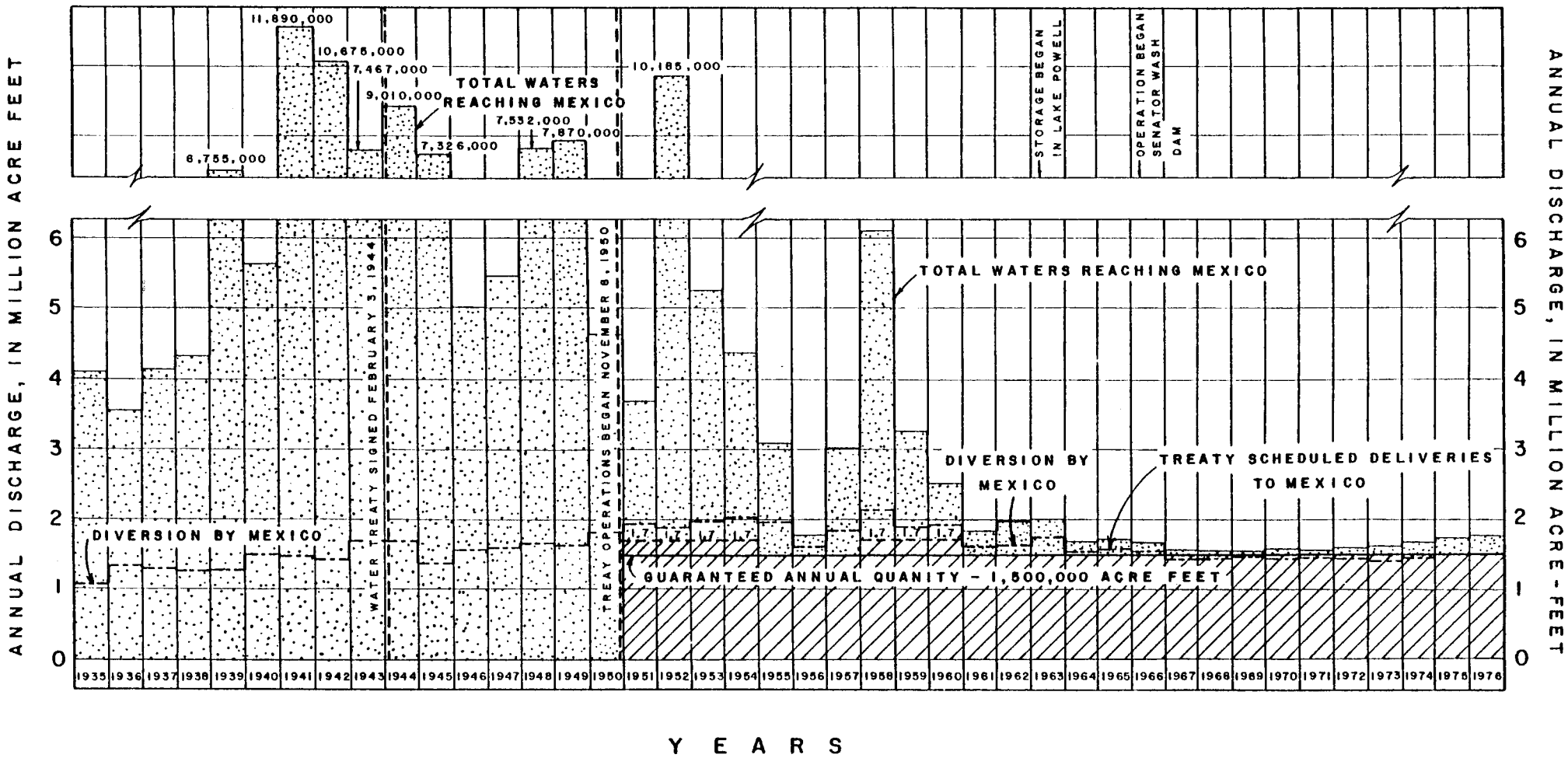


FIGURE 16.--COLORADO RIVER WATERS REACHING MEXICO 1944 TREATY SCHEDULED DELIVERIES AND DIVERSIONS BY MEXICO