Analog Simulation of the Ground-Water System, Yuma, Arizona

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WATER RESOURCES OF LOWER COLORADO RIVER-SALTON SEA AREA

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By EUGENE P. PATTEN, JR.

ABSTRACT

An electric analog model was used to simulate the ground-water system of the Yuma area, Arizona, and to predict the magnitude of southwesterly flow of ground water across the limitrophe section of the Colorado River. An evaluation of alternative ground-water recovery plans indicated that there would be little effect on the flow across the limitrophe section but a substantial decrease in flow across the Arizona-Sonora international boundary.

INTRODUCTION

This report summarizes the progress of the analog modeling of the ground-water system underlying parts of the United States and Mexico in the vicinity of Yuma, Ariz. The project was begun in April 1966 at the request of the U.S. Section of the International Boundary and Water Commission, and resulted in a cooperative scientific effort among personnel of the Boundary Commission, the Bureau of Reclamation, and the Geological Survey.

As a result of that request and subsequent meetings among the U.S. agencies, it was agreed that an analog model would be constructed of the Yuma ground-water basin and of the contiguous areas in Sonora and Baja California, Mexico. The broad objectives of the model study were to be threefold: (1) to construct a three-dimensional electric analog model of the study area which would incorporate all known and inferred data pertaining to the geologic and hydrologic characteristics of the system; (2) to impose upon the model, as a criterion of validity, the time sequence of historical events that altered the equilibrium system of 1925 into the dynamic system of 1966; and (3) to utilize the model to describe more fully the regional effects of past hydrologic events, and to predict the future response of the system to proposed increases in ground-water pumping. The specific objectives under (3), above, included the prediction of the magnitude of the southwesterly flow of ground water across the limitrophe (international boundary) section of the Colorado River and an evaluation of the effects of alternative ground-water recovery plans on that southwesterly flow.

The ground-water system underlying the Yuma area is a part of an extensive aquifer composed of permeable alluvial material deposited by the Colorado River, the Gila River, and the earlier drainage systems that created the delta of the Colorado River. The aquifer system of the delta area underlies parts of Arizona, California, and the Mexican States of Sonora and Baja California.

The Yuma ground-water system, shown on plate 1*A*, is in the apex of the delta and includes the Yuma Mesa, an extensive desert area lying east and south of Yuma, Ariz., the Mexicali and Yuma Valleys to the west, and the South Gila Valley to the north. The entire delta area is in one of the driest regions of North America, with summers that are hot and winters that are mild, precipitation less than 5 inches annually, and agriculture possible only by irrigation. Historically, water diverted from the Colorado River has been the principal source of irrigation supply in both the United States and Mexico. Since before 1955 ground water has been pumped in Mexicali Valley to supplement the supply available from the Colorado River. In recent years the water pumped has supplied one-third of the irrigation demand. While the area irrigated by ground water in the Yuma Area of the United States is relatively small, it has increased since 1966.

The application of Colorado River water to lands in the Yuma Mesa was started about 1924, but full-scale irrigation activity was not started until 1946. The ground-water recharge from irrigation on the permeable soils of the Yuma Mesa resulted in substantial rise in regional ground-water levels, which eventually overwhelmed the capabilities of the existing drainage system in the adjacent valley areas. As a consequence, drainage wells were installed to control the ground-water levels.

Prior to 1955 there were only privately owned wells operating in Mexicali Valley. In 1955 and 1957 the Mexican Government authorized drilling wells to supplement its canal-water supply and to control rising water levels.

The influence that the water-level change in both countries has on water movement across the international boundary was part of the Geological Survey appraisal, which began in 1961, of the water resources of the lower Colorado River area. This report is one of a series that constitute an appraisal of the water resources of the Lower Colorado River-Salton Sea area. The analog model was first used to simulate the historical water-level changes that occurred in the Yuma Mesa to help define the hydraulic characteristics and water movement in the aquifer system. That aspect of the model study is described in Olmsted, Loeltz, and Irelan (1973). Later the model was used to assist in studies of the effects of pumping from the aquifer system under various assumed future conditions. This report summarizes the results of those studies.

The present model is not the first electronic representation of the Yuma ground-water flow system; during the course of previous studies, Brown and Skibitzke (1956) used a steady-state cross-sectional model to demonstrate the effects of anisotropic permeability in the system, and Jacob (1960) used a differential analyzer to study the nature of the ground-water mound underlying Yuma Mesa.

THE HYDROLOGIC MODEL

Hydrologic data in the Yuma area have been collected by the Bureau of Reclamation since the first decade of the 20th century. Subsequently other agencies participated in the collection and interpretation of hydrologic data, principally the Yuma County Water Users' Association and the Geological Survey. The Survey's activity in the Yuma area culminated in 1969 with the publication of a comprehensive report by Olmsted, Loeltz, and Irelan (1973) that contained the hydrologic description upon which the analog-model analysis was based. It is beyond the scope of this report to recapitulate Olmsted's findings except to note how his description of the hydrologic system was simplified and translated into analogous electrical form.

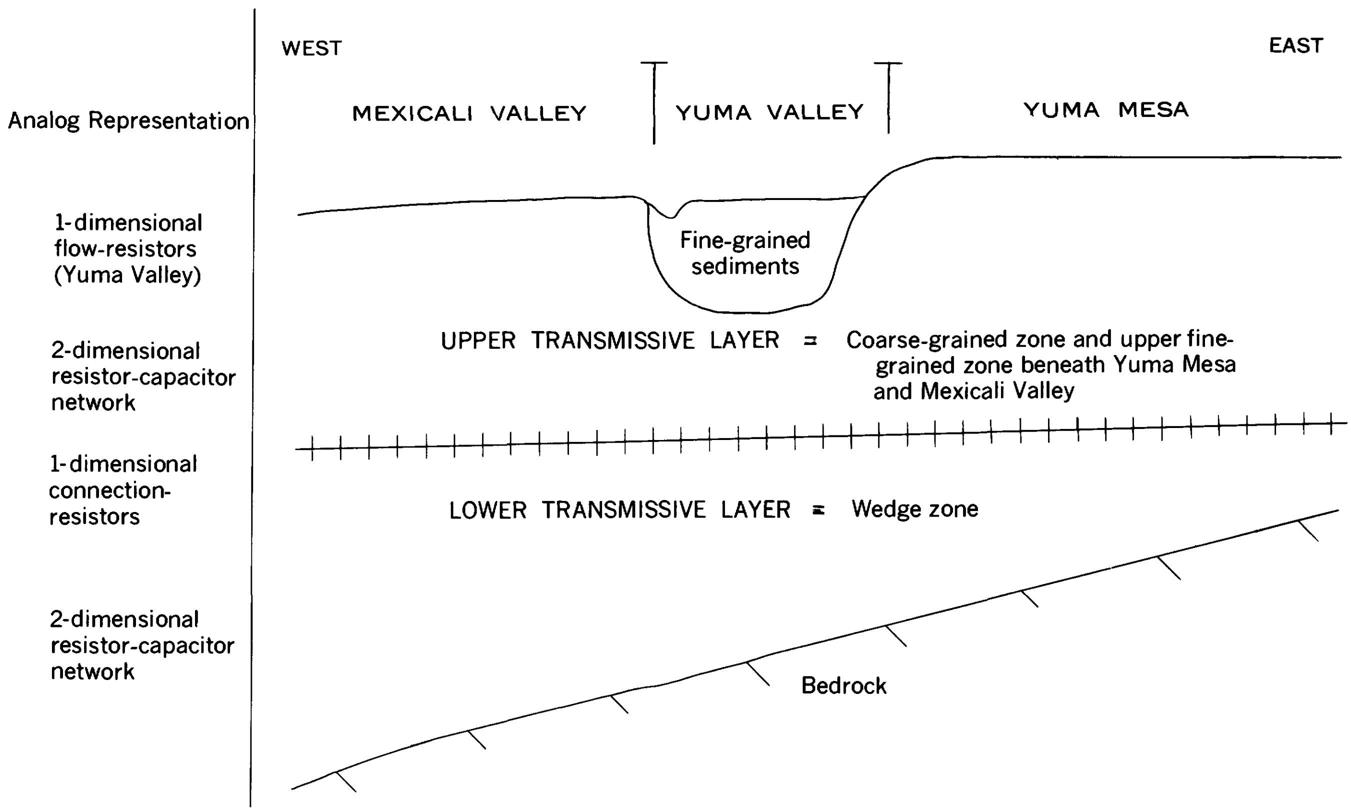

FIGURE 1.—Hydrologic model and analog representation.

For the purposes of this analog study, the hydrologic system is regarded as a three-dimensional flow field idealized into two two-dimensional transmissive layers and two zones of purely one-dimensional flow (fig. 1). The upper transmissive layer is composed chiefly of the "coarse gravel zone" which underlies most of the Yuma Mesa and river valleys, and in which most of the wells of the area have been completed. Overlying that zone are much finer sediments, which in the Yuma Valley have been modeled as a confining layer, allowing vertical flow between the gravel zone and land surface according to the direction of the hydraulic gradient. Elsewhere in the modeled area, the upper fine-grained material is lumped with the gravel zone. Underlying the gravel zone are alluvial sediments in a wedge-shaped body with a total thickness as much as 3,600 feet; that body of sediments has been modeled as a lower transmissive layer in hydraulic connection with the upper transmissive layer, and bounded by impermeable material or basement below. An effective parameter, representing the average vertical hydraulic conductivity and the average flow distances between the two layers, simulates the head loss resulting from vertical flow between the two aquifers.

The analog model of the Yuma ground-water basin represents an area of about 1,600 square miles, and, where practical, the positions of natural hydrologic boundaries were used to terminate the model system. For instance, the poorly permeable Gila Mountains form the eastern boundary of the model, and the alinement of the northern boundary is represented by the decreasing permeability or decreasing saturated thickness of the sediments several miles north of the international boundary; the western boundary of the model is about 10 miles west of Tecolote, Baja California, roughly coincident with the increasing clay content of the Imperial Valley sediments; the southern boundary of the model, which is about 15 miles south of San Luis, is purely arbitrary and represents the ability of the sediments south of the modeled area to yield water in response to changes in water level.

A constant-head surface represents the drains which maintain an effectively constant water table in the one-dimensional flow system that simulates the fine-grained material in the Yuma and South Gila Valleys.

One of the important features of the hydrologic system for which there were no physical data was the fault zone extending southeast approximately through the center of the ground-water mound. The fault is a partial barrier throughout the "wedge" aquifer and along the southeast half of its trace in the upper transmissive layer; but on the basis of water levels, it appears to have little hydrologic significance in the upper transmissive layer northwest of the center of the mound. In general, the fault diverts water applied northeast of it to the east and southeast, but allows water applied southwest of it to flow to the south or southwest.

The hydraulic significance of the fault zone is demonstrated in some places by wells on opposite sides of the fault that have a measured head differential of about 30 feet. In order to duplicate that differential on the model, an effective transmissivity of about 200 gpd/ft (gallons per day per foot) was required in a narrow strip of each aquifer along the fault trace. The effect of the fault on water levels is clearly demonstrated on plate 1*B–N*. Where the fault is shown as a solid line it is hydrologically significant in both aquifers, but where its trace is dotted it is significant only in the wedge-shaped lower transmissive layer.

The values and areal distribution of transmissivity and storage coefficient, given by Olmsted, Loeltz, and Irelan (1973), were derived from their extensive field studies; owing to the difficulty in obtaining regionally significant data, however, the values of vertical permeability were inferred from the analog-model analysis.

THE ELECTRIC ANALOG MODEL

The electric analog model is basically a tool that the hydrologist uses to bring the hydrologic environment under study into the laboratory where it may be dissected and each of its individual hydrologic parameters evaluated. It should be recognized from the onset, however, that the model is not a literal replica of the real hydrologic system but is, rather, an approximation based on a considerably simplified set of idealizations that allows the highly complex hydrologic system to be modeled with an analog of manageable complexity. The power of the modeling procedure stems from the model's ability to use all known geologic and hydrologic data applicable to the area, and to predict the results of hydrologic stress on the system.

The construction of the analog model requires that each element of the hydrologic model be translated into an equivalent electrical parameter; thus transmissivity is represented in the electrical system by resistors, and the storage coefficient by capacitors. Other equivalents are given below.

Hydraulic system	*Electrical model*
Hydraulic head, feet	Voltage
Volume rate of flow, acre-feet per year	Current, amperes
Time, years	Time, seconds

Each of these equivalents is established by a simple and essentially arbitrary constant of proportionality. Thus 40 feet of change in hydraulic head is represented by 1 volt on the model; 1 second of model time is the equivalent of 240,000 days of real time; and 1 ampere of electrical current equals a flow of 110,000,000 acre feet per year. A thorough treatment of the theory and technique of analog modeling is given by Skibitzke (1961), Wood and Gabrysch (1965), and Karplus (1958).

The hydrologic system in the Yuma area is modeled by two resistor-capacitor networks that represent, respectively, the upper transmissive layer and the wedge-shaped lower transmissive layer. The two networks are connected at equivalent nodes by resistors that represent the average vertical hydraulic conductivity and distance along the flow path between the two aquifers. Resistors also represent the fine-grained sediment of Yuma Valley which overlies the upper transmissive layer and which provides a one-dimensional flow path to land surface. There are 10,500 nodes on the model, with a nodal spacing of ½ inch=1,500 feet on Yuma Mesa and 1 inch=3,000 feet elsewhere. About 22,000 resistors and 5,500 capacitors were used to construct the model.

STRESS APPLIED TO THE SYSTEM

Although the major irrigation activity in the Yuma Valley started in the early 1900's, the hydrologic system probably had regained equilibrium by 1925 when irrigation started on the Yuma Mesa; that is, inflow equaled outflow and there was little or no change in storage with time. The initial condition of the analog model reflects that equilibrium, and the water levels and ground-water flows measured on the model are changes in water levels and changes in flow from those that existed in 1925.

Effective or net recharge to the Yuma Mesa, which started in 1925, was computed on the basis of irrigation deliveries minus consumptive use. The net recharge was distributed areally according to the acreage irrigated in 1925, 1947, 1952, and 1957; and it was assumed that the acreage did not change appreciably after 1957. Table 1 shows the programed rates of recharge to Yuma Mesa for the seven time periods modeled. Note that it was assumed the 1965 recharge rate will continue into the future.

Ground-water withdrawals from the system started in 1948 when the first of the "early" drainage wells were installed in Yuma Valley. Private pumping started on Yuma Mesa in 1965 and was followed in 1967 by pumping from the six "new" Yuma Valley wells. Pumping from the 12 Yuma

TABLE 1.—*Well discharge and irrigation recharge programed on the Yuma analog model, in thousands of acre-feet per year*[1]

	Recharge	Pumpage				
	Yuma Mesa[2]	Early drainage wells	New Yuma Valley wells	Yuma Mesa wells	Private wells	Mexicali well field[2]
1925–47[3]	4					
1943–47	51					
1948–52	102	19				
1953–57	157	36				
1958–62	208	78				117
1963–64	228	119				165
1965	188	126			4	212
1966	(188)	(126)			4	212
1967	(188)	(126)	23		16	(212)
1968	(188)	(126)	20		21	(212)
1969	(188)	(126)	21		(21)	(212)
1970	(188)	(126)	(21)		(21)	(212)
1971	(188)	(126)	(21)	12	(21)	(212)
1972	(188)	(126)	(21)	(25)	(21)	(212)
1973	(188)	(126)	(21)	(37)	(21)	(212)
1974	(188)	(126)	(21)	(50)	(21)	(212)
1975	(188)	(126)	(21)	(63)	(21)	(212)
	(188)	(126)	(21)	(69)	(21)	(212)
	(188)	(126)	(21)	(69)	(21)	(212)
	(188)	(126)	(21)	(69)	(21)	(212)
2000	(188)	(126)	(21)	(69)	(21)	(212)

[1] Figures in parentheses are projected.
[2] Net quantity.
[3] Auxiliary project.

Mesa wells started in 1970. With the exception of the private wells, all data on pumping rates were provided by the Bureau of Reclamation; data on the private wells were provided by the Geological Survey, Yuma, Ariz.

Pumping from the Mexicali Valley started prior to 1955, but few if any data were available to document the net draft on the ground-water system. Data were available, however, that showed the seasonal decline in water levels as the result of pumping. Lacking a better or more direct method of determining the net draft in the Mexicali Valley, the analog model was used to compute the net pumpage necessary to produce the average water-level decline observed from 1953 to 1965. The rate necessary to produce that drawdown was 212,000 acre-feet per year, and it was assumed that quantity would be representative of the net draft in the future. Because of the uncertainties in modeling the western and northern boundaries of the model, and because of the great water demand in Mexicali Valley, the derived pumping figure is probably conservative.

VERIFICATION OF THE ANALOG MODEL

The adequacy of the analog model of the hydrologic system was tested according to the criterion of the 1925–66 water-level changes. The degree that the model could reproduce these changes according to the known recharge and pumping stresses would determine its usefulness in predicting the effects of future stress that might be imposed on the system. The procedure and results of the model verification are described in detail by Olmsted, Loeltz, and Irelan (1973) and will not be given here. It is sufficient to report that the analog model duplicated the historic response of the system satisfactorily, and was deemed appropriate for use in predicting the future response of the system to new stresses.

RESULTS OF MODEL PREDICTIONS

The basic prediction obtained from the analog model is simply an extension to the year 2000 of the stress conditions that existed in 1965 and which are shown in table 1. Plate 1*B* and *C*, respectively, show the computed changes in water level in 1975 and 2000 resulting from recharge to the ground-water mound applied to the 1965 rate, and from pumping all wells that existed in 1965. As a result of those conditions, computed drawdown in the Mexicali well field will increase to a maximum of 30 feet by 1975 and to 35 feet by the year 2000; the ground-water mound underlying Yuma Mesa will attain its maximum rise in water level of 55 feet by 1975. In the year 2000, the mound should still be rising in the area northeast of the fault, as is shown clearly by the position of the 20-foot change line on plate 1*B* and *C*; southeast of the fault, however, the mound will decrease slightly by the year 2000 as the result of diminished recharge to the mound after 1964, and because of the effects of Mexicali Valley pumping. Figure 2 shows that, as the result of those conditions, the change in ground-water flow to Mexico across the limitrophe section from 1925 to 2000 will be 72,000 acre-feet per year; during the same interval the change in flow to Mexico across the Arizona-Sonora boundary will be about 21,000 acre-feet per year. It should be noted here, and in the following discussion of results, that the predicted changes are changes from the 1925 base. Thus, the predicted rise in water levels under Yuma Mesa of 55 feet by 1975 is a rise of 55 feet during 1925–75.

Plate 1*D* and *E* show the effects of full development in the Yuma area as it is presently planned. The early drainage wells are pumping a total of 126,000 acre-feet per year, and the new Yuma Valley wells are pumping a total of about 21,000 acre-feet per year; the 12 proposed Yuma Mesa wells are pumping their proposed capacity of 69,000 acre-feet per year, and private wells account for the total pumping of 21,100 acre-feet per year. The location of these wells is shown on plate 1*F*. Under those conditions, U.S. pumpage in 1975 will exceed recharge to the ground-water mound by about 50,000 acre-feet per year, and total ground-water withdrawals from the system, including Mexican pumpage, will exceed recharge by 260,000 acre-feet per year. As the result of that overdraft, the maximum height of the mound is expected to be 40 feet by 1975, which is 15 feet less than the height to be expected if no new development occurred after 1965, as shown on plate 1*B*. By the year 2000 the ground-water mound northeast of the fault will have declined substantially from its 1975 position, and almost all the area southwest of the fault will show water-level declines. Figure 2 shows that, as the result of pumping, by 1975 the change in flow to Mexico across the limitrophe section will have been reduced by 2,000 acre-feet per year to 66,000 acre-feet per year, and that by the year 2000 the total change in flow will be 69,000 acre-feet per year. The computed change in flow across the Arizona-Sonora boundary will be 5,000 acre-feet per year in 1975 and 3,500 acre-feet per year in the year 2000.

Plate 1*G* and *H* show the effects of development with Yuma Valley and Yuma Mesa wells added. By

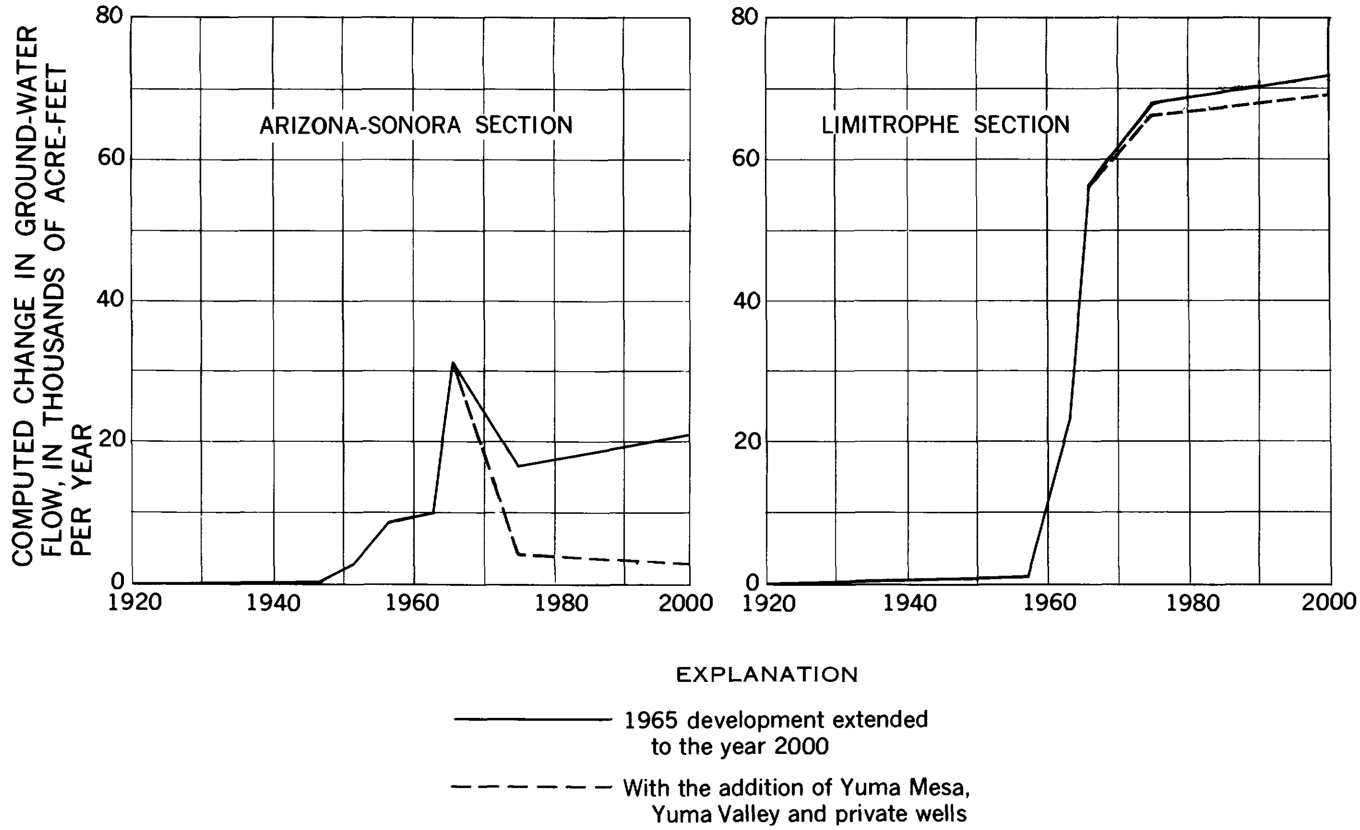

FIGURE 2.—Computed change in ground-water flow across international boundaries, 1925–2000.

1975 the maximum computed change of water level on the mound will be 50 feet (pl. 1*G*), or 10 feet higher than the equivalent situation when private development wells are included (pl. 1*D*). Note from plate 1*F* that eight of the private wells (as of 1968) are northeast of the fault, which probably accounts for the relatively large change in water level on the mound for only a rather small quantity of pumpage. By the year 2000 (pl. 1*H*), there will be only slight additional changes in water levels, principally in the Mexicali Valley and in the southern part of the Yuma Mesa where the long-term effects of the 1965 reduction of recharge and the effects of Mexicali pumping will alter the shape of the ground-water mound. The computed flow of ground water across the limitrophe section in the year 2000 is not affected by pumpage from the private wells, and therefore the change in flow will remain at 66,000 acre-feet per year in 1975 and 69,000 acre-feet per year in the year 2000. The flow across the Arizona-Sonora boundary, however, shows the effects of private development; the change in ground-water flow resulting from the water-level changes shown on plate 1*G* will be 8,500 acre-feet per year by 1975; by the year 2000 the change in ground-water flow will be increased to 9,500 acre-feet per year as the result of Mexicali pumping (pl. 1*H*).

Plate 1*I* and *J* show for 1975 and 2000, respectively, the computed changes in water levels for a situation in which it was assumed there was no Mexicali pumping and no private development; the changes in water levels will result only from the programed recharge to Yuma Mesa, and from Yuma Mesa and Yuma Valley pumping as shown in table 1. A comparison of plate 1*J* with plate 1*I* shows that the ground-water mound on the northeast side of the fault will undergo little change from 1975 to 2000. The mound on the southwest side of the fault, however, will show a considerable change in areal extent. Table 1 shows that recharge to the ground-water system through infiltration of irrigation water will exceed U.S. pumping until 1973, but by 1975 pumping will exceed recharge to the mound by about 28,000 acre-feet per year. As a result of that continuing deficit, the ground-water mound southwest of the fault will decline, while the mound northeast of the fault will remain fairly stable. Under the foregoing conditions, the computed change in flow across the limitrophe section in 1975 is 2,000 acre-feet per year to the United States from Mexico. At

TABLE 2.—*Effects of Mexicali pumping on computed change in ground-water flow to Mexico across international boundaries, in acre-feet per year*

	Change in flow of ground water to Mexico			
	Across limitrophe section		Across Arizona-Sonora boundary	
	1975	2000	1975	2000
Total U.S. development[1] with Mexacali Valley pumping	66,000	69,000	8,500	9,500
Total U.S. development[1] with no Mexicali Valley pumping	—2,000	—2,000	7,000	6,000

[1] Excluding private development in United States.

the same time, the computed change in flow to Mexico across the Sonoran boundary is 7,000 acre-feet per year. In the year 2000 the flow across the limitrophe section will be unchanged at 2,000 acre-feet per year, while the flow across the Sonoran boundary will have decreased to 6,000 acre-feet per year. Table 2 shows the effects of Mexicali pumping on the boundary flows.

In order to assess more clearly the regional effects of present (1968) private pumping, and of the existing new Yuma Valley wells and proposed Yuma Mesa wells, a more detailed analysis was made. Plate 1*K* and *L* show the computed declines in water levels in 1975 and 2000, respectively, resulting from pumping the new Yuma Valley wells and the Yuma Mesa wells without any other stress applied to the system. Plate 1*M* and *N* show, respectively, the 1975 and 2000 declines resulting from pumping only private wells. This technique of showing the effects of only one of several stresses on the system is possible because the system is linear (in the mathematical sense) and the principal of superposition can be employed. That principal states that in a linear hydrologic system the total water-level change at a particular point and at a particular time is the (algebraic) sum of all the individual changes caused by separate stresses; for example, the water-level decline at a point between two wells is the sum of the drawdown caused by well "A" plus the drawdown caused by well "B." In the present case, the technique was employed so that the rather small water-level changes caused by the private pumping and the new Yuma Valley and Yuma Mesa wells could be measured in greater detail without being masked by the much larger water-level changes caused by recharge to the Yuma Mesa, pumping from the early valley wells, or by pumping from the

TABLE 3.—*Effects of U.S. pumping starting in 1967 on computed change in ground-water flow to Mexico across international boundaries, in acre-feet per year*

[—indicates decreases in flow to Mexico]

	Change in flow of ground water to Mexico			
	Across limitrophe section		Across Ariozna-Sonora boundary	
	1975	2000	1975	2000
Pumping from New Yuma Valley and Yuma Mesa wells	—1,400	—2,400	—8,500	—11,500
Pumping from private wells[1]	0	0	—3,500	—6,000

[1] At 1968 rates.

Mexicali well field. The boundary flows associated with each well group are given in table 3, and are shown graphically in figure 3.

The major significance of these data is the small change in flow across the limitrophe section resulting from that pumping in the United States. The reduction of flow of 2,400 acre-feet per year computed at the end of the year 2000 is small compared with either the net recharge to the Yuma Mesa (188,000 acre-feet per year) or to the net withdrawal from the early valley drainage well (126,000 acre-feet per year). The profiles of ground-water change shown in figure 4 suggest the reason for that small change; the dashed profile shows the effects of recharge to Yuma Mesa and of pumping from the early drainage wells, new Yuma Valley wells, and Yuma Mesa wells, excluding private pumping and pumping from the Mexicali well field. The solid curve includes the effects of pumping from private and Mexicali wells in addition to the above. The "X" curve includes pumping from the Mexicali Valley only, and excludes all pumping in the United States.

Under full Mexican and U.S. development there will be a mound under the Yuma Mesa, a ground-water depression at the western edge of the Mesa resulting from new Yuma Valley and Yuma Mesa drainage wells, and a ground-water trough in the Mexicali Valley reflecting the effects of Mexican pumping. The other two curves show the effects, respectively, of no U.S. pumping and no Mexican pumping. Under each of those conditions there will be little, if any, water-level decline under the Yuma Valley, indicating that the Yuma Valley acts as a buffer or "hinge" that effectively separates the ground-water regimens of Yuma Mesa and Mexicali Valley. The greatest part of the water flowing westward across the limitrophe section to Mexico will be derived from salvaged water that would otherwise flow from the upper transmissive layer upward through the fine-grained sediments of Yuma

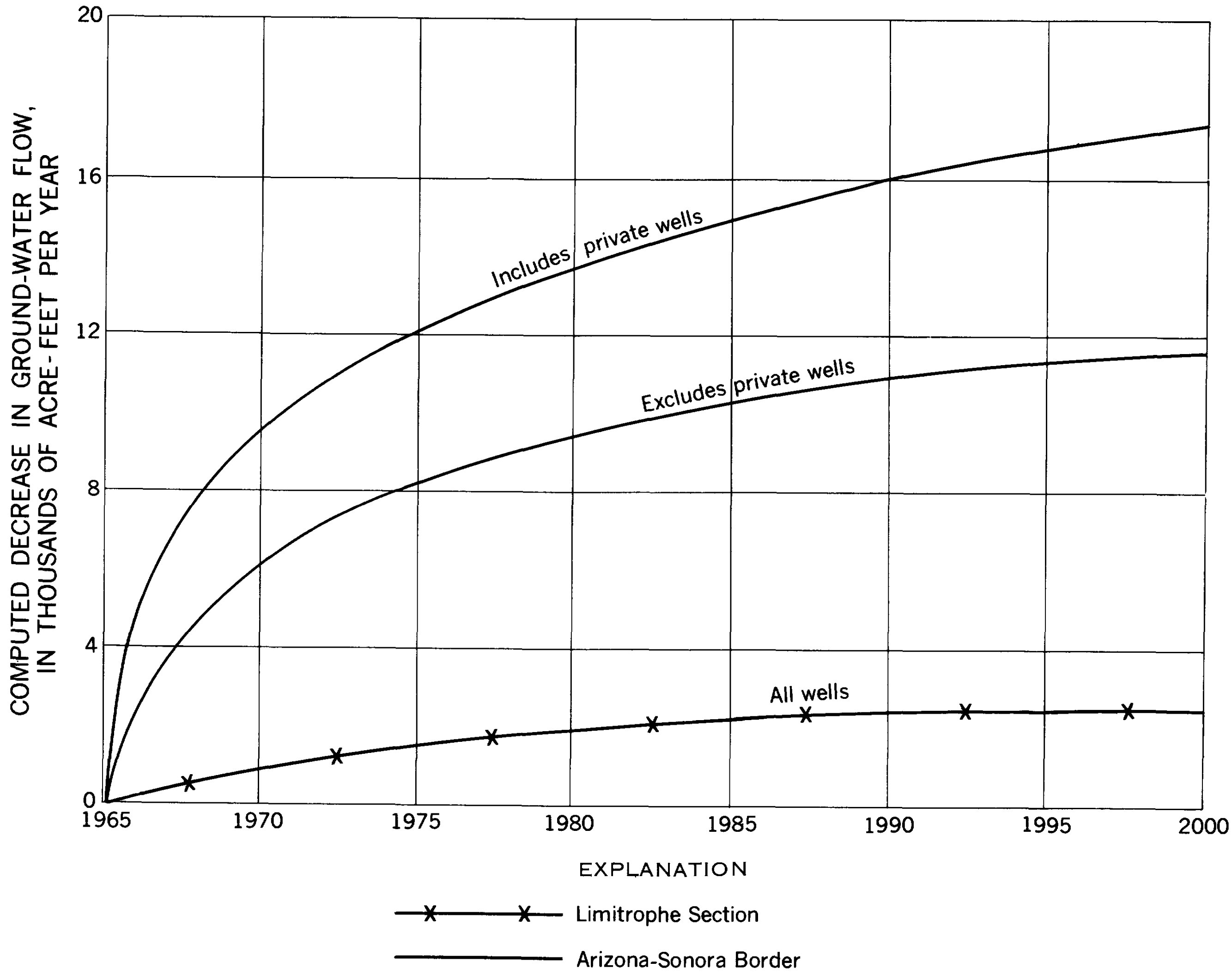

FIGURE 3.—Computed decrease in ground-water flow across international boundaries resulting from pumping in United States, 1965–2000.

Valley to be discharged either to the Yuma Valley drains or to the atmosphere as evapotranspiration. The hydraulic gradient that causes that salvage will be established principally by pumping in the Mexicali well field, although some salvage is effected by Yuma Valley and Yuma Mesa pumping. Under the pumping and recharge conditions shown in table 1, the computed rate of discharge salvaged from Yuma Valley by the year 2000 will exceed 100,000 acre-feet per year.

Measurements were made on the analog model to predict the changes in flow that may occur across the international boundaries from 1925 to 2000. Those data are shown in figure 2. Measurements along the limitrophe section showed that little change in flow occurred before 1958, but that after that time there was a rapid increase until by 1966 the total increase in flow across the limitrophe to Mexico was about 58,000 acre-feet per year. The model shows that if the conditions of 1965 are extended to the year 2000 (no pumpage from the new Yuma Valley, Yuma Mesa, or private wells), the total change in flow across the limitrophe section will be 72,000 acre-feet per year increase. The graph also shows that when the additional wells are considered after 1965 (dotted curve), the change in flow in the year 2000 is decreased by about 3,000 acre-feet per year to 69,000 acre-feet per year, or only about 4 percent of the total change in flow. It is concluded from this illustration that the changes in flow across the limitrophe section are almost wholly influenced by pumping in the Mexicali Valley and that the effects of pumping in the United States are largely dissipated before they reach across Yuma Valley to the limitrophe section.

The Arizona-Sonora boundary, however, showed changes in flow before 1958 when Mexicali pumping became significant. By 1958 the flow southwestward to Mexico had already increased by about 9,000 acre-feet per year in response to the rising ground-water mound on Yuma Mesa. By 1966 the ground-water flow from the United States to Mexico had increased

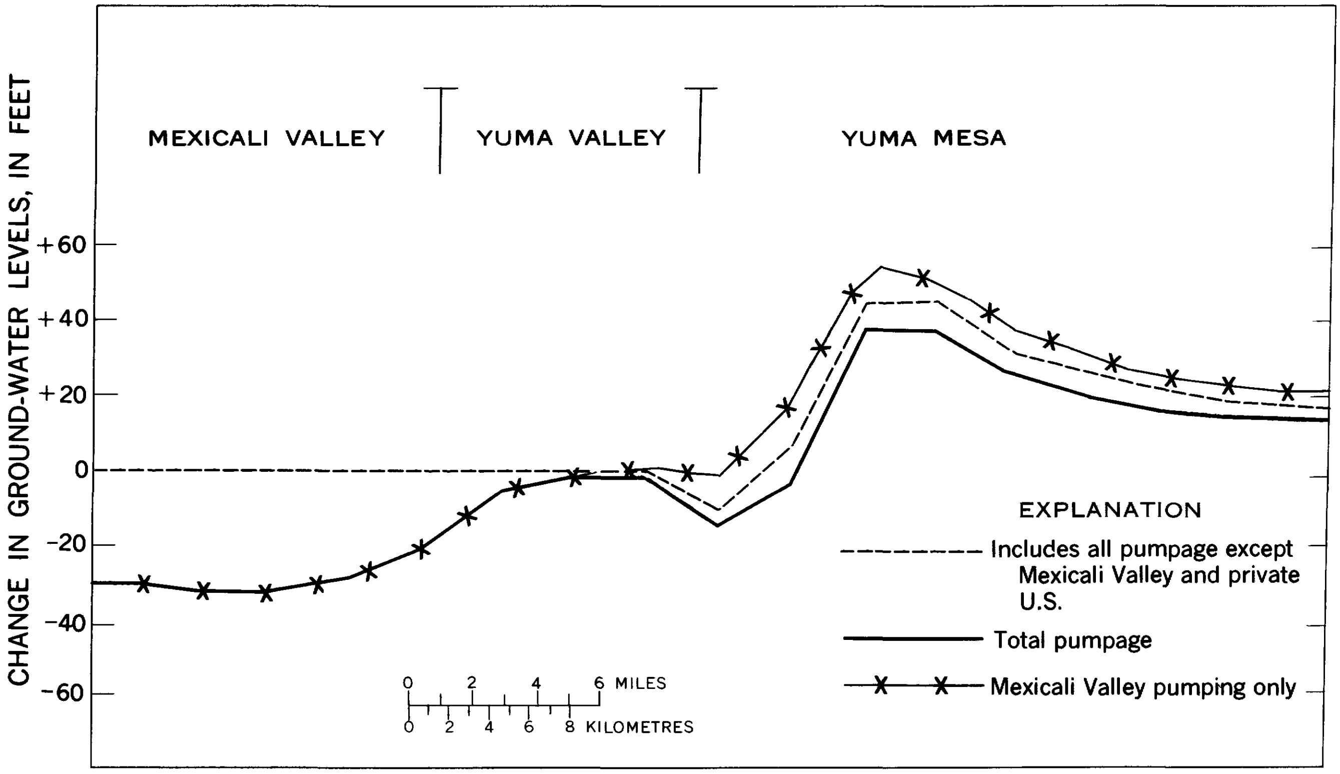

FIGURE 4.—Profiles of change in water levels resulting from pumping, 1925–2000: cross section eastward from about Tecolote, Mexico.

to 31,000 acre-feet per year, accelerated to some degree by water-level declines caused by pumping in the Mexicali Valley. The decrease in boundary flow to 17,000 acre-feet per year in 1975 will result primarily from the effects of pumping 111,000 acre-feet per year from the new Yuma Valley, Yuma Mesa, and private wells, and to a lesser degree from the reduction in recharge to the Yuma Mesa ground-water mound after 1964. The increase in flow to 21,000 acre-feet per year in the year 2000 includes the effect of the expanding cone of depression from the Mexicali Valley well field.

Flow across the Arizona-Sonora boundary is also greatly affected by the Yuma Valley, Yuma Mesa, and private wells, as shown by the dotted curve in figure 2. By 1975 flow will have decreased by about 12,000 acre-feet per year as the result of pumping, and by the year 2000 the flow will have been reduced by about 18,000 acre-feet per year to 3,500 acre-feet per year. The effects of pumpage on the change in flow across the international boundary is summarized in figure 3. Note that private well development (as of 1968) is not sufficient to cause any measureable change in flow across the limitrophe section.

CONCLUSIONS

The results of the model analysis are shown most clearly in figures 2 and 3, and tables 2 and 3. The important conclusions that emerge from those data are as follows:

1. The major change in the flow of ground water to Mexico across the limitrophe section of the Colorado River started in 1958, coincident with accelerated pumping in the Mexicali valley. Prior to that year, the increase in flow to Mexico across the limitrophe section was about 1,000 acre-feet per year, but by 1962 the flow had increased to more than 20,000 acre-feet per year; by the year 2000 the model study indicates the increase will be about 72,000 acre-feet per year.
2. The full development of existing and proposed wells in the United States by the year 2000 will diminish the increase in flow across the limitrophe section to Mexico by about 4 percent, from 72,000 to 69,000 acre-feet per year.
3. Flow across the Sonoran boundary to Mexico began to increase in the 1940's as the result of the growing ground-water mound under Yuma Mesa, and after 1958 was somewhat accelerated by water-level declines caused by the Mexicali Valley pumping.
4. Ground-water flow across the Sonoran boundary is sensitive to pumping in the United States, and under the full development shown in table 1, the model indicates it will diminish from

31,000 acre-feet per year in 1966 to 3,500 acre-feet per year by the year 2000. That computed decrease includes the effects of pumping in the Mexicali Valley.

5. If Mexicali Valley pumpage were omitted, the computed changes in flow across the limitrophe section would be 2,000 acre-feet per year to the United States by the year 2000; thus the net effect of Mexicali pumping on the flow across the limitrophe would be an increase of about 71,000 acre-feet per year.
6. The largest part of the ground-water flow to Mexico across the limitrophe section is derived from water that would otherwise discharge to Yuma Valley; that is, if it were not for the gradients established by Mexicali Valley pumping, much more water would flow upward from the coarse gravel zone underlying Yuma Valley through the overlying fine-grained sediments, and would discharge either to drains or to the atmosphere.
7. Taken as a whole, pumpage in the Yuma ground-water system now exceeds recharge to the ground-water mound underlying Yuma Mesa by about 65 percent, and by 1975 existing and proposed pumpage will be almost 2.5 times the annual recharge to the ground-water mound.
8. As a result of that imbalance, water levels will decline indefinitely and on a regional scale. The effects of the expanding cones of depression will be mitigated to some degree by ground water salvaged from areas that have been points of discharge. The model study indicates that by the year 2000 salvage in excess of 100,000 acre-feet per year will be recovered from the Yuma Valley. Owing to the present and proposed patterns of pumping, however, little water will be recovered from the South Gila Valley.

SUMMARY

The electric analog simulation of the ground-water system in the Yuma area has provided an abundance of detailed predictions on the response of the system to proposed hydrologic stress. It would be desirable here to give some quantitative measures of the accuracy of those predictions, measured against some set of independent standards. Unfortunately, the only standard is the prototype ground-water system itself, and that system was deliberately simplified so that a model of manageable complexity could be conceived and implemented; thus fundamental to the simulation procedure is the exchange of "accuracy" for insight.

As an example, the model study predicts that under the proposed ground-water recovery plans almost 2 feet of water a year would be salvaged from the Yuma Valley by the year 2000; whether this is an "accurate" prediction is moot; it is accurate only to the extent that the hydrologic model is analogous to the prototype system, and that the analog representation is correct. In the Yuma analog model the upper fine-grained sediments of Yuma Valley are modeled as a vertical-flow system that allows upward ground-water flow to be discharged to the drains and by the evapotranspirative processes. Although that representation appears to be appropriate on the basis of regional analysis, it fails to distinguish locally, in the Yuma Valley, the components of that salvage: which portion is discharged to the drains, which to evapotranspiration, and which is possibly derived from the dewatering of the valley-fill sediments. Accordingly, while reasonably accurate on a regional scale, the model is inadequate in its representation of the Yuma Valley. If the model were modified to incorporate those variables, its adequacy for providing hydrologic predictions would be improved while its overall accuracy would be unchanged. An appraisal of the accuracy of the simulation study requires constant monitoring of the ground-water system and comparison of the analog-model predictions with the actual response of the system.

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