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Use of Superposition Models to Simulate Possible Depletion of Colorado River Water by Ground-Water Withdrawal

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By Stanley A. Leake, William Greer, Dennis Watt, and Paul Weghorst

Prepared in cooperation with Bureau of Reclamation

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FRONT COVER—The Lower Colorado River and adjacent farmland. Photograph from the Bureau of Reclamation.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Leakance	
foot per day per foot [(ft/d)/ft]	1	meter per day per meter

Vertical coordinate information is referenced to the National Vertical Geodetic Datum of 1929 (NGVD 29).
Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).
Elevation, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Use of Superposition Models to Simulate Possible Depletion of Colorado River Water by Ground-Water Withdrawal

By Stanley A. Leake, William Greer[1], Dennis Watt[2], and Paul Weghorst[3]

Abstract

According to the “Law of the River,” wells that draw water from the Colorado River by underground pumping need an entitlement for the diversion of water from the Colorado River. Consumptive use can occur through direct diversions of surface water, as well as through withdrawal of water from the river by underground pumping. To develop methods for evaluating the need for entitlements for Colorado River water, an assessment of possible depletion of water in the Colorado River by pumping wells is needed. Possible methods include simple analytical models and complex numerical ground-water flow models. For this study, an intermediate approach was taken that uses numerical superposition models with complex horizontal geometry, simple vertical geometry, and constant aquifer properties. The six areas modeled include larger extents of the previously defined river aquifer from the Lake Mead area to the Yuma area. For the modeled areas, a low estimate of transmissivity and an average estimate of transmissivity were derived from statistical analyses of transmissivity data. Aquifer storage coefficient, or specific yield, was selected on the basis of results of a previous study in the Yuma area. The USGS program MODFLOW-2000 (Harbaugh and others, 2000) was used with uniform 0.25-mile grid spacing along rows and columns. Calculations of depletion of river water by wells were made for a time of 100 years since the onset of pumping. A computer program was set up to run the models repeatedly, each time with a well in a different location. Maps were constructed for at least two transmissivity values for each of the modeled areas. The modeling results, based on the selected transmissivities, indicate that low values of depletion in 100 years occur mainly in parts of side valleys that are more than a few tens of miles from the Colorado River.

Background

The Consolidated Decree of the United States Supreme Court in Arizona v. California, 547 U.S.150 (2006) recognizes that consumptive use of water from the Colorado River can occur by underground pumping. According to the “Law of the River,” users within the lower Colorado River Basin States can divert tributary inflow before it reaches the Colorado River. Once the water reaches the Colorado River, however, entitlements are required for diversions. For wells pumping in the aquifer connected to the river, determination of a tributary source of ground water pumped can be difficult. Wilson and Owen-Joyce (1994), and Owen-Joyce and others (2000) presented the “Accounting-Surface Method.” The accounting surface is defined by ground-water levels that would occur if the Colorado River were the only source and sink for water in the connected aquifer. The theory is that static (non-pumping) ground-water levels in the aquifer that are higher than the accounting surface indicate the presence of tributary water. The accounting-surface method could be used by managers to determine the need for entitlements for river water for wells pumping in the river aquifer. Wiele and others (2008) presented an updated accounting surface based on conditions in 2007–2008.

Wilson and Owen-Joyce (1994) and Owen-Joyce and others (2000) defined the “river aquifer” as the saturated ground-water system adjacent to the Colorado River, including the flood plain sediments, older alluvial sediments, and sediments in connected adjacent valleys (fig. 1). The accounting surface was defined over the area of the river aquifer beyond the Colorado River flood plain.

The accounting surface includes some parts of the river aquifer that are many tens of miles from the Colorado River. The States along the lower Colorado River have expressed interest in Federal water managers considering the timing over which wells at great distance would deplete water in the Colorado River. To further understand the temporal effects of pumping wells on the Colorado River, Reclamation subsequently set up the Non-Contract Use Modeling technical team to explore methods of assessing the timing over which wells would deplete water in the Colorado River. Team members include staff of the Bureau of Reclamation (Reclamation) and the U.S. Geological Survey (USGS). This report describes the method developed by the technical team and results for larger portions of the river aquifer along the lower Colorado River.

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Ruth Thayer of Reclamation in Boulder City, Nevada, provided leadership and direction for the Non-Contract Use

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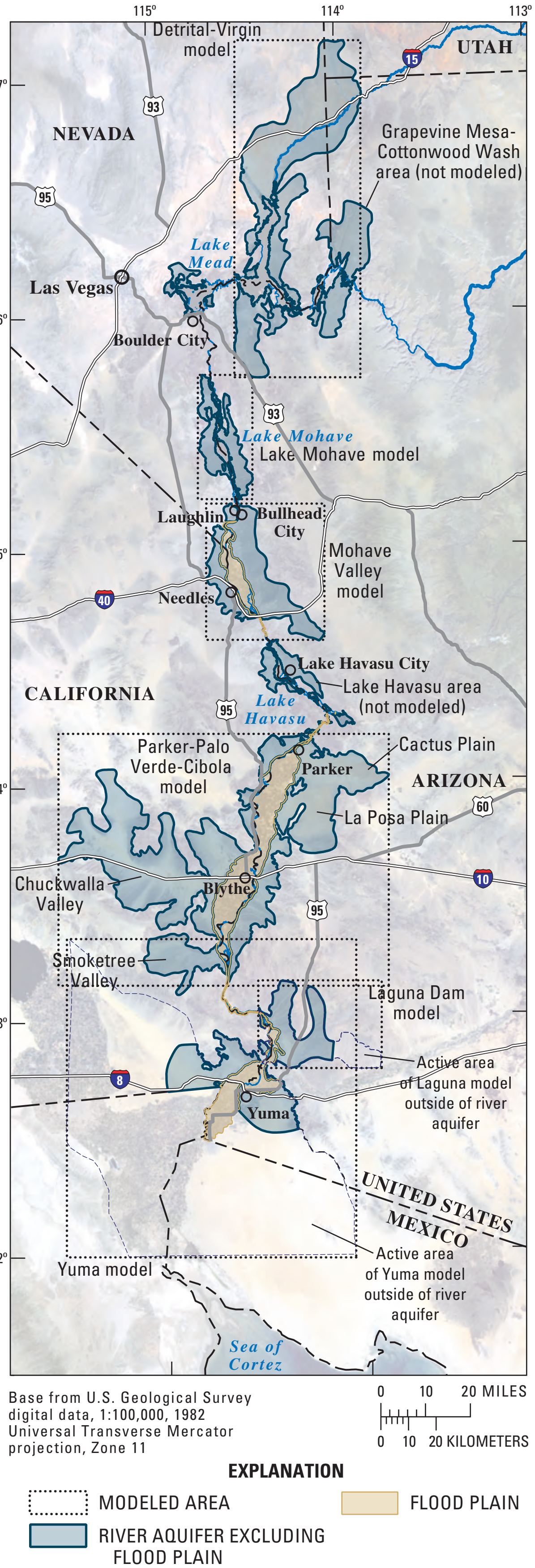


Figure 1. Study area along the lower Colorado River.

Modeling technical team. Jeff Addiego, formerly of Reclamation in Boulder City, Nevada, helped with aspects relating to the water-accounting procedures. Carroll Brown, of the Reclamation in Yuma, Arizona, contributed advice on aspects of geology. Sandra Owen-Joyce, of the USGS in Tucson, Arizona, helped with previous work on the accounting-surface method, including the river aquifer. Steve Belew, Reclamation in Boulder City, and Jim Monical, USGS in Tucson, helped with spatial data sets needed to construct models and mapping of model results.

Approach

C.V. Theis (1940) provided the first comprehensive description of the sources of water to pumped wells. He indicated that pumped water initially comes from storage in the aquifer. With time, however, cones of depression can spread to areas of ground-water recharge and discharge, resulting in additional sources of increased inflow to the aquifer and decreased outflow from the aquifer. Along the Colorado River, the interest is in depletion of surface-water resources from ground-water pumping. The depletion can result from decreased flow from the aquifer to the river, increased flow from the river to the aquifer, or a combination of these two conditions.

An example of the progression of depletion over time for a point in a hypothetical aquifer is shown in figure 2. At time zero, when pumping starts, the source of all of the water pumped by the well is from ground-water storage. With time, however, this source decreases and the complementary source, depletion of surface water, increases. At the end of 50 years in this example, only 5 percent (a fraction of 0.05) of the pumping rate is from ground-water storage, and 95 percent is from depletion of surface water. If the well pumping was continued indefinitely, a new steady-state condition would be reached in which all of the well pumping rate would be depletion of surface water, assuming that water available in surface-water bodies is sufficient to supply the total rate of well pumping.

The time over which depletion of river water by underground pumping occurs is dependent on the river and aquifer geometry, location of the pumping, and the aquifer hydraulic diffusivity, T/S, where T is transmissivity and S is storage coefficient. It is important to note that depletion of surface water by pumping ground water is independent of the rates and directions of ground-water flow. For example, depletion can occur from decreased flow from the aquifer to the river and increased flow from the river to the aquifer. For both of these cases, the amount of water in the river is reduced and the total depletion of the flow in the river is the sum of the two quantities. If the flow system changed by means such as changing recharge amounts or locations and (or) changing river stages, the total depletion by a well would be the same as depletion by a well at the same location in the unchanged system as long as the changes to the system did not affect the aquifer diffusivity and the location of the surface-water features.

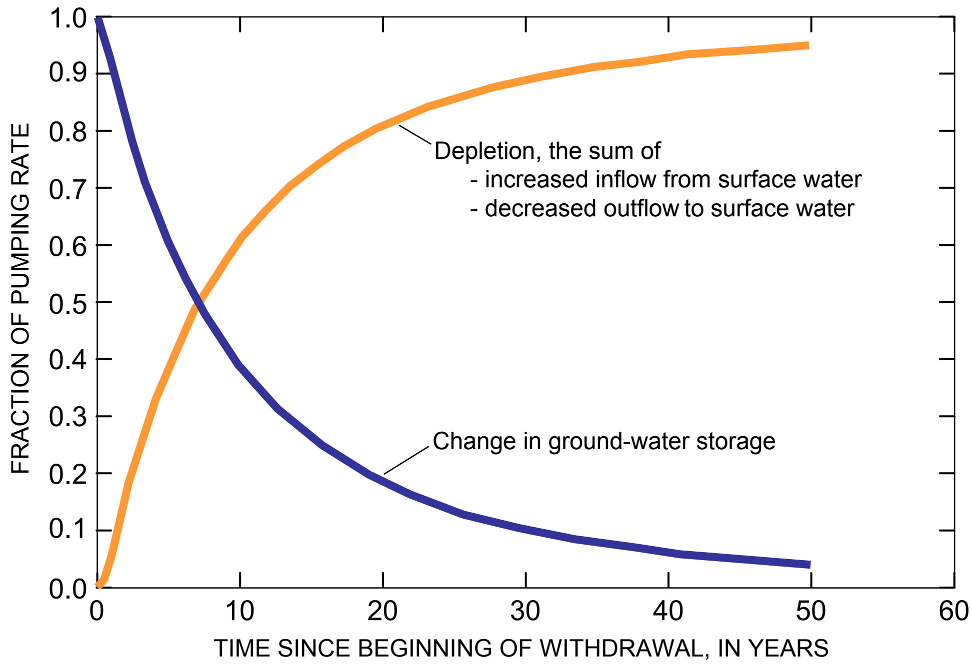


Figure 2. Sources of water to a well through time in a river-aquifer system, expressed as a fraction of the pumping rate.

If the interest is in total depletion, mathematical solution can be done using the principle of superposition in an analytical or numerical method that solves for changes in a system that is initially static. In a solution using the superposition approach, total depletion from a surface-water boundary from ground-water pumping is directly computed, and individual components of decreased flow from the aquifer to the river and increased flow from the river to the aquifer cannot be computed. The simplest approach to calculating depletion from ground-water pumping is the analytical solution by Glover and Balmer (1954). This approach assumes the river is a line source–straight and infinitely long, and fully penetrates the thickness of the aquifer, which extends an infinite distance away from the river. Using the theory of image wells, depletion in a bounded aquifer can be computed by the analytical solution, with a lateral no-flow boundary that is parallel to the river. Aquifer properties are assumed to be homogeneous. Because of the complex geometry of the Colorado River and the river aquifer (fig. 1), the analytical solution by Glover and Balmer (1954) is difficult to apply, especially in and around side valleys that are a part of the river aquifer.

A more common approach to calculating depletion is to use calibrated numerical ground-water flow models. Such models approximate the vertical and horizontal geometry of the aquifer, as well as flow patterns within the aquifer. The approach generally includes first running the model without a pumping well of interest and saving model-computed rates of ground-water flow to and from the river. The next step involves running the model again, this time with the pumping center added, again saving model-computed rates of ground-water flow to and from the river. For the two model runs, depletion is calculated as the sum of the decrease in ground-water flow to the river and increase in ground-water flow from the river.

Calibrated ground-water flow models do not exist for most parts of the lower Colorado River aquifer, and construction of such models was beyond the scope of this study. For this study, an approach was taken that is intermediate to the approaches using analytical solutions and calibrated numerical models. The intermediate approach uses numerical models that incorporate the complex horizontal geometry of the aquifer and river, but incorporate the simplifying principle of superposition, and the simple vertical geometry and homogeneity assumptions that are part of the analytical-solution approach.

Numerical superposition models for evaluating possible depletion of water in the Colorado River by ground-water pumping in the connected river aquifer were constructed for select areas along the lower Colorado River from Lake Mead to the Yuma area. The areas modeled include the river aquifer as defined by Wilson and Owen-Joyce (1994) and Owen-Joyce and others (2000). In a few of the modeled areas, the model boundaries extend beyond the defined river aquifer boundary where the defined boundary does not represent a physical no-flow boundary. Some general aspects of the modeling strategy are as follows:

1. Depletion is calculated using numerical superposition or change models. In plan view the aquifers are complexly shaped, based on the outline of the mapped river aquifer, with any mapped no-flow areas removed from the active model domain. In cross-sectional view the aquifers are simple two-dimensional horizontal slabs.

2. Models are constructed for the largest of the river-aquifer areas from Lake Mead to the Yuma area along the lower Colorado River. Smaller areas of the river aquifer are not modeled where experience with larger models indicates that computed depletion of surface water after 100 years of withdrawal for narrow sections is relatively high.

3. The models do not represent spatial variations of aquifer hydraulic properties. The models use a constant storage coefficient (specific yield), and two or more statistically derived transmissivity values. The transmissivity values are selected to simulate aquifer hydraulic diffusivity that represents (a) a conservative (or low) value that would underestimate depletion, and (b) an average value.

4. The only surface-water boundaries included in the models are the Colorado River, reservoirs along the river, and wetlands connected to the river.

5. Depletion is mapped for 100 years of withdrawal for the area of the river aquifer outside of the flood plain. The period of 100 years is commonly used as a timeframe in water management rules, such as Assured Water Supply criteria of the State of Arizona (http://www.azwater.gov/dwr/WaterManagement/Content/OAAWS/default.asp, accessed October 10, 2008).

Further details on implementation of the method are given in the following sections.

Areas Simulated

Models were constructed for six areas of the river aquifer. Starting with the most upstream reach, models included (1) Detrital-Virgin, (2) Lake Mohave, (3) Mohave Valley, (4) Parker-Palo Verde-Cibola, (5) Laguna Dam, and (6) Yuma area (fig. 1). The two largest river-aquifer areas not modeled are the Grapevine Mesa-Cottonwood Wash area and the Lake Havasu Area.

Aquifer Properties

Aquifer hydraulic diffusivity is the aquifer property that controls the rate that the depletion curve (fig. 2) progresses from zero at the start of pumping, towards 1.0 as pumping time continues. Diffusivity is T/S, where T is transmissivity and S is the storage coefficient. A lower transmissivity will result in slower propagation of drawdown and slower progression of depletion from zero to 1.0 through pumping time and a higher transmissivity will result in faster propagation of drawdown and progression of depletion through time. Conversely, a lower storage coefficient will result in faster progression of depletion and a higher storage coefficient will result in slower progression of depletion. The distribution of diffusivity, or the distributions of both transmissivity and storage coefficient over the entire river aquifer is not known, so the approach taken here calculates depletion using (a) a uniform low (or conservative from the standpoint of effects of a pumping well on the river) estimate of diffusivity and (b) a uniform average estimate of diffusivity. For this study, low and average diffusivities were computed using an estimate of the average storage coefficient and estimates of the low and average transmissivity. Methods and rationales for selecting these values are given in the following two sections.

Transmissivity

Although detailed distributions of transmissivities for the river aquifer are not known, many estimates of transmissivity for sediments in the river aquifer were published by Metzger and Loeltz (1973, table 2), Metzger and others, (1973, table 5), and Olmstead and others, (1973, table 7). The best of these estimates were used to develop log-normal distributions of transmissivity for several subreaches of the river aquifer. From those log-normal distributions, low and average transmissivity values were selected.

The best values of transmissivity were selected from Metzger and Loeltz (1973, table 2), Metzger and others, (1973, table 5), and Olmstead and others, (1973, table 7) using the following two criteria:

1. Only transmissivity values from tests in the younger and older alluvium of the lower Colorado River are used.

2. Test results are listed in the source reports as being fair, good, or excellent, in terms of conformance to theoretical values and reliability of the estimate.

Published values were available for Mohave Valley, Parker-Palo Verde-Cibola, and Yuma areas. The first two of these areas are above Laguna Dam, and the Yuma area is below Laguna Dam. Published values of transmissivity that meet the criteria are generally higher in the Yuma area than in the areas above Laguna Dam. For this reason, separate log-normal distributions of transmissivity were developed for reaches above and below Laguna Dam. Transmissivity values used are given in tables 1 and 2. In some cases, the source documents listed multiple estimates for an individual well. Where these estimates met the criteria for inclusion in the analysis, multiple values for the same well were included.

The statistical analyses used 25 estimates of transmissivity upstream of Laguna Dam (table 1) and 58 estimates downstream of Laguna Dam (table 2). Best-fit log-normal distributions to these data are shown in figures 3*A* and 3*B*. The low estimate of transmissivity was selected as the value for which probability is 0.05 (5 percent) that transmissivity is less than or equal to the value. The average estimate of transmissivity was selected as the value for which probability is 0.5 (50 percent) that transmissivity is less than or equal to the value. The low and average estimates of transmissivity for areas upstream of Laguna Dam are 6,300 ft^2/day (47,000 gal/day/ft), and 26,200 ft^2/day (196,000 gal/day/ft), respectively (fig. 3*A*). The low and average estimates of transmissivity for

Table 1. Transmissivity values above Laguna Dam used for statistical analysis.
[Type of test: D, drawdown; R, recovery; S, specific capacity; numbers in square brackets are range interval tested, in depth below land surface, in feet]

Well Name	Other Identifier	Transmissivity, in gallons per day per foot	Transmissivity, in feet squared per day	Method of analysis
Mohave Valley (Metzger and Loeltz, 1973, table 2)				
(B-18-22)15aab	D. Hulet	240,000	32,100	R
(B-18-22)27bbc	G. McKellip	600,000	80,200	D
(B-18-22)27bbc	G. McKellip	900,000	120,300	R
(B-18-22)27bbc	G. McKellip	240,000	32,100	S
9N/23E-29F1	City of Needles	600,000	80,200	R
9N/23E-29F1	City of Needles	300,000	40,100	S
9N/23E-32K1	City of Needles	450,000	60,200	R
9N/23E-32K1	City of Needles	70,000	9,400	S
11N/21E-36G2	Soto Brothers	94,000	12,600	R
11N/21E-36G2	Soto Brothers	75,000	10,000	S
11N/21E-36Q1	W. Riddle	160,000	21,400	D
11N/21E-36Q1	W. Riddle	170,000	22,700	R
11N/21E-36Q1	W. Riddle	140,000	18,700	S
Parker Valley (Metzger and others, 1973, table 5)				
(B-7-21)14dcd	USBIA No.8	460,000	61,500	R
(B-9-20)11dbc	USBIA No.2	400,000	53,500	R
(B-9-19)5ddd	USGS LCRP-15	300,000	40,100	R [175-199]
(B-7-21)14acd	USBIA No.7	75,000	10,000	R
(B-7-21)23acd	USBIA No.9	120,000	16,000	D,R
(B-7-21)23dcd	USBIA No.10	40,000	5,300	D,R
Palo Verde Valley (Metzger and others, 1973, table 5)				
5S/22E-28C2	U.S. Citrus Corp	64,000	8,600	R
6S/22E-11H1	H. M. Neighbor	700,000	93,600	R
6S/22E-15Q1	E. Weeks	290,000	38,800	R
6S/22E-35R2	Southern Counties Gas Co	150,000	20,100	R
8S/21E-13A1	USGS LCRP-16	63,000	8,400	D
8S/21E-13A1	USGS LCRP-16	170,000	22,700	R

areas downstream of Laguna Dam are 15,500 ft^2/day (116,000 gal/day/ft) and 45,900 ft^2/day (343,000 gal/day/ft), respectively (fig. 3*B*).

Storage coefficient

In aquifers such as the river aquifer along the lower Colorado River, the storage coefficient accounts for processes including (a) draining and filling of pore spaces at the water table, (b) contraction and expansion of the aquifer skeleton, and (c) decompression and compression of water in the pore spaces. The property that accounts for the first of these processes is designated as the aquifer specific yield. The property that accounts for the remaining two of these processes is the elastic aquifer storage coefficient. In the river aquifer along the lower Colorado River, the specific yield accounts for the dominant mechanism of storage change. Specific yield in the river aquifer is several orders of magnitude larger than the elastic storage coefficient, and therefore is used to define low and average diffusivity. The best estimate of specific yield in the area is from Loeltz and Leake (1983). They published estimates of specific yield from neutron-probe studies along both sides of the Colorado River at 18 cross sections, spaced at approximate 1-mile intervals. The average specific-yield value from these studies was about 0.2, and this value is used in this study of depletion along the lower Colorado River.

Table 2. Transmissivity values below Laguna Dam used for statistical analysis; all transmissivity values are from Olmstead and others (1973, table 7).

[Type of test: D, drawdown; R, recovery; LA, leaky artesian analysis with observation wells; numbers in square brackets are interval tested, in depth below land surface, in feet]

Well Name	Other Identifier	Transmissivity, in gallons per day per foot	Transmissivity, in feet squared per day	Type of test
16S/22E-29Gca2	USGS LCRP-26	570,000	76,200	R
16S/23E-8Ecc	USBR CH5	340,000	45,500	D
16S/23E-8Ecc	USBR CH5	750,000	100,300	R
16S/23E-22Fdc	H. Mitchell	440,000	58,800	R
16S/23E-9Naa	M. E. Spencer	300,000	40,100	R
16S/23E-8Ecc	USGS LCRP-23	240,000	32,100	R
16S/23E-10Rcc	Dover and Webb	420,000	56,100	R
(C-7-22)14bcd	USGS LCRP-14	110,000	14,700	R
(C-8-21)19dad	F. J. Hartman	230,000	30,700	R
(C-8-21)30cdc	F. J. Hartman	1,800,000	240,600	R
(C-8-22)13bdd2	S. Sturges	65,000	8,700	R
(C-8-22)18cbd	Powers	610,000	81,600	R
(C-8-22)18ddd	Powers	800,000	107,000	R
(C-8-22)19ccc	USBR CH702	68,000	9,100	R
(C-8-22)21ddd	B. Church	390,000	52,100	R
(C-8-22)22caa	B. Church	430,000	57,500	R
(C-8-22)22cda1	B. Church	320,000	42,800	R
(C-8-22)22cda2	B. Church	380,000	50,800	R
(C-8-22)25bad	F. J. Hartman	400,000	53,500	R
(C-8-22)26adb	S & W	290,000	38,800	R
(C-8-22)28aaa	B. Church	350,000	46,800	R
(C-8-22)30cab	C. Lord	380,000	50,800	R
(C-8-22)30ddd	C. Lord	360,000	48,100	R
(C-8-22)34aaa	W. R. Whitman	960,000	128,300	R
(C-9-23)20cdd	YCWUA 5	250,000	33,400	D
(C-9-23)29adb	Yuma Mesa Fruit Growers	600,000	80,200	D
(C-9-23)30cba2	YCWUA 6	200,000	26,700	D
(C-9-24)13cdd	USBR CH3	300,000	40,100	D
(C-9-24)13cdd	USBR CH3	300,000	40,100	R
(C-9-24)36aaa	McDaniel & Sons, Inc.	160,000	21,400	R
(C-10-23)12aba1	J. F. Nutt	210,000	28,100	D
(C-10-23)12aba1	J. F. Nutt	260,000	34,800	R
(C-10-23)12bda	J. F. Nutt	500,000	66,800	R
(C-10-23)15aab	J. F. Nutt	270,000	36,100	R
(C-10-23)31bbb1	USGS LCRP-1	280,000	37,400	LA
(C-10-24)12bcc2	YCWUA 8	260,000	34,800	R
(C-10-24)13bbd1	YCWUA 9	540,000	72,200	R
(C-10-25)1bba	P. R. Sibley	443,000	59,200	R
(C-10-24)2cda	F. Jeffries	460,000	61,500	R
(C-10-24)35cab	J. F. Barkley	600,000	80,200	R
(C-11-23)34bbc	USGS LCRP-30	1,300,000	173,800	R
(C-11-24)2abd	J. F. Nutt	1,100,000	147,100	D and R
(C-11-24)23bcb	USGS LCRP 10	740,000	98,900	R
(C-11-25)3dac	E. Hughes	730,000	97,600	R
(C-9-23)17abc1	YCWUA 3	230,000	30,700	D
(C-8-22)34add	USBR CH750	150,000	20,100	R

Table 2. Transmissivity values below Laguna Dam used for statistical analysis; all transmissivity values are from Olmstead and others (1973, table 7)—Continued.

[Type of test: D, drawdown; R, recovery; LA, leaky artesian analysis with observation wells; numbers in square brackets are interval tested, in depth below land surface, in feet]

Well Name	Other Identifier	Transmissivity, in gallons per day per foot	Transmissivity, in feet squared per day	Type of test
(C-8-22)35caa1	USBR CH704	340,000	45,500	R [435-570]
(C-8-22)35caa1	USBR CH704	1,100,000	147,100	R [99-170]
(C-8-22)35caa2	USBR CH751	190,000	25,400	R
(C-8-22)35cca	Az. Western College	230,000	30,700	R
(C-8-22)35cad	USBR CH752	200,000	26,700	R
(C-8-23)25acb	Gunther and Shirley	260,000	34,800	R
(C-8-23)25dab	Gunther and Shirley	300,000	40,100	R
(C-8-23)26bac	G. Ogram	180,000	24,100	R
(C-8-23)27ada	USBR CH701	330,000	44,100	D
(C-8-23)27ada	USBR CH701	230,000	30,700	R
(C-8-23)27ddd1	Carter	120,000	16,000	R
(C-8-24)22ccd	McLaren Produce Co.	300,000	40,100	D

Characteristics of Models

All models were constructed and implemented in the same way, with the major differences being the geometry of the domain and surface-water features simulated and the transmissivity values tested. Simulations were carried out with the USGS model program MODFLOW-2000 (Harbaugh and others, 2000). Common characteristics of the models are as follows:

1. Each model domain represents a major contiguous area of saturated alluvium and adjacent saturated older alluvium along the lower Colorado River. The lateral boundaries of the active model domain were determined by the outermost position of (a) the "river aquifer" as mapped by Wilson and Owen-Joyce (1994) or (b) the Colorado River alluvium upstream and downstream boundaries of each model where no adjacent river aquifer was mapped. The areas modeled are shown in figure 1. Coordinates for perimeters of the active model domains were prepared in the coordinate system defined by Universal Transverse Mercator Zone 11, 1927 North American Datum. In some areas, the model perimeters were smoothed to remove unnecessary details in the river aquifer boundaries.
2. Units of length in the models are feet. As discussed in following sections, however, some computations used coordinates in meters to construct model data sets. Units of time in the models are days.

Model grids were oriented with rows in an east-west direction and columns in a north-south direction. The origin of each model is the northwest corner of the domain, so that model rows increment in a southerly direction and model columns increment in an easterly direction (fig. 4). The lateral grid spacing was 0.25 mile (402.3 m) along rows and columns.

The number of rows in each model, N_{row}, was computed as

$$N_{row} = INT\left[\frac{(Y_{\max} - Y_{\min})}{\Delta} + 0.49999\right],$$

where

INT is a function that converts a real number to an integer by truncating digits to the right of the decimal place,

$Y_{\max}$ is the maximum of all UTM easting coordinates (in meters) along the model perimeter,

$Y_{\min}$ is the minimum of all UTM easting coordinates (in meters) along the model perimeter, and

Δ is the grid spacing (402.3 m).

Similarly, the number of columns in each model, N_{col}, was computed as

$$N_{col} = INT\left[\frac{(X_{\max} - X_{\min})}{\Delta} + 0.49999\right],$$

where

$X_{\max}$ is the maximum of all UTM northing coordinates (in meters) along the model perimeter,

$X_{\min}$ is the minimum of all UTM northing coordinates (in meters) along the model perimeter.

The active part of the model grid was determined in a two-step process using the model perimeter polygon and polygons denoting areas of no flow within the model perimeter (fig. 4). Areas of no flow can occur where low permeability rocks are surrounded by the river aquifer. For the first step,

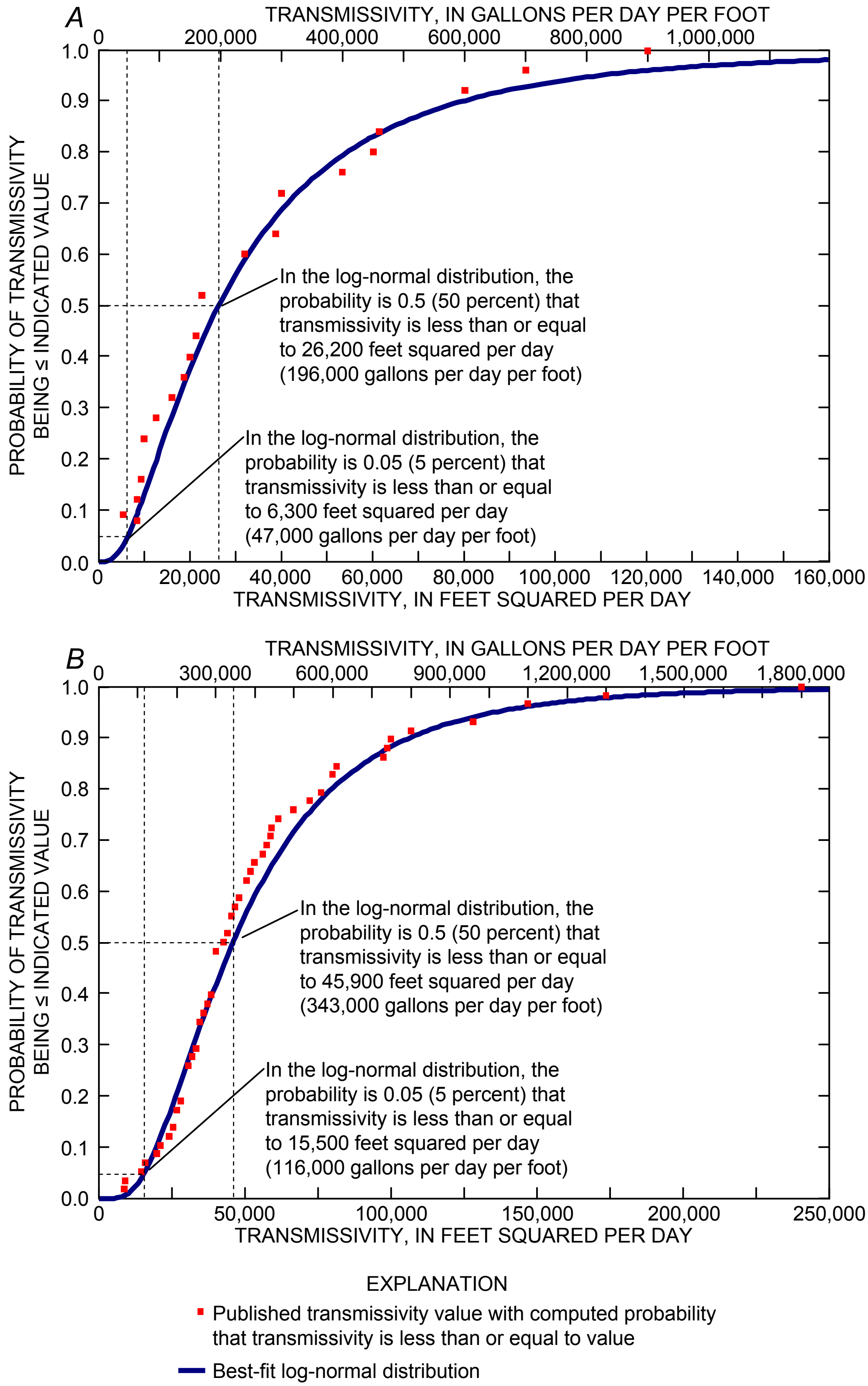


Figure 3. Cumulative distribution functions for best-fit log-normal distributions of transmissivity along the Lower Colorado River. *A*, Distribution function for data north of the Yuma area. *B*, Distribution function for data in the Yuma area.

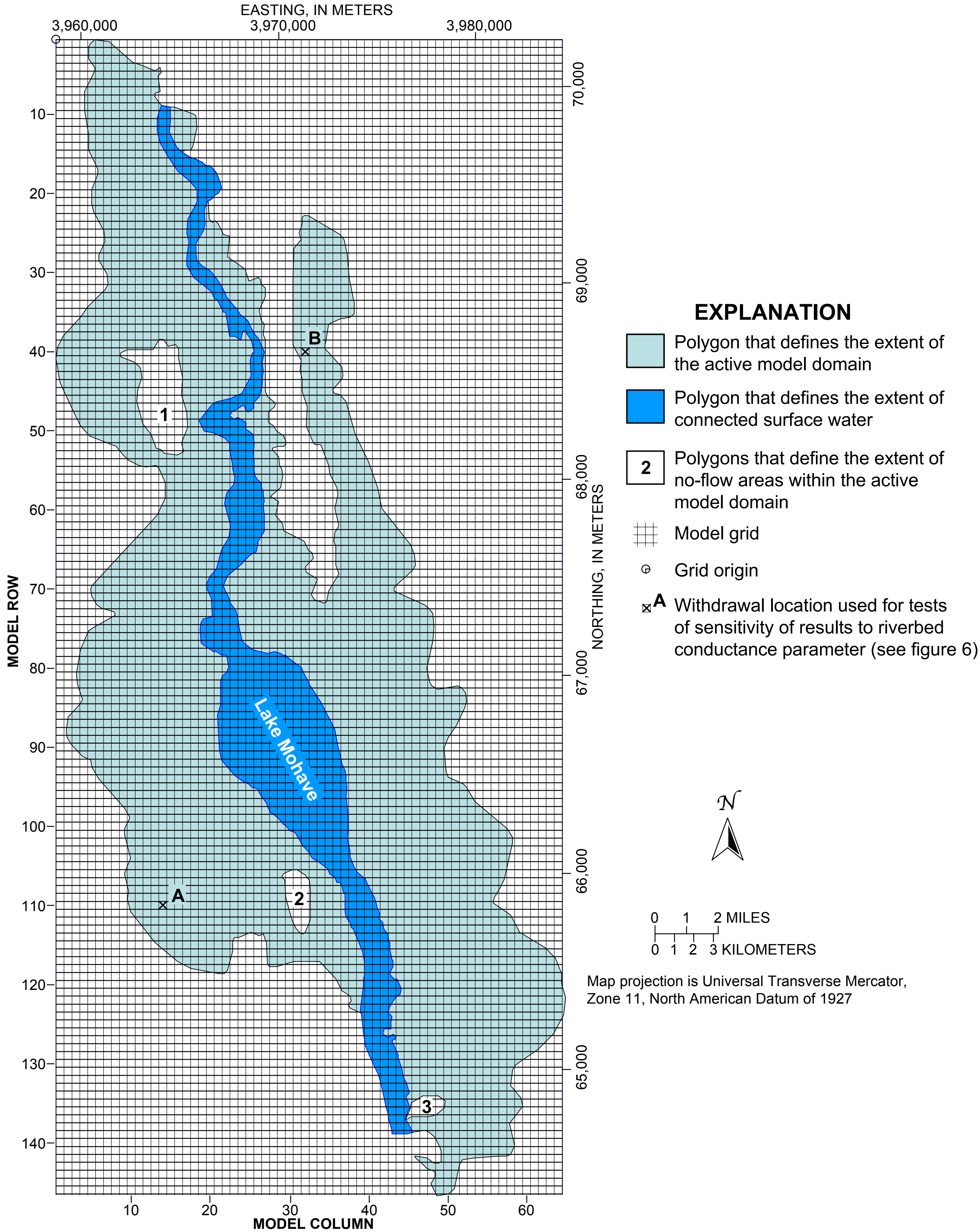


Figure 4. Model grid and features of the Lake Mohave ground-water superposition model.

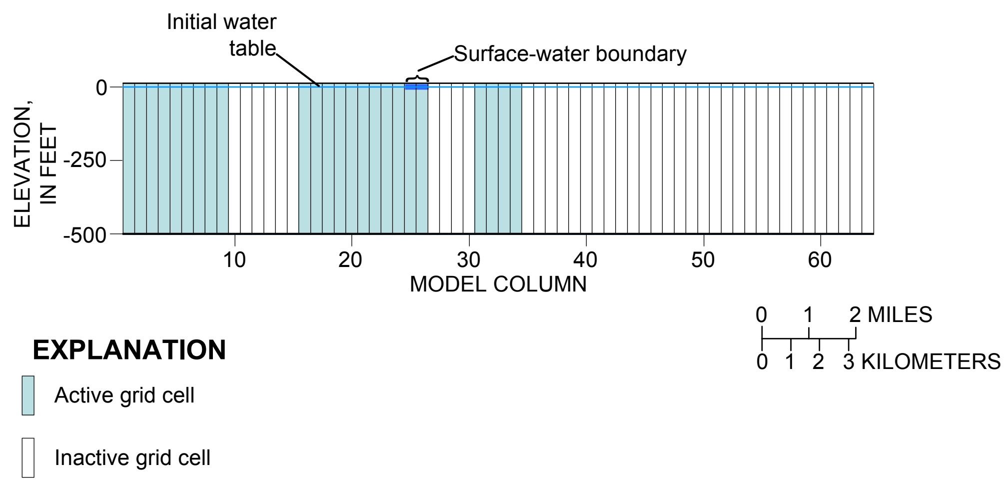


Figure 5. Vertical section along row 40 of the Lake Mohave ground-water superposition model.

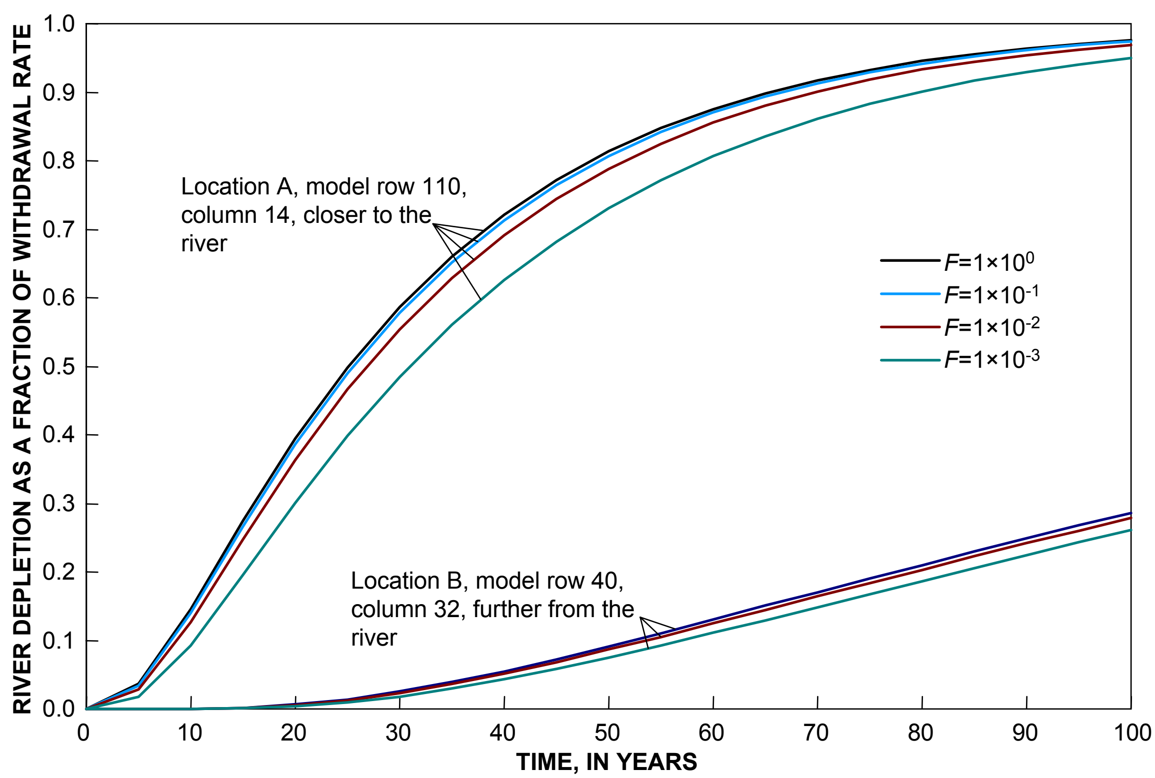


Figure 6. Results from sensitivity tests of the riverbed conductance parameter in the Lake Mohave ground-water superposition model for two withdrawal locations (see fig. 4). Multiple depletion curves were generated by multiplying all conductance values by the parameter *F*.

Table 3. Characteristics of superposition models constructed for parts of the flood plain and river aquifer adjacent to the lower Colorado River.
[Transmissivity values run: Yes, depletion analysis was completed for value; No, depletion analysis was not completed for value.]

Model name	UTM Easting of west edge of grid, meters[1]	UTM Northing of north edge of grid, meters[1]	Number of model rows	Number of model columns	Number of active model cells	Transmissivity values run, feet squared per day (gallons per day per foot)				
						980 (7,300)	6,300 (47,000)	15,500 (116,000)	26,200 (196,000)	45,900 (343,000)
Detrital-Virgin	719593.75	4116963.00	396	148	21,025	Yes	Yes	No	Yes	No
Lake Mohave	702348.12	3958695.50	146	64	4,103	No	Yes	No	Yes	No
Mohave Valley	706260.69	3897829.00	160	139	8,976	No	Yes	No	Yes	No
Parker-Palo Verde-Cibola	636450.00	3789000.00	296	388	40,292	No	Yes	No	Yes	No
Laguna Dam	730897.38	3672455.25	103	145	6,302	No	Yes	No	Yes	No
Yuma	640414.62	3691950.25	374	340	59,645[2]	No	Yes	Yes	Yes	Yes

[1]Coordinates are UTM Zone 11, North American Datum of 1927.

[2]For the model in the Yuma area, depletion was not calculated for active model cells in Mexico and areas in USA west of the area of the accounting surface published by Owen-Joyce and others (2000). A total of 16,147 simulations were made for each of four transmissivity values.

all cells that were more than 50 percent within the model perimeter were denoted as active, and all cells that were 50 percent or less within the model perimeter were denoted as inactive. Second, all cells that were more than 50 percent within any area of no flow were denoted as inactive.

3. Each model consists of one layer of cells with a bottom elevation of –500 ft and an initial head elevation of 0 ft for each active cell (fig. 5). This results in a uniform starting saturated thickness of 500 ft. The top elevation of the model was set at a uniform elevation of 10 ft.

4. Connected surface-water features were simulated using the River Package of MODFLOW-2000. For all models, river stages were set to an elevation of zero, thereby allowing computation of change in flow to or from surface-water features that result from change in head in connected cells. In the River Package, the degree of connection between the surface water and a connected cell is controlled by the riverbed conductance term, C_{riv} , which is defined as

$$C_{riv} = K_{rb} A / b_{rb},$$

where

K_{rb} is the vertical hydraulic conductivity of the riverbed,

A is the area of the river in the cell, and

b_{rb} is the thickness of the riverbed.

Large riverbed conductance values were specified so that simulated surface-water features are hydraulically well connected to underlying model cells. This approach approximates a specified-head boundary at the location of surface-water feature. For the Parker-Palo Verde-Cibola model the River Package data set was constructed using the program RIVGRID (Leake and Claar, 1999), using an approximate river centerline, an assumed river width of 100 ft, an assumed K_{rb} of 50 ft/day, and an assumed b_{rb} of 5 ft. The area, A , used to compute the riverbed conductance, C_{riv} is computed by program RIVGRID as the product of the length of the river traversed in a cell by the centerline and the assumed river width. The average value of C_{riv} for the Parker-Palo Verde-Cibola model was 2.3×10^5 ft^2/day. For all other models A was computed as the area of intersection of a polygon representing the Colorado River and (or) reservoirs (fig. 4) and the model cell. The quantity was set at 0.929 day^{-1}, therefore the maximum conductance (for the case of a cell entirely within the river/reservoir polygon) is about 1.62×10^6 ft^2/day. The average riverbed conductance for the Mohave Valley model is 7.3×10^5 ft^2/day. For the Lake Mohave model (fig. 4) the average riverbed conductance was 1.3×10^6 ft^2/day reflecting a wider surface-water body than is present in the Mohave Valley model.

The sensitivity of model results to the value of riverbed conductance was tested using the Lake Mohave model. Depletion curves were computed by the model for withdrawal at two locations. For the first point, labeled “A” on figure 4, depletion can occur when effects of withdrawal propagate about 4.5 miles northeastward to the edge of Lake Mohave. For the second point, labeled “B” on figure 4, depletion can occur when effects of withdrawal propagate about 14 miles along a side valley and then southwestward to the edge of Lake Mohave. Because of the shorter distance to surface water, depletion occurs more rapidly from withdrawals at point A than at point B. For each location, depletion curves were computed using a multiplication factor, *F*, of 1×10^{-1}, 1×10^{-2}, and 1×10^{-3}, for all riverbed conductance values (fig. 6). Curves shown for F=1×10^0 use the original riverbed conductance values. As can be seen on figure 6, differences in depletion calculated with the original riverbed conductance values and with values that are three orders of magnitude lower are relatively minor, with the greatest differences occurring at location A. This observation along with the fact that thick, low-permeability riverbed sediments are not known to occur along the lower Colorado River leads to the conclusion that the strategy of using relatively high riverbed conductance values is reasonable.

A summary of characteristics of the six superposition models is given in table 3. The Laguna and Yuma models included parts of the model domain that extend beyond the mapped area of the river aquifer (fig. 1). The Laguna model was extended to the east because of uncertainty in where the river aquifer ends. An extension of the model domain such as this tends to slow down the progression of simulated depletion through time in comparison to that simulated in a model that includes a no-flow boundary. The Yuma model was extended southward and westward into the delta region of the Colorado River to reflect the continuous nature of the ground-water flow system thought to exist there.

Estimates of depletion in all models were made using the low and average transmissivity values from data upstream of Laguna Dam, 6,300 ft^2/day (47,000 gal/day/ft) and 26,200 ft^2/day (196,000 gal/day/ft), respectively. In addition, for the Yuma area, estimates of transmissivity were made using low and average transmissivity values derived from data downstream from Laguna Dam. Finally, for the Detrital-Virgin model, depletion also was calculated using a lower estimate of transmissivity, 980 ft^2/day (7,300 gal/day/ft). This was done because there were no published estimates of transmissivity in this area in the sources of data used in the statistical analyses. Transmissivity from one location in the Virgin Valley was inferred to be about 980 ft^2/day (7,300 gal/day/ft) from hydraulic conductivity and thickness estimates in a report by Las Vegas Water District (1992).

Procedure for Computing and Displaying Areal Representation of Depletion

A computer program was written to run each superposition model repeatedly to calculate depletion at 100 years for every active model grid cell. The program required that most MODFLOW data sets for the model be constructed prior to running the program. Steps taken by the program to calculate depletion for each active cell in the model grid are as follows:

1. Calculate the northing and easting of the cell center in Universal Transverse Mercator Zone 11 coordinates.
2. Construct a MODFLOW-2000 Well Package data set for a single well at the row and column location of the cell using the flow rate of -1.431×10^5 ft^3/day (a withdrawal of 1,200 acre-ft/year). The final results are independent of this rate because the system responds linearly to withdrawal (Leake and Reeves, 2008). The superposition model only considers the effects of the well being added, not effects of other wells that may exist in the real system.
3. Run the model.
4. Open the listing file from the model run and read the induced flow from the river in the volumetric mass balance for a simulation time of 100 years.
5. Divide the induced flow rate by the withdrawal rate to get the fraction of withdrawal rate that is accounted for as depletion at 100 years.
6. Save information including row and column location, northing and easting, and depletion fraction at 100 years.

When these steps are completed for each active cell in the model grid, the program is terminated. The northing and easting coordinates and depletion values then can be mapped using a geographic information system or other contouring program. The grid spacing of 0.25 mile results in a dense network of points for mapping over the area of the river aquifer.

Note that the method as implemented requires one simulation (model run) for each cell in the model grid for each transmissivity value used. For example, the Parker-Palo Verde model has 40,292 active model cells, requiring a total of 80,584 simulations for two uniform values of transmissivity. For the Yuma model, the active area is much larger than the area over which Owen-Joyce and others (2000) mapped the accounting surface. The mapped depletion, however, was restricted to a subarea of the model domain, requiring a total of 64,588 simulations for four uniform transmissivity values.

Results

Distributions of simulated depletion in the six model areas are shown on maps in figures 7–17. The maps show the simulated depletion at 100 years for one pumping well, as a function of the position of that well. Values shown are depletion as a percentage of the well pumping rate, expressed as colored areas in ten intervals ranging from 0–10 to 90–100. Supplemental contours showing 1 percent and 5 percent depletion are shown where values in this range were computed. Depletion percentages are not shown for areas within the flood plain of the Colorado River or areas underlying surface water. In the following discussions of results for the six areas modeled, particular focus is on any areas where depletion is 5 percent or less in 100 years.

Detrital-Virgin Area

This area includes Detrital Valley south of Lake Mead and the much larger Virgin Valley north of Lake Mead. With the lowest transmissivity value tested, 980 ft^2/day (7,300 gal/d/ft), the 5 percent depletion contour is within 5–10 miles of Lake Mead (fig. 7). Results for the two higher transmissivity values shown in figures 8 and 9, increased depletion can be seen by the increasing distance of the 5 percent contour from Lake Mead. For the highest value tested, 26,200 ft^2/day (196,000 gal/d/ft), depletion is greater than 5 percent in all of Detrital Valley and in all but the uppermost part of Virgin Valley.

Lake Mohave Area

This area was the smallest among the six areas modeled. For the two transmissivity values tested, 6,300 and 26,200 ft^2/day (47,000 and 196,000 gal/d/ft), no areas of depletion less than 10 percent were simulated (fig. 10). The lowest values of depletion are in a narrow north-south trending side valley on the east side of the river.

Mohave Valley Area

In this area, depletion simulated using the higher transmissivity value tested, 26,200 ft^2/day (196,000 gal/d/ft), is higher than 50 percent over the entire model domain (fig. 11). Using the lower value tested, 6,300 ft^2/day (47,000 gal/d/ft), a small area of depletion less than 5 percent was simulated in a side valley in the southeast part of the model domain.

Parker-Palo Verde-Cibola Area

This area is the largest river-aquifer area modeled and is the most complex in terms of horizontal geometry. Side valleys in the river aquifer include Chuckwalla and Smoketree Valleys in the west-central and southwest part of the area, and Cactus and La Posa Plains in the northeast part of the area. Using the lower transmissivity value tested, 6,300 ft^2/day (47,000 gal/d/ft), 5 and 1 percent simulated depletion contours can be seen in each of these side valleys (fig. 12). With the higher transmissivity value tested, 26,200 ft^2/day (196,000 gal/d/ft), only Chuckwalla Valley has simulated depletion values less than 10 percent (fig. 13).

Laguna Dam Area

This area includes the part of the river aquifer that is immediately above Laguna Dam. Much of this part of the river aquifer is east of the river. Using the lower transmissivity value tested, 6,300 ft^2/day (47,000 gal/d/ft), 5 and 1 percent simulated depletion contours can be seen around Castle Dome Plain (fig. 14). With the higher transmissivity value tested, 26,200 ft^2/day (196,000 gal/d/ft), simulated depletion is greater than 10 percent for the entire area (fig. 15).

Yuma Area

For the Yuma area, depletion was simulated for the area of the accounting surface mapped by Owen-Joyce and others (2000). For the two transmissivity values used in models upstream from Laguna Dam, 6,300 and 26,200 ft^2/day (47,000 and 196,000 gal/d/ft), areas of depletion of 5 percent or less were simulated with the lower of these values (fig. 14), but no areas of depletion of 10 percent or less were simulated with the higher value (fig. 15). Depletion also was simulated using two additional transmissivity values, 15,500 and 45,900 ft^2/day (116,000 and 343,000 gal/d/ft). For the lower transmissivity, a small area of depletion less than 10 percent was simulated on the west side of the mapped area in southeastern Imperial Valley (fig. 16). For the higher transmissivity, simulated depletion is greater than 20 percent throughout the model domain (fig. 17).

Summary and Conclusions

The Accounting-Surface Method was developed (Wilson and Owen-Joyce, 1994; Owen-Joyce and others, 2000; Wiele and others, 2008) to provide water managers with a possible tool help evaluate the need for entitlements by wells pumping in the river aquifer. To further understand temporal effects of pumping wells on the Colorado River, Reclamation set up a technical team to assess timing over which wells at great distance would deplete water in the Colorado River. Possible methods for calculating depletion of surface water from ground-water pumping range from simple analytical solutions to complex numerical ground-water flow models. For this study, an intermediate approach was taken, using numerical superposition models with complex horizontal geometry and simple vertical geometry. Six areas of the river aquifer along the lower Colorado River were modeled. Published transmissivity values were analyzed to determine low and average transmissivity values. A value of 0.2 was used for the aquifer specific yield (or storage coefficient) in all models. All model grids consisted of one layer of cells, with model rows and columns oriented in east-west and north-south directions, respectively.

Distribution of depletion was simulated using MODFLOW-2000. One simulation was done for each active cell in the model grid for each transmissivity value tested. Maps were prepared to show the simulated depletion at 100 years for one pumping well, as a function of the position of that well.

Areas in which simulated depletion at 100 years was less than or equal to 5 percent generally occurred only in side valleys with the lower or more conservative transmissivity values tested. For the smaller areas modeled, and for the river aquifer within the river valley adjacent to the flood plain in all models, simulated depletion at 100 years was generally in the range of 10–100 percent of the pumping rate.

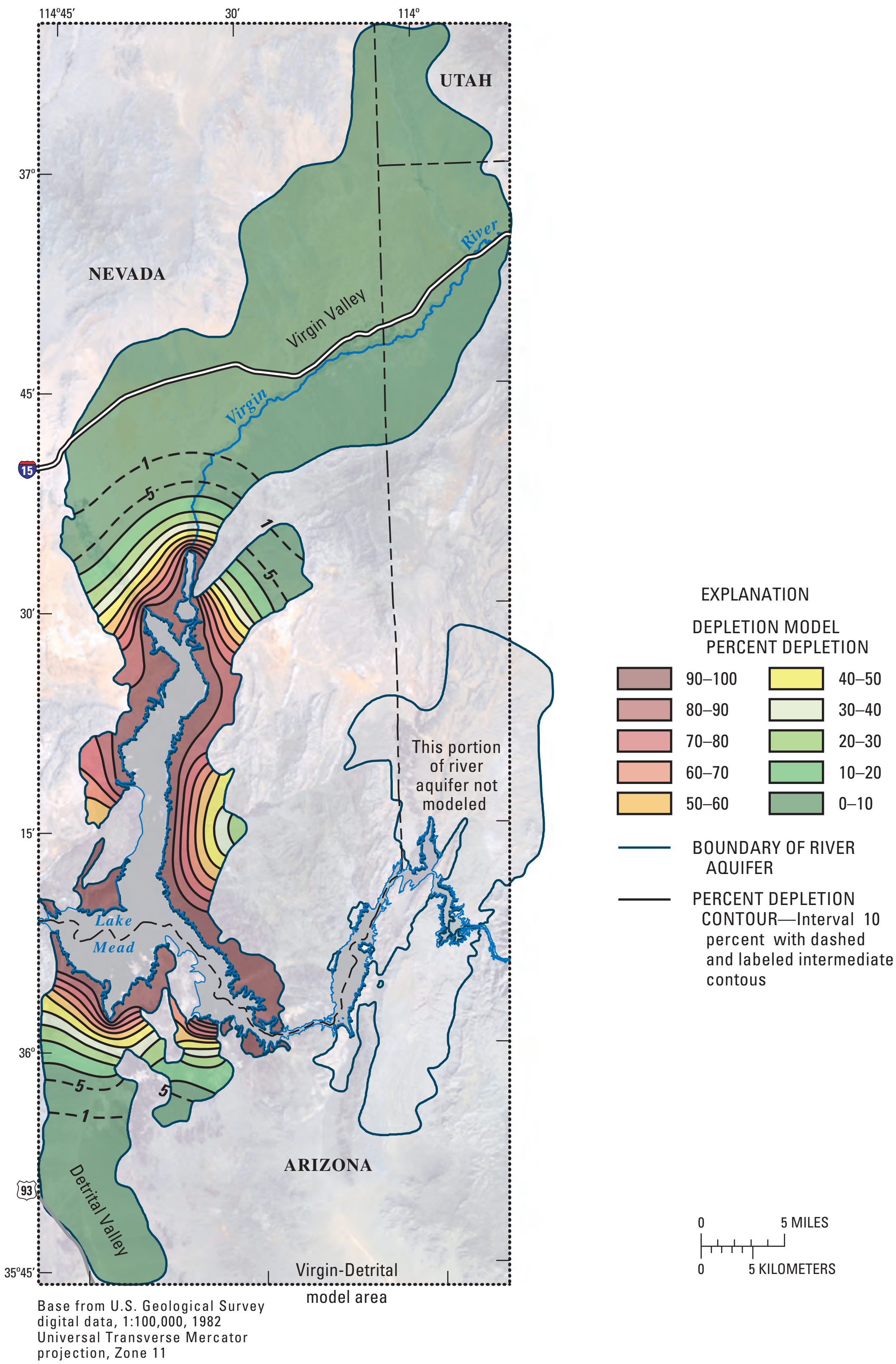


Figure 7. Percent depletion in 100 years by pumping wells within the Virgin-Detrital model area of the Colorado River aquifer assuming a transmissivity rate of 980 feet squared per day (7,300 gallons per day per foot).

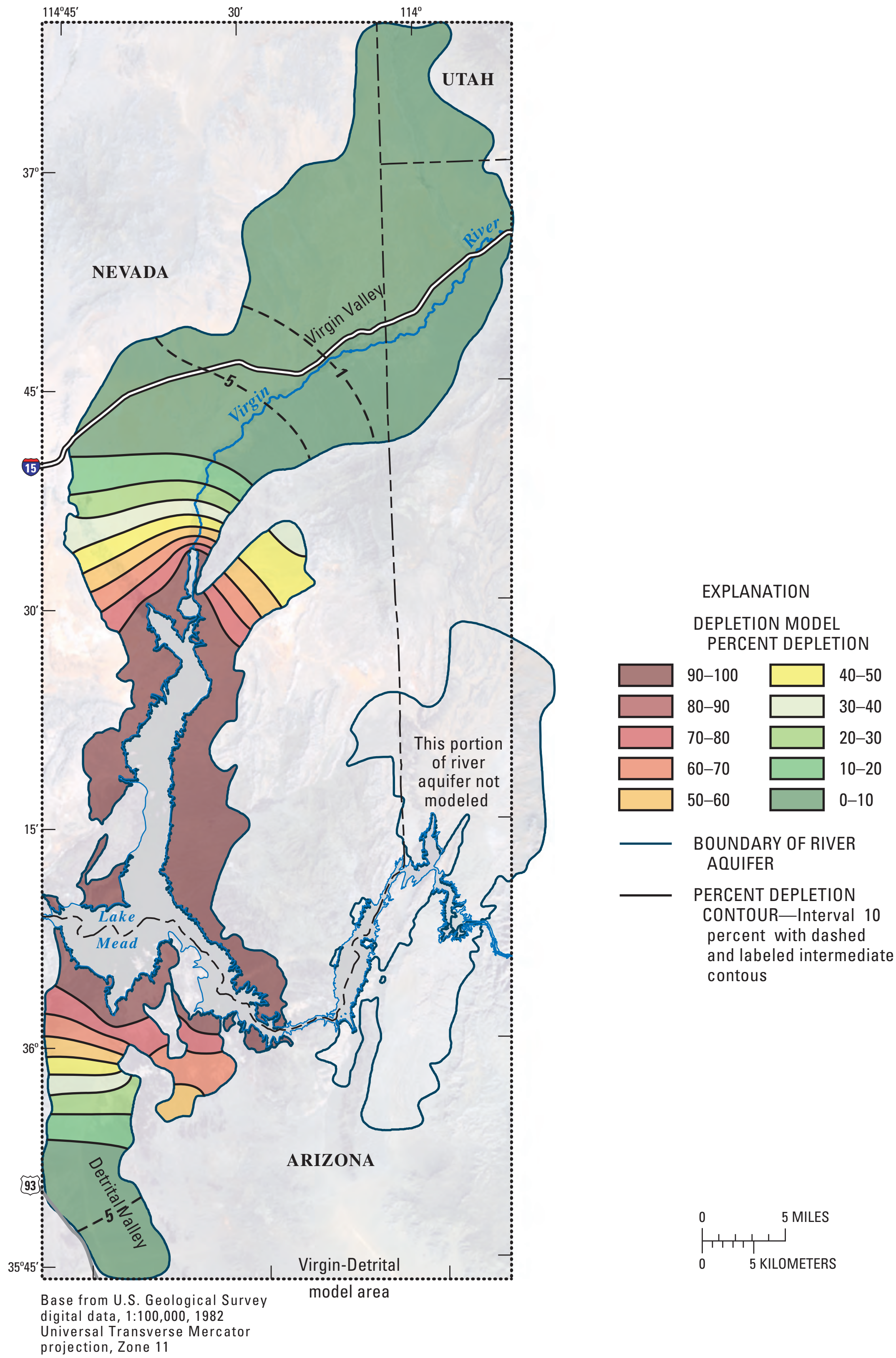


Figure 8. Percent depletion in 100 years by pumping wells within the Virgin-Detrital model area of the Colorado River aquifer assuming a transmissivity rate of 6,300 feet squared per day (47,000 gallons per day per foot).

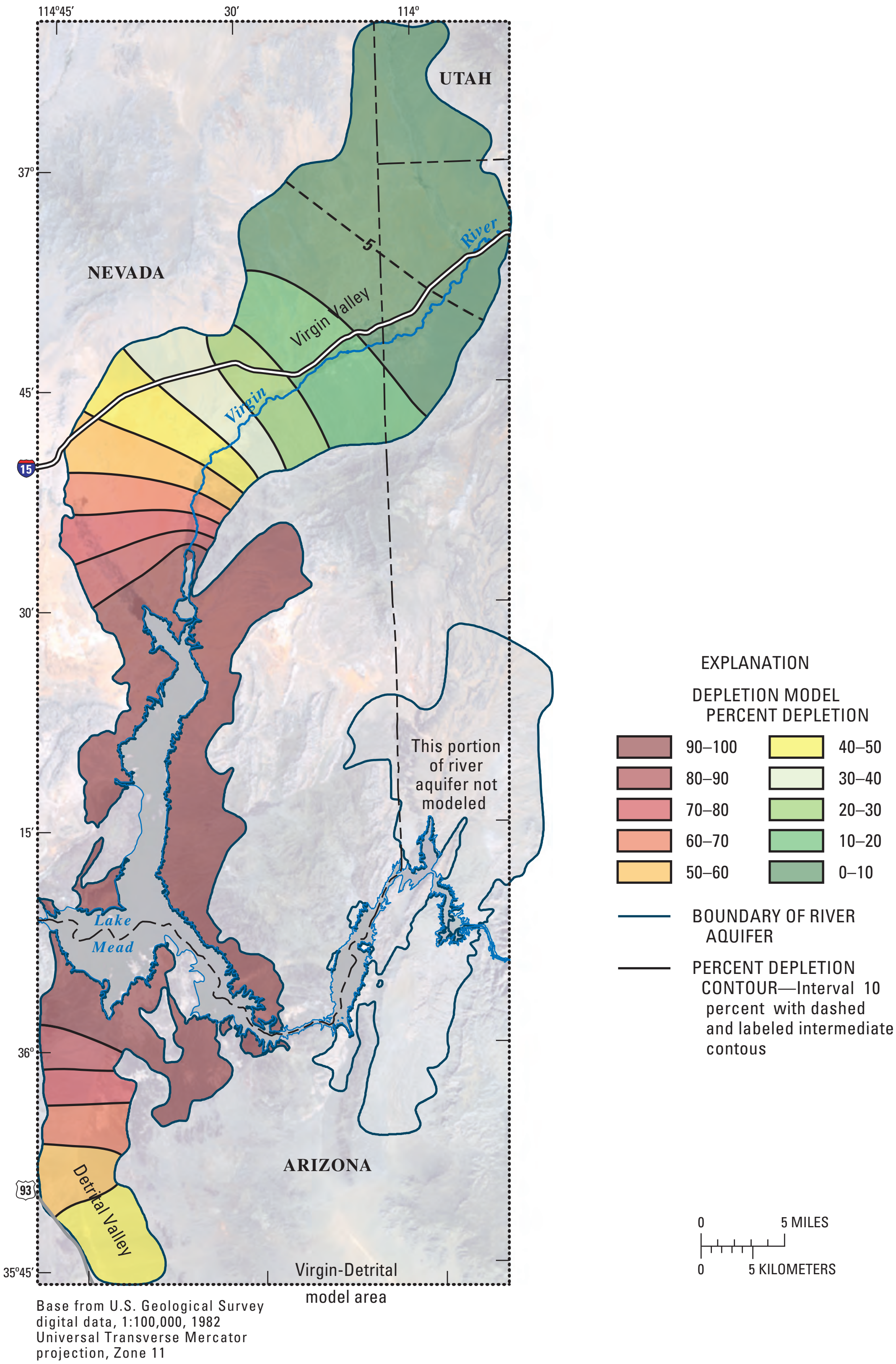


Figure 9. Percent depletion in 100 years by pumping wells within the Virgin-Detrital model area of the Colorado River aquifer assuming a transmissivity rate of 26,200 feet squared per day (196,000 gallons per day per foot).

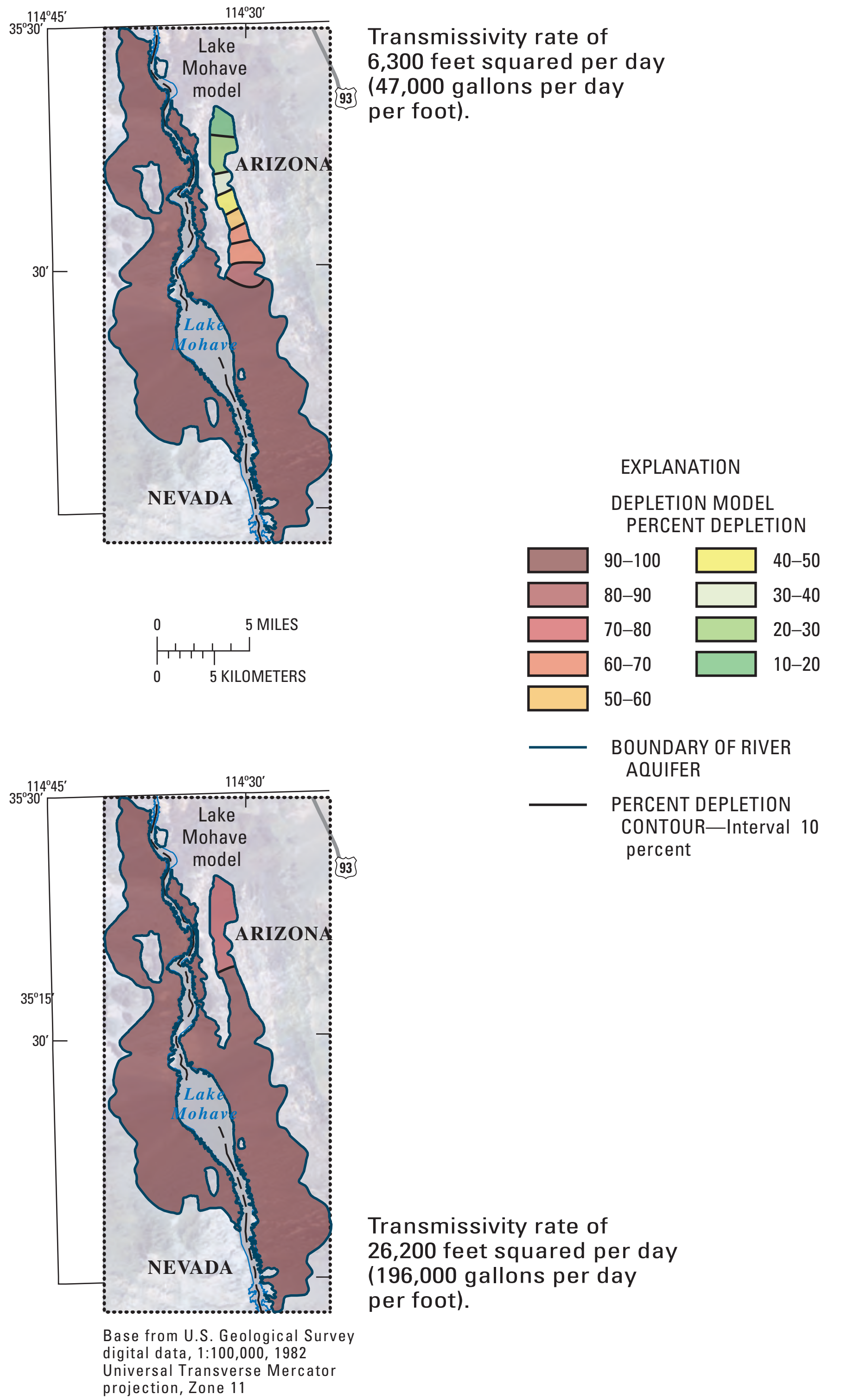


Figure 10. Percent depletion in 100 years by pumping wells within the Lake Mohave model area of the Colorado River aquifer assuming a transmissivity rate of 6,300 and 26,200 feet squared per day (47,000 and 196,000 gallons per day per foot).

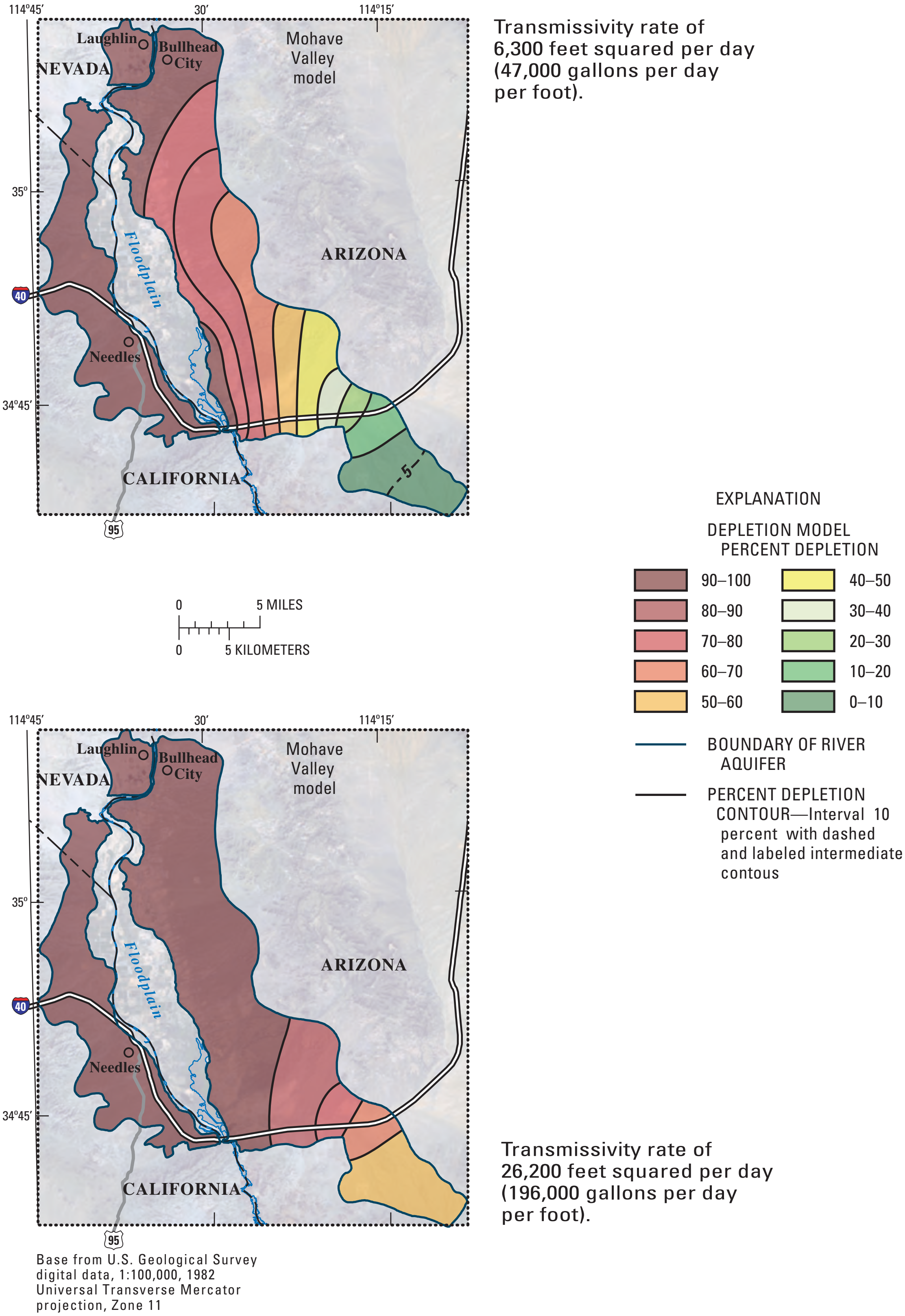
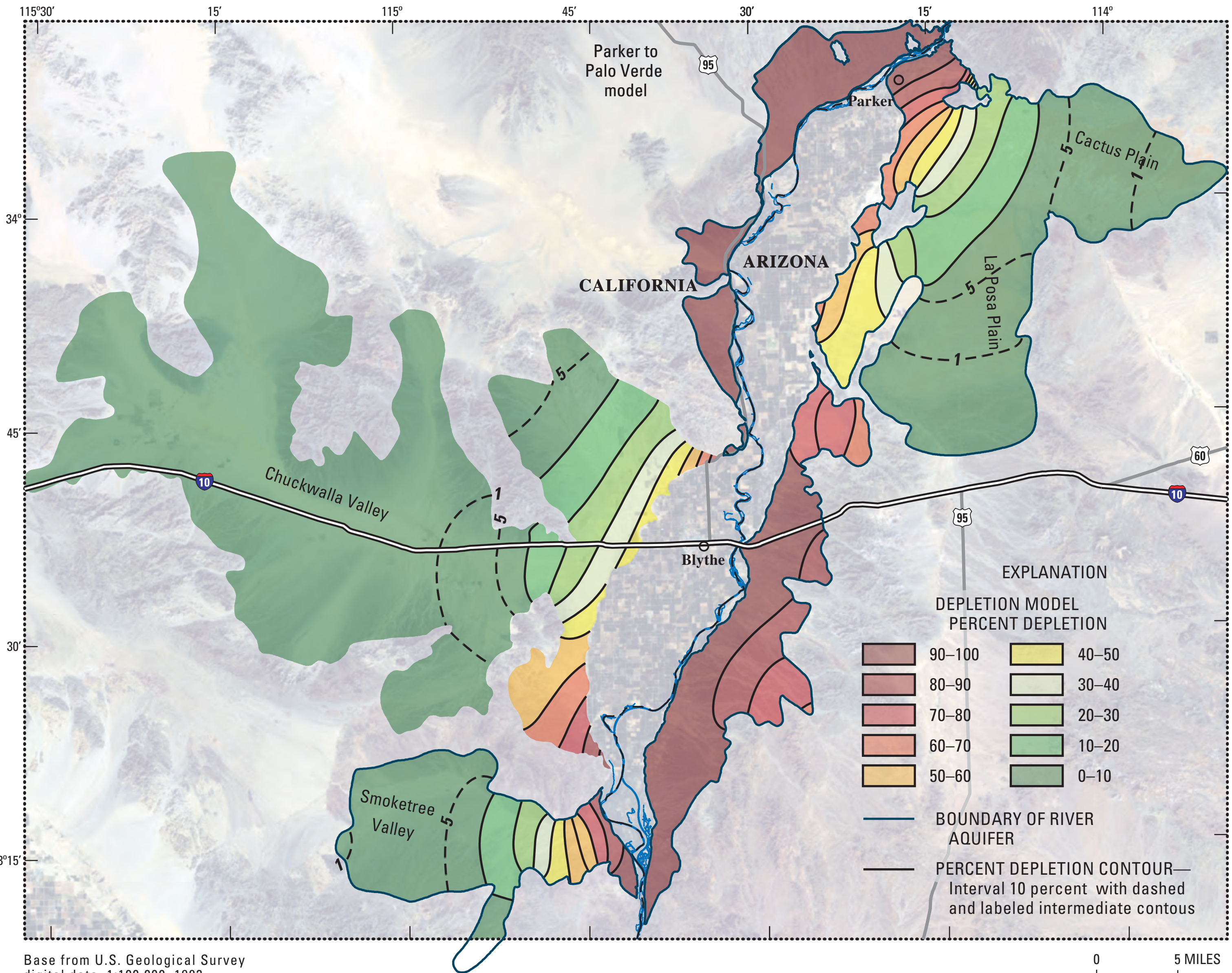


Figure 11. Percent depletion in 100 years by pumping wells within the Mohave Valley model area of the Colorado River aquifer assuming a transmissivity rate of 6,300 and 26,200 feet squared per day (47,000 and 196,000 gallons per day per foot).



Base from U.S. Geological Survey
digital data, 1:100,000, 1982
Universal Transverse Mercator
projection, Zone 11

Figure 12. Percent depletion in 100 years by pumping wells within the Parker-Palo Verde-Cibola model area of the Colorado River aquifer assuming a transmissivity rate of 6,300 feet squared per day (47,000 gallons per day per foot).

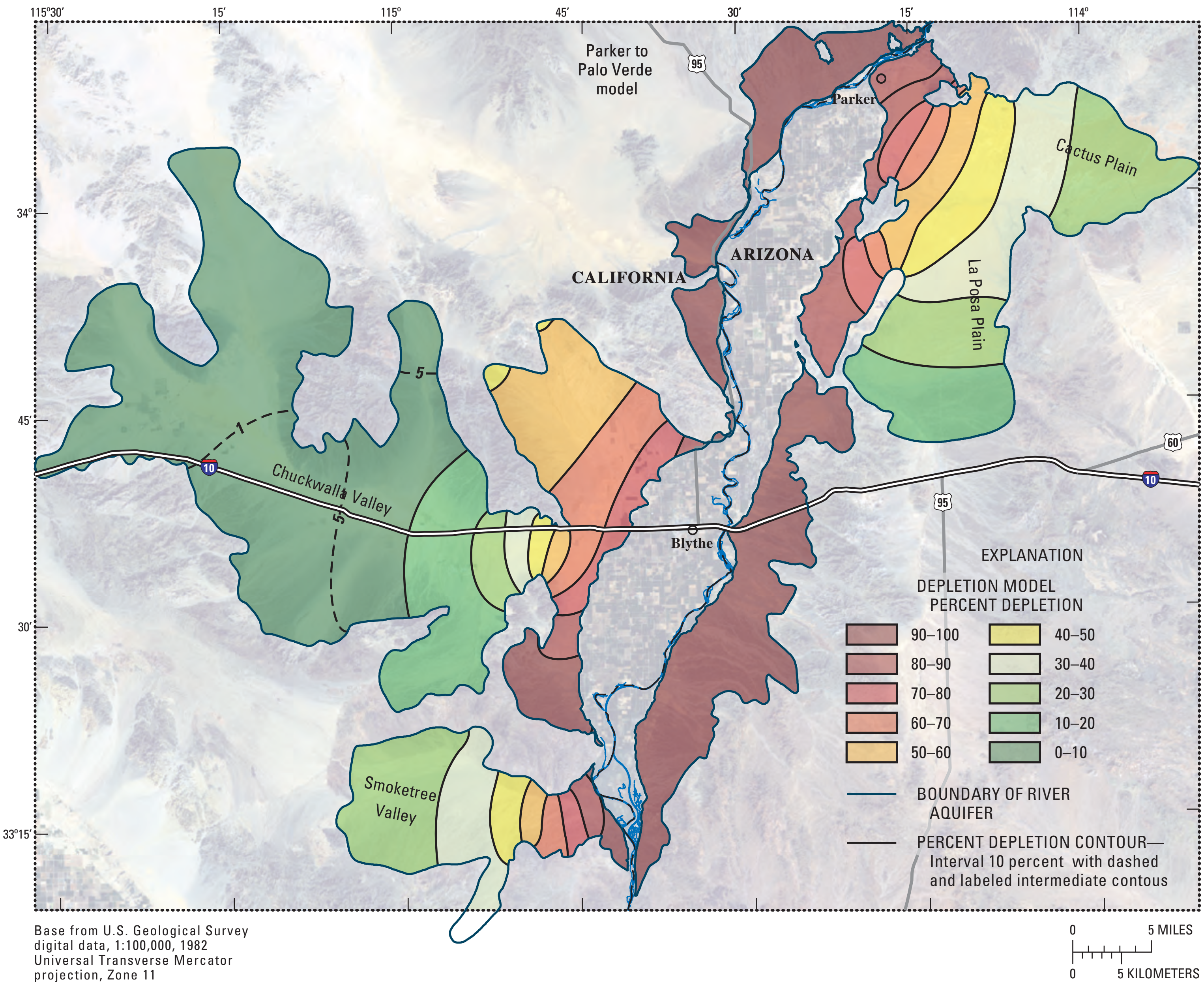


Figure 13. Percent depletion in 100 years by pumping wells within the Parker-Palo Verde-Cibola model area of the Colorado River aquifer assuming a transmissivity rate of 26,200 feet squared per day (196,000 gallons per day per foot).

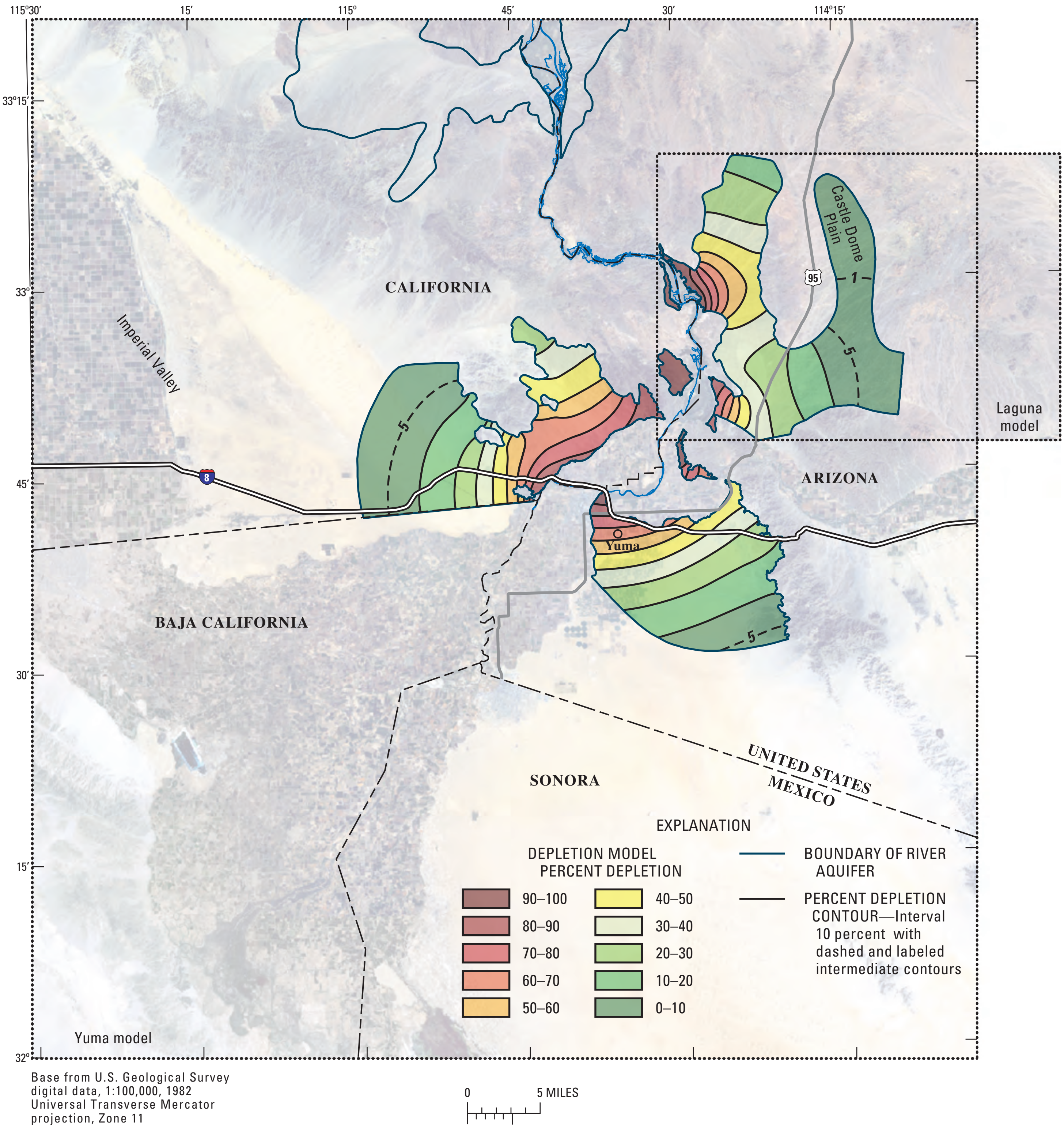


Figure 14. Percent depletion in 100 years by pumping wells within the Yuma and Laguna model areas of the Colorado River aquifer assuming a transmissivity rate of 6,300 feet squared per day (47,000 gallons per day per foot).

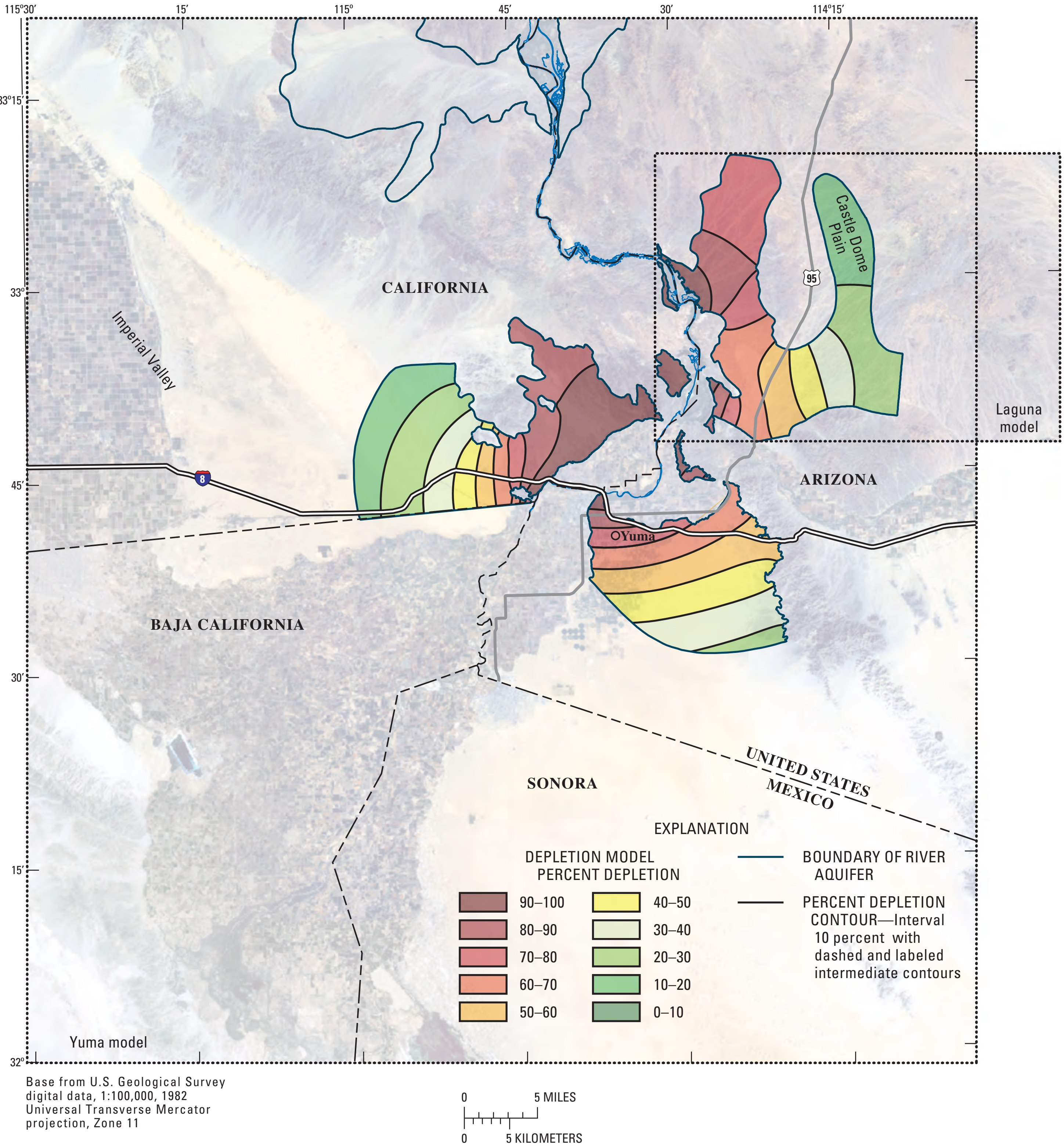


Figure 15. Percent depletion in 100 years by pumping wells within the Yuma and Laguna model areas of the Colorado River aquifer assuming a transmissivity rate of 26,200 feet squared per day (196,000 gallons per day per foot).

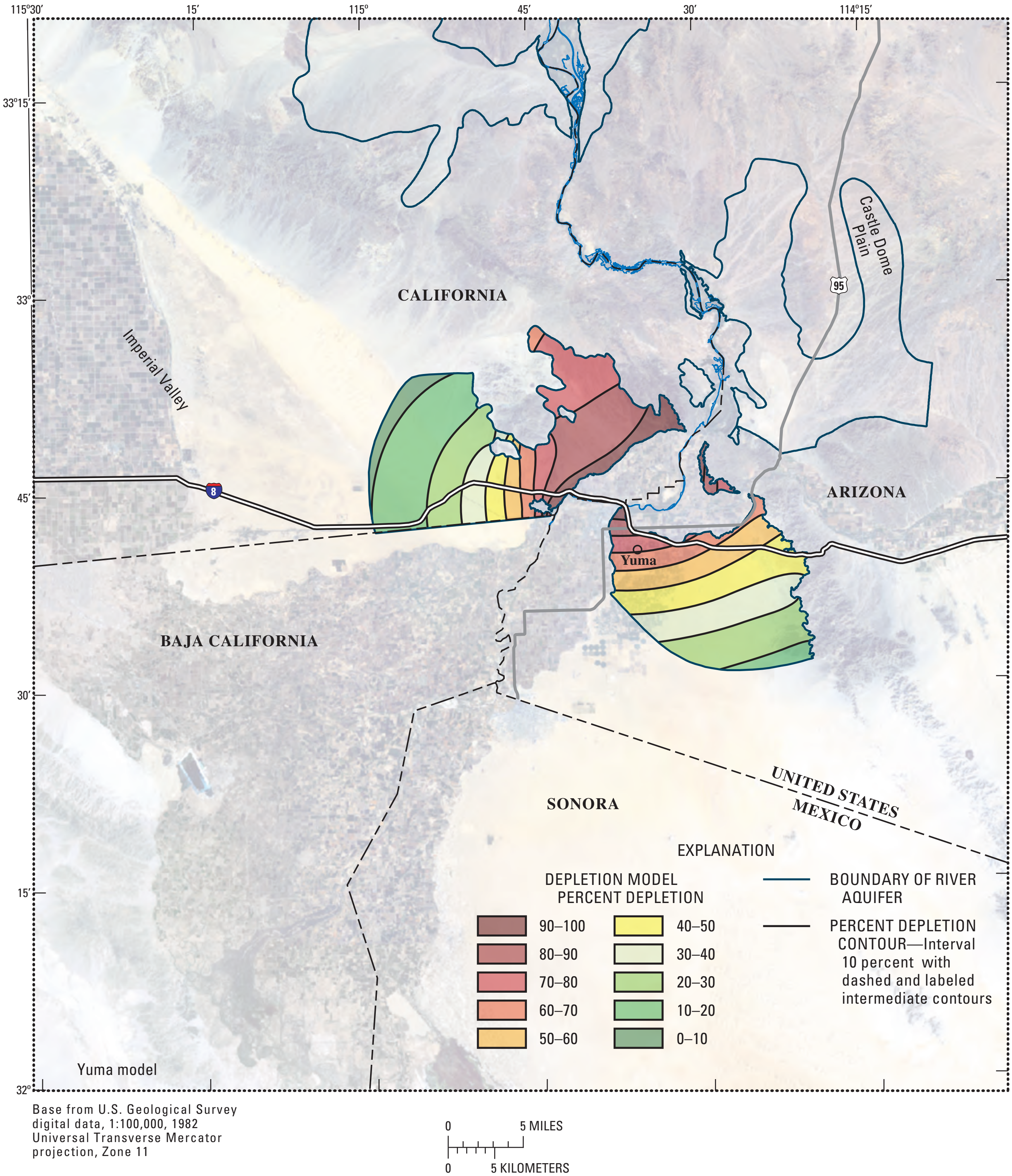


Figure 16. Percent depletion in 100 years by pumping wells within the Yuma model area of the Colorado River aquifer assuming a transmissivity rate of 15,500 feet squared per day (116,000 gallons per day per foot).

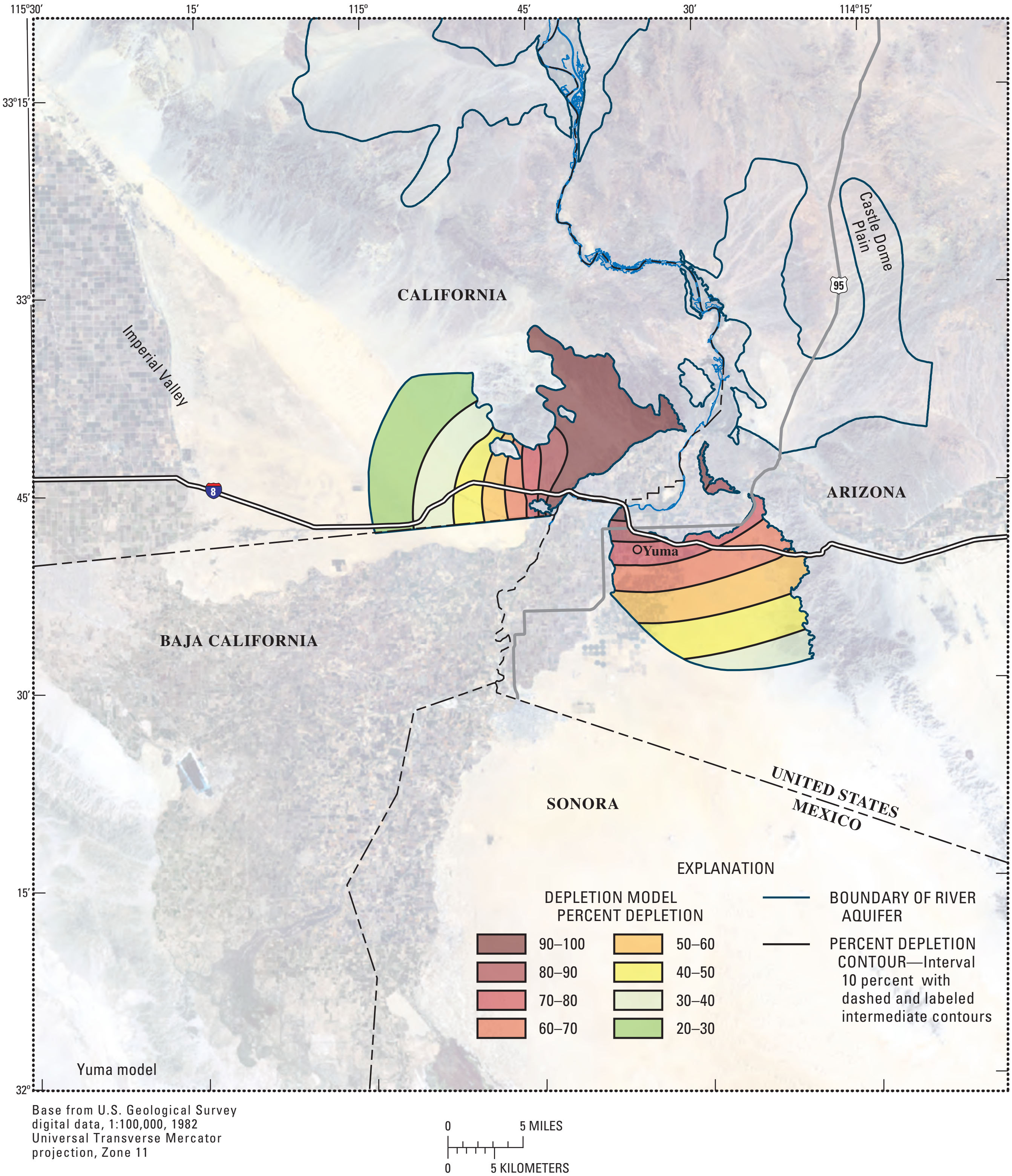


Figure 17. Percent depletion in 100 years by pumping wells within the Yuma model area of the Colorado River aquifer assuming a transmissivity rate of 45,900 feet squared per day (343,000 gallons per day per foot).

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