EFFECTS OF FUTURE GROUND–WATER PUMPAGE ON THE HIGH PLAINS AQUIFER IN PARTS OF COLORADO, KANSAS, NEBRASKA, NEW MEXICO, OKLAHOMA, SOUTH DAKOTA, TEXAS, AND WYOMING

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1400–E

Effects of Future Ground-Water Pumpage On the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming

By RICHARD R. LUCKEY, EDWIN D. GUTENTAG, FREDERICK J. HEIMES, *and* JOHN B. WEEKS

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck
Director

PREFACE

The Regional Aquifer-System Analysis of the High Plains was conducted by U.S. Geological Survey personnel in each of the eight States in the High Plains—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. To provide assistance, technical support, and additional information, contracts were awarded to the Kansas Geological Survey, New Mexico Natural Resources Department, Oklahoma Water Resources Board, and Texas Department of Water Resources. In addition, valuable information was provided by many other State and local agencies throughout the High Plains. Their contributions are an integral part of this investigation without which this report would not have been possible.

The U.S. Geological Survey coordinated its investigation of the High Plains aquifer with a concurrent study by the Economic Development Administration of the Department of Commerce. The Six-State High Plains—Ogallala Aquifer Area study conducted by the Ecomomic Development Administration was authorized by Congress in 1976. The study was charged with the responsibility of examining the feasibility of increasing water supplies to insure the economic growth and vitality of the High Plains. The results of that study are used extensively in this report. Together, these two studies provide a comprehensive evaluation of the High Plains aquifer and the potential impacts of declining ground-water supplies on the region. The Economic Development Administration study developed and proposed alternative strategies to alleviate or mitigate those adverse effects and the U.S. Geological Survey has provided hydrologic data and models needed to evaluate the effects of those strategies on the ground-water resource.

CONVERSION FACTORS

The following report uses inch-pound units as the primary system of measurements. The units commonly are abbreviated using the notations shown below in parentheses. Inch-pound units can be converted to metric units by multiplying by the factors given in the following list.

Inch-pound unit	Multiply by	To obtain metric unit
inch (in.)	2.540×10^{1}	millimeter
foot (ft)	3.048×10^{-1}	meter
mile (mi)	1.609	kilometer
acre	4.047×10^{-1}	hectare
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	1.233×10^{-3}	cubic hectometer
acre-foot per year (acre-ft/yr)	1.233×10^{-3}	cubic hectometer per year
cubic foot per second (ft^3/s)	2.832×10^{-2}	cubic meter per second
gallon per minute (gal/min)	6.308×10^{-2}	liter per second
inch per year (in./yr)	2.540×10^{-1}	millimeter per year
foot per day (ft/d)	3.048×10^{-1}	meter per day

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ABSTRACT

The U.S. Geological Survey conducted a geohydrologic study of the High Plains regional aquifer system to help State and local agencies manage the ground-water resource. Digital, finite-difference models of the ground-water flow system in the southern, central, and northern High Plains were developed during the study. The models were calibrated by matching the simulated and measured water levels, water-level changes, and streamflow prior to and after development. The calibrated models were used to project future water levels based on a baseline strategy (continuation of current economic trends and government policies) and on alternatives involving a voluntary reduction in water use (management strategy 1) and a mandatory reduction in water use (management strategy 2).

In the southern High Plains, the total simulated pumpage from 1980 to 2020 would be 113 million acre-feet for the baseline strategy, 109 million acre-feet for management strategy 1, and 88 million acre-feet for management strategy 2. For the baseline strategy, water levels in the southern High Plains are projected to decline more than 150 feet between 1980 and 2020 in about 700 square miles. More than one-half of the aquifer would have less than 25 feet of saturated thickness remaining by 2020, and slightly more than 100 million acre-feet of drainable water would remain in storage compared to about 200 million acre-feet during 1980. By 2020, probable well yields throughout most (80 percent) of the southern High Plains would be less than 250 gallons per minute. Similar water-level declines are projected for management strategy 1. For management strategy 2, water-level declines would continue to 2020 but would be less severe, resulting in about 125 million acre-feet of drainable water remaining in storage by 2020.

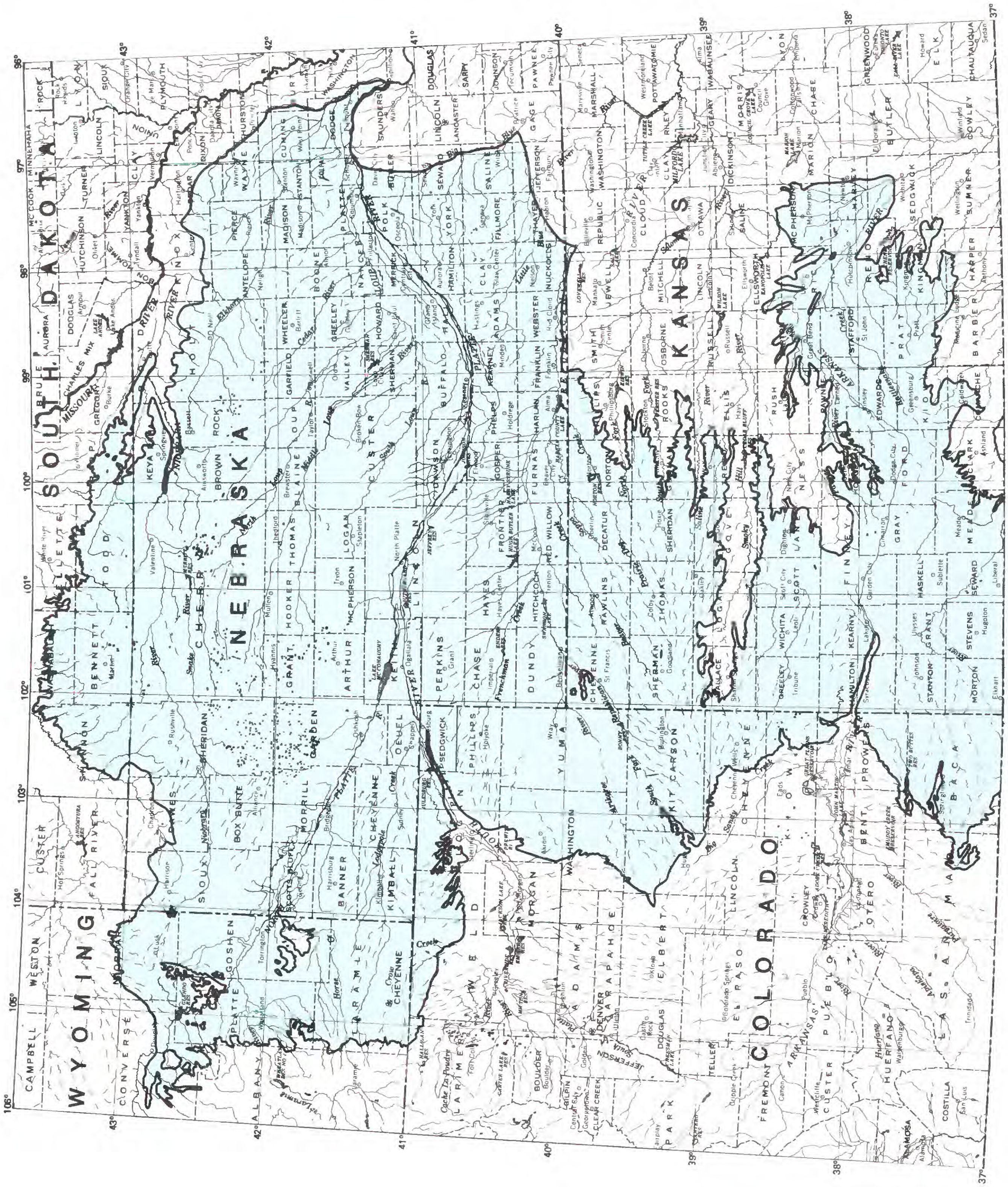
In the central High Plains, simulated pumpage from 1980 to 2020 would be 158 million acre-feet for the baseline strategy, 178 million acre-feet for management strategy 1, and 138 million acre-feet for management strategy 2. For the baseline strategy, water levels in the central High Plains are projected to decline more than 100 feet from 1980 to 2020 in about 3,000 square miles. Although more than 400 feet of saturated thickness are projected to remain in a few small areas, the average saturated thickness would be about 100 feet by 2020. Probable well yields in the central High Plains would decrease by more than 25 percent from 1980 to 2020 in 22,750 square miles (47 percent of the area), but would be more than 750 gallons per minute in 32 percent of the area. For management strategy 1, water-use per acre would decrease, but irrigated acreage would increase, so total water use would increase and water-level declines would be larger. For management strategy 2, water-level declines in excess of 100 feet from 1980 to 2020 are projected in about 1,700 square miles.

In the northern High Plains, simulated pumpage from 1980 to 2020 would be 357 million acre-feet for the baseline strategy, 360 million acre-feet for management strategy 1, and 271 million acre-feet for management strategy 2. For the baseline strategy, water levels in the northern High Plains are projected to decline more than 100 feet from 1980 to 2020 in about 10,000 square miles. Probable well yields are projected to decrease by more than 75 percent from 1980 to 2020 in parts of the northern High Plains. However, probable well yields in excess of 750 gallons per minute are projected for 58 percent of the area by 2020. For management strategy 1, water-level declines would be virtually identical to those for the baseline strategy. For management strategy 2, water-level declines in excess of 100 feet from 1980 to 2020 are projected in about 5,400 square miles. For all strategies, more than 800 feet of saturated thickness are projected to remain in part of central Nebraska by 2020.

INTRODUCTION

The U.S. Geological Survey began a study of the High Plains regional aquifer in 1978 (Weeks, 1978) as part of its program of regional aquifer-system analysis (Sun, 1986). Major objectives of the High Plains study were to (1) provide hydrologic information needed to evaluate the effects of continued ground-water development; (2) design and develop computer models to simulate the aquifer system; and (3) evaluate aquifer response to future ground-water development. The first objective was met with the publication of the geohydrologic description of the High Plains aquifer (Gutentag and others, 1984). The second objective was met with the publication of the description of the ground-water simulation models (Luckey and others, 1986). This report discusses the effects of future ground-water development.

The High Plains aquifer underlies about 174,000 mi^2 of the central United States east of the Rocky Mountains in the southern part of the Great Plains. Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming are underlain by the High Plains aquifer (fig. 1). The High Plains aquifer is the shallowest and most abundant source of ground water in the region. The economy of the area depends in large part on irrigated agriculture; the economic growth of this region would not have occurred to the extent that it has without the High Plains aquifer.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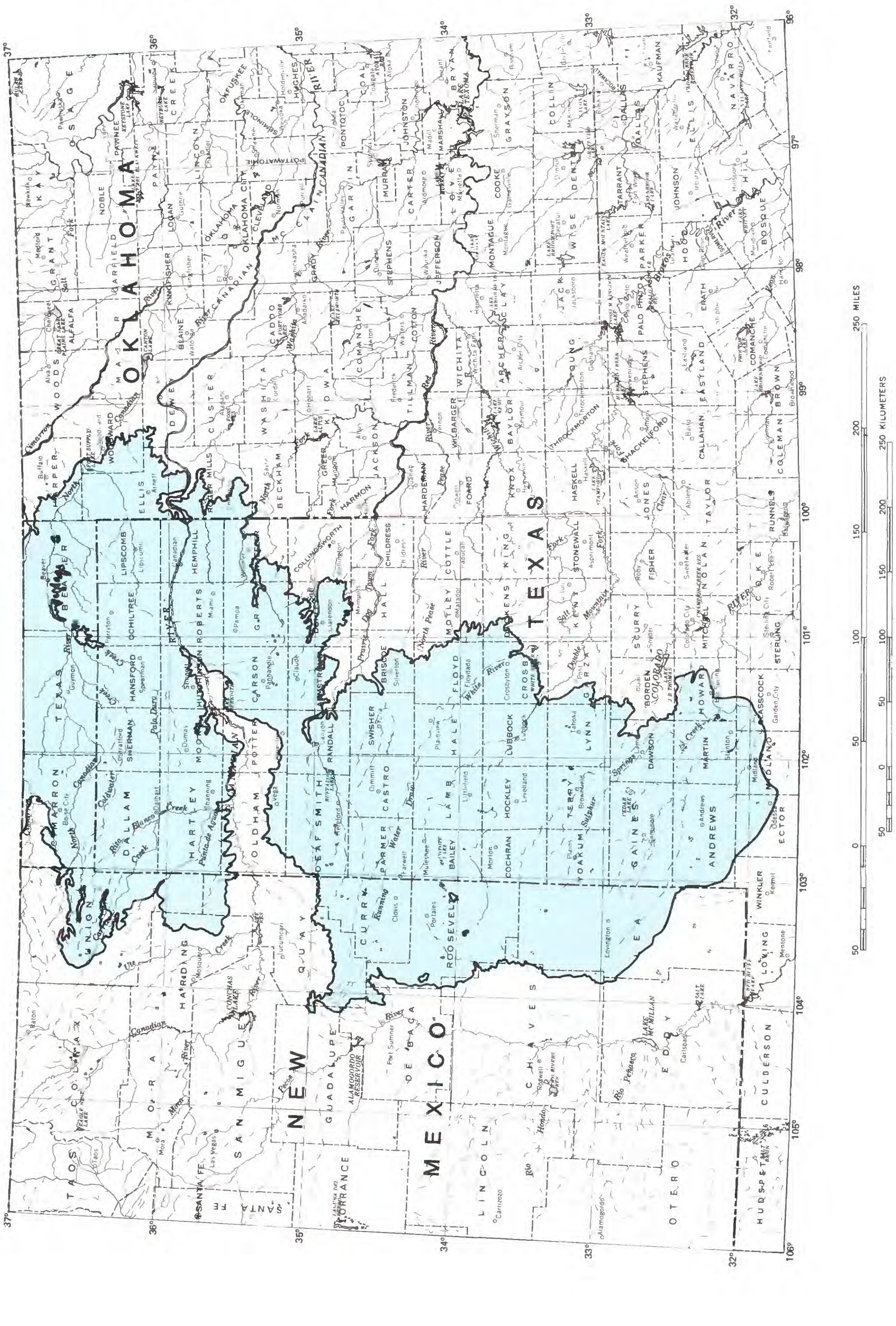

FIGURE 1.—Location of High Plains aquifer.

More than 20 percent of the irrigated land in the United States overlies the High Plains aquifer. About 30 percent of all ground water used in the Nation during 1980 was pumped from the High Plains aquifer. Throughout much of the High Plains, the rate of ground-water withdrawal greatly exceeds the rate of natural replenishment, and this results in water-level declines. Consequently, many irrigators have experienced increased pumping costs and decreased well yields and are understandably concerned about the future of irrigated farming on the High Plains. This report describes future water-level declines and the effects of declining water levels on well yields as a result of future ground-water development.

PURPOSE AND SCOPE

The general purpose of the High Plains Regional Aquifer-System Analysis was to provide the hydrologic information and understanding of the aquifer system which were needed for effective management of the ground-water resource of the High Plains. The aquifer system was analyzed by computer-based models which are discussed in a report by Luckey and others (1986). The models also were used to evaluate the ground-water development strategies. The purpose of this report is to describe the effects of three different future pumping strategies on the High Plains aquifer.

HIGH PLAINS AQUIFER

The High Plains aquifer consists mainly of hydraulically connected geologic units of late Tertiary and Quaternary age. The Ogallala Formation of Tertiary age underlies 134,000 mi^2 of the 174,000-mi^2 High Plains and is the principal geologic unit of the High Plains aquifer. Other older Tertiary units include part of the Brule Formation and the Arikaree Group (or Formation). Quaternary deposits included in the aquifer are alluvium, dune-sand, and valley-fill deposits (Gutentag and others, 1984, p. 8–13).

Water levels in the High Plains aquifer range from just below land surface to almost 400 ft below land surface. The saturated thickness ranges from almost zero to about 1,000 ft. Hydraulic conductivity ranges from about 25 to 300 ft/d and averages 60 ft/d. Specific yield ranges from about 10 to 30 percent and averages 15 percent. Ground water discharges naturally to streams and springs and directly to the atmosphere by evapotranspiration where the water table is near land surface. Precipitation is the principal source of recharge to the High Plains aquifer. Recharge rates estimated with the calibrated model ranged from 0.056 to 1.52 in./yr (Luckey and others, 1986, p. 52–53). Typically, recharge estimates are greatest for areas with sandy soils. During 1980, the High Plains aquifer contained about 3.25 billion acre-ft of drainable water (Gutentag and others, 1984, p. 34). About 66 percent of the water in storage was in Nebraska, 12 percent was in Texas, and about 10 percent was in Kansas.

About 95 percent of all water pumped from the High Plains aquifer is used for irrigation. During 1980, more than 170,000 irrigation wells pumped an estimated 18 million acre-ft of water from the High Plains aquifer to irrigate 13 million acres (Heimes and Luckey, 1983, p. 34).

Large water-level declines have occurred in some areas of the aquifer. Water levels have declined more than 100 ft from predevelopment to 1980 in areas totaling 2,500 mi^2 in parts of Kansas, New Mexico, Oklahoma, and Texas (Luckey and others, 1981). Water levels declined more than 50 ft in areas totaling 12,000 mi^2 in the same four states and more than 10 ft in areas totaling 50,000 mi^2 in Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Texas. By 1980, the volume of water in storage in the aquifer had decreased about 166 million acre-ft since ground-water development began (Gutentag and others, 1984, table 11). Most of the depletion of water in storage had occurred in Texas and Kansas; about 114 million acre-ft had been depleted in Texas, and 29 million acre-ft had been depleted in Kansas.

Water-level declines increase pumping lift, decrease well yields, increase the cost of water, and generally limit development of the ground-water resource. Although well yields of more than 750 gal/min generally can be obtained throughout large areas of the High Plains (Gutentag and others, 1984, fig. 24), only wells yielding less than 250 gal/min can be constructed where the saturated thickness is thin near the edge of the aquifer or where water-level declines have greatly decreased the saturated thickness.

GROUND-WATER FLOW MODELS

The High Plains was divided into three parts, as shown in figure 2, for modeling purpose. The southern High Plains is that part of the High Plains in Texas and New Mexico south and west of about lat 35° N., long 102° W. The central High Plains includes the area north and east of about lat 35° N., long 102° W. and south of about lat 39° N. The northern High Plains includes all of the High Plains north of about lat 39° N.

A narrow strip of aquifer, about 12 mi wide, joins the southern and central High Plains in the vicinity of

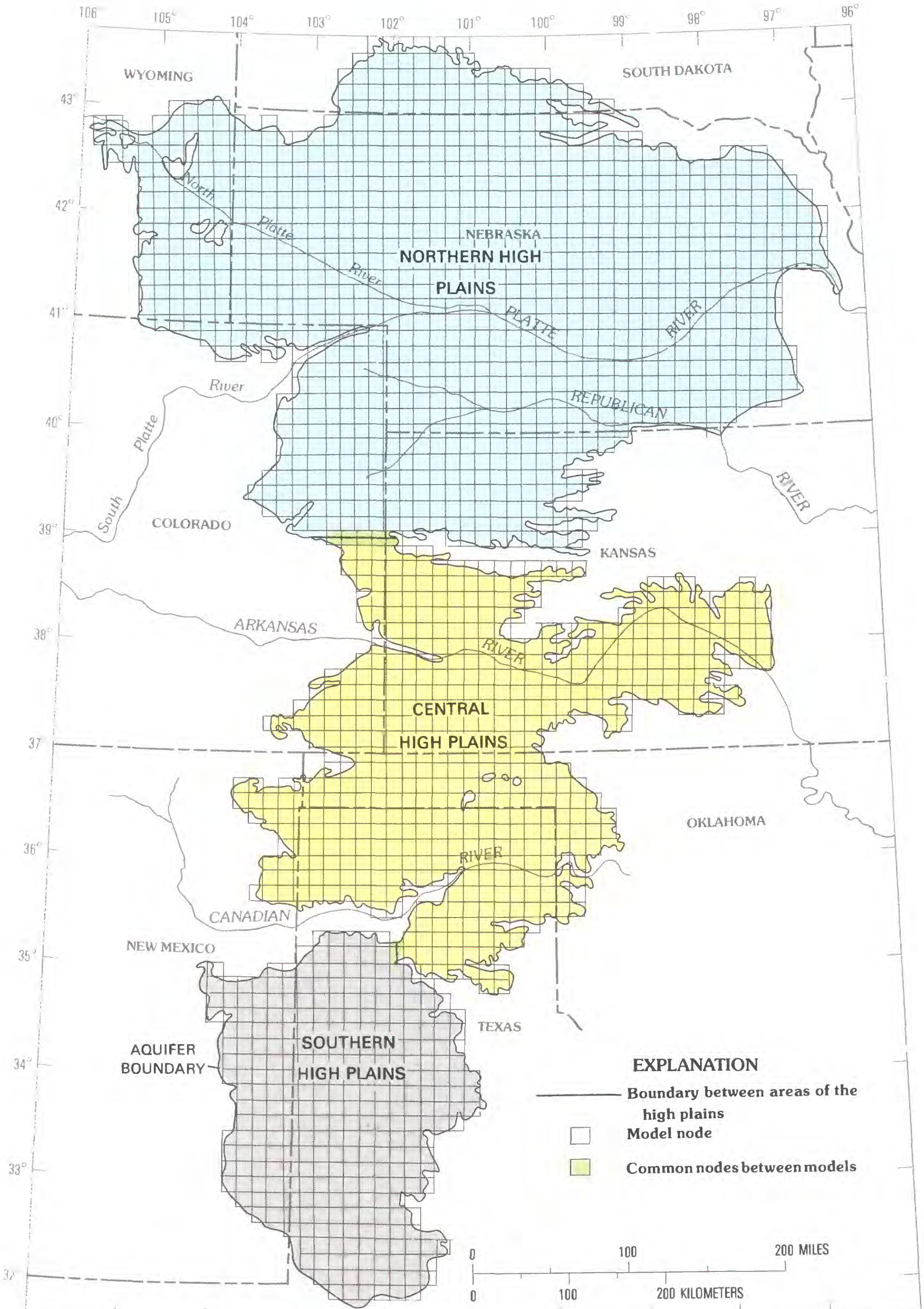

FIGURE 2.—Division of the High Plains and grids for the models.

Amarillo, Tex. (fig. 1). The strip of aquifer joining the central and northern High Plains is about 32 mi wide and follows a bedrock high and a thin saturated section of the aquifer. There probably is very little exchange of water between the southern and central High Plains or between the central and northern High Plains. Because of the narrowness of the strips joining the three separate parts of the High Plains aquifer, construction of separate ground-water flow models for each part of the High Plains probably did not create significant errors.

The history of ground-water development in the High Plains was divided into two periods, the period prior to large-scale development of irrigation (predevelopment period) and the period after the beginning of significant development of irrigation (development period). Irrigation development began prior to 1940 in Texas and by 1978 had spread throughout much of the High Plains (fig. 3). By 1978, more than one-half of the land was irrigated in large parts of the southern High Plains and in smaller parts of the central and northern High Plains. The development period was further subdivided as needed.

The ground-water flow model used during this study solves the ground-water flow equation in two dimensions at a regular network of nodes that are spaced 10 mi apart in both the north-south and east-west directions (fig. 2). The computer code that solves the flow equations was described by Trescott and others (1976). Basically, the flow model integrates information on aquifer geometry, boundary conditions, aquifer parameters, and stresses with initial conditions to calculate a resulting water-level configuration, base flow to streams, flow across aquifer boundaries, and change of water in storage. Before the models were used to evaluate future hydrologic conditions due to pumping, they were calibrated to the degree that the models could adequately simulate historical hydrologic conditions. The model calibration was described in detail by Luckey and others (1986), and only a brief summary of the calibration is given here.

MODEL CALIBRATION

The models of each of the three parts of the High Plains aquifer were calibrated individually. Simulations were made for each part of the system prior to large-scale irrigation development (predevelopment period) and during large-scale irrigation development (development period).

The model of the 29,000-mi^2 southern High Plains aquifer had 303 active nodes (fig. 2). The predevelopment-period (prior to 1940) model was used to estimate the predevelopment recharge rate over the area and to refine estimates of aquifer parameters. The estimated predevelopment recharge rate ranged from 0.086 to 1.03 in./yr and averaged 0.13 in./yr. The simulated predevelopment water level was compared to the historical predevelopment water level, and the average difference between the two potentiometric surfaces was +0.22 ft. The simulated predevelopment water levels became the initial water level for the first development-period (1940–60) model. During this simulation, return flow from irrigation was varied until the model adequately simulated the 1960 water level. Once the simulated 1960 water level adequately represented the measured 1960 water level, the model was used to simulate the second development period (1960–80). Again return flow from irrigation was varied during calibration. For both periods, calibration was achieved when return flow was adjusted such that net withdrawal (total pumpage minus return flow) was equal to 90 percent of the estimated irrigation requirement (Heimes and Luckey, 1982). During the second development period (1960–80), 2 in. of additional recharge were added to all agricultural land as described by Luckey and others (1986, p. 18). The simulated change in storage for 1940 to 1980 was 7 percent less than the actual change in storage for the same period (Luckey and others, 1986, p. 54).

The model of the 48,500-mi^2 central High Plains aquifer had 513 active nodes (fig. 2). There was one common node between the southern and central High Plains models. The predevelopment-period (prior to 1950) model was used to estimate the predevelopment recharge rate and to refine estimates of aquifer parameters. The estimated predevelopment recharge rate ranged from 0.056 to 0.84 in./yr, averaged 0.13 in./yr, and was distributed according to soil type. When the model was calibrated, the mean difference between the simulated and historical predevelopment water levels was −0.28 ft. The simulated predevelopment water level was used as the initial water level for a single development period (1950–80). During the development-period calibration, return flow was adjusted to obtain the best correlation between the simulated and measured 1950–80 water-level changes. Calibration was obtained when return flow was adjusted such that net pumpage equaled 100 percent of the estimated irrigation requirement. The simulated change in storage was 9 percent less than the actual change in storage (Luckey and others, 1986, p. 31).

The model of the 96,500-mi^2 northern High Plains aquifer had 943 active nodes (fig. 2). There were five common nodes between the central and northern High Plains models. The predevelopment-period (prior to 1960) model of the northern High Plains was used to

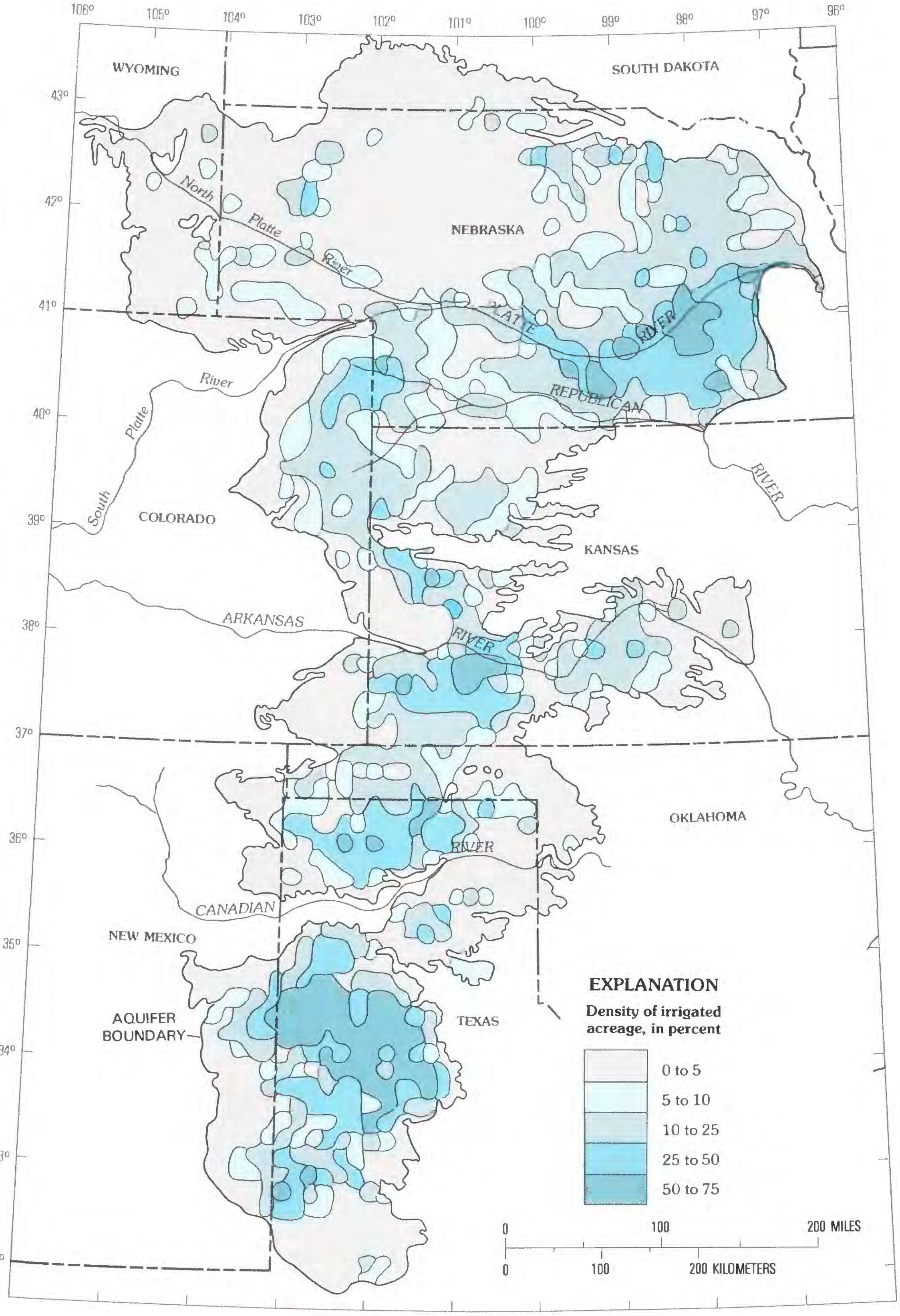

FIGURE 3.—Density of acreage irrigated by ground water in the High Plains, 1978.

estimate predevelopment recharge from precipitation and to refine estimates of aquifer parameters. The estimated predevelopment recharge ranged from 0.076 to 1.52 in./yr, averaged 0.46 in./yr, and was distributed according to soil type. An analysis of the flow of streams originating in the sandhills of central Nebraska indicated that recharge in the sandhills probably is greater than the estimated 1.52 in./yr. When the model was calibrated, the mean difference between the simulated and historical predevelopment water levels was +0.30 ft and the simulated base flow was 61 percent of the historical base flow. The simulated predevelopment water level was used as the initial water level for a development-period calibration. In the development-period (1960–80) calibration, return flow from irrigation was adjusted and the best correlation between simulated and measured water-level changes from 1960 to 1980 was achieved when net withdrawal equaled 100 percent of the estimated irrigation requirement. In the northern High Plains, there was substantial recharge due to agricultural practices and leakage from canals and surface-water reservoirs. This additional recharge and return flow from irrigation in large part counterbalanced the pumpage. Hence, although large pumping and recharge stresses have occurred in some areas, the net overall change in storage from predevelopment to 1980 was small. The simulated change in storage was 15 million acre-ft, and the actual change in storage was 6 million acre-ft. This difference of 9 million acre-ft is less than 10 percent of the total pumpage from 1960 to 1980.

GROUND-WATER MANAGEMENT STRATEGIES

After the models of each area of the High Plains were calibrated and the 1980 water levels were computed, the models were used to project water levels and water-level changes from 1980 to 2020. The simulation of future water levels required estimates of future rates of withdrawal of water. A concurrent study done for the U.S. Department of Commerce, Economic Development Administration, projected pumpage throughout much of the High Plains aquifer for 1977, 1985, 1990, 2000, and 2020 (High Plains Associates, 1982; High Plains Study Council, 1982). The study evaluated several different water-resource management strategies in parts or all of a six-State area. The pumpage estimates for three of these strategies were used to project future water levels in the High Plains.

The three ground-water management strategies defined by High Plains Associates (1982, p. 7) that were used to project water levels are:

1. "A 'Baseline' trend projection of currently available water conservation and use technology and practices already in use to some extent, with no new purposeful public policy to intervene with action programs for altering the course of irrigation water consumption. (the Baseline);"
2. "A strategy which would stimulate voluntary action to reduce water demands through research, education, demonstration programs and incentives, using technology and practices either not considered in the Baseline analysis or reflected at rates which would be purposefully accelerated. (Management Strategy One);" and
3. "A strategy which assumes Strategy One policies and programs, and in addition projects further water demand reduction by mandatory programs of a regulatory nature to control water use. (Management Strategy Two)."

The baseline strategy assumes a continuation of current government policies and economic trends with no new State or Federal programs undertaken that have not already been implemented or authorized. Management strategy 1 assumes faster adoption of new techniques to conserve water and voluntary measures to decrease irrigation water use. Management strategy 1 decreases per-acre water use, but in some areas the strategy may result in increased irrigated acreage and, hence, increased pumpage. Management strategy 2 is based on the assumption that, in addition to all the voluntary water conservation measures assumed under management strategy 1, mandatory water conservation measures would be imposed by governmental agencies. For management strategy 2, water application rates for 1985, 1990, 2000, and 2020 were assumed to be decreased to 90, 80, 70, and 70 percent of those projected for management strategy 1, respectively. For management strategy 2, the irrigated acreage is assumed to be equal to the irrigated acreage for management strategy 1.

In addition to the regional reports by High Plains Associates (1982) and High Plains Study Council (1982), other reports resulting from the Economic Development Administration study were published for each of the six States involved. The Colorado part of the study was summarized by the Colorado Department of Agriculture (1983) with more detail given by Burns (1982), McBroom (1982), McKean (1982), and Young and others (1982). The results of the Kansas part of the study were reported by Buller (1982), Emerson and others (1982), and Wagner and others (1982). The Nebraska Natural Resources Commission (1981) summarized that State's part of the study. The New Mexico part of the study was summarized by Lansford and others (1982f) with details given by Lansford and others (1982a, b, c, d, e). The results of the Oklahoma part of the study were given by Warren and others (1981). The results of the

Texas part of the study were given by Grubb (1984). Supalla (1982) summarized the methodology of the Economic Development Administration study while Warren and others (1981) determined that the irrigated-acreage projections and, hence, pumpage projections are very sensitive to the assumed real commodity prices.

PROJECTED WATER LEVELS AND SATURATED THICKNESS

SOUTHERN HIGH PLAINS

The southern High Plains is an area of 29,000 mi^2 in Texas and New Mexico south and west of about lat 35° N., long 102° W. The southern High Plains constitutes 17 percent of the total area of the High Plains. About one-half of the water pumped from the High Plains aquifer prior to 1980 was from the southern High Plains.

Pumpage projections were available for the eight regions in the southern High Plains shown in figure 4. Four of the regions are in Texas, and four are in New Mexico. The regions in Texas correspond to the subregions defined by High Plains Associates (1982, fig. II-1), and the regions in New Mexico correspond to counties. Region I is part of Subregion 2 of Texas (High Plains Associates, 1982) which includes part of the central High Plains. Pumpage projections for this region were divided by assigning 90 percent of the pumpage to the southern High Plains and 10 percent to the central High Plains. Pumpage projections for the regions in Texas were available on an annual basis from 1980 through 2020 (H.W. Grubb, Texas Department of Water Resources, written commun., August 1983). Pumpage estimates for the regions in New Mexico were available for 1977, 1985, 1990, 2000, and 2020 (Lansford and others, 1982a, table 1; 1982b, table 2; 1982c, table 1; 1982d, table 1; 1982e, table 2). Pumpage projections for individual years from 1980 to 2020 were made for regions V-VIII by linear interpolation between the years for which pumpage estimates were available.

The pumpage had to be distributed to the model nodes, which are considerably smaller than the regions. The projected pumpage was distributed throughout the area that was irrigated during 1980, as mapped by digital analysis of Landsat imagery (Thelin and Heimes, in press). During simulation, the pumpage for each region was distributed according to the 1980 irrigated area in the region until the average saturated thickness at a model node decreased to less than 5 ft. If saturated thickness was less than 5 ft at the beginning of a 5-year simulation period, irrigated acreage in the node was assumed to be zero, pumpage at that node ceased, and the projected pumpage was redistributed to the remaining irrigated acreage in the region. If saturated thickness for the node decreased to less than 2 ft during a 5-year simulation period, pumpage was immediately curtailed at that node and the pumpage was not redistributed to other nodes until the beginning of the next 5-year simulation period. This procedure for distributing pumpage to model nodes also was used for the central model and part of the northern model.

The simulated pumpage for the southern High Plains is given in table 1. For the baseline strategy, total pumpage would be about 113 million acre-ft for the 40 years. The pumpage would range from almost 4.9 million acre-ft/yr for 1980–84 to less than 2.0 million acre-ft/yr for 2015–19. For management strategy 1, pumpage would be about 109 million acre-ft for the 40 years. The pumpage would range from 4.6 million acre-ft/yr for 1980–84 to less than 2.0 million acre-ft/yr for 2015-19. For management strategy 2, pumpage would be about 88 million acre-ft for the 40 years. The pumpage would range from almost 4.6 million acre-ft/yr for 1980–84 to slightly more than 1.4 million acre-ft/yr for 2015–19. For management strategy 2, simulated pumpage by 2020 would be less than one-third of the 1980 pumpage. For all three strategies the pumpage in Region I would be about one-half of the total pumpage.

The simulated pumpage for the southern High Plains is summarized in figure 5. During the first two 5-year simulation periods, pumpage for management strategy 1 would be significantly smaller than pumpage for the baseline strategy, but after 1990, pumpage for management strategy 1 and the baseline strategy would be practically identical. Pumpage for management strategy 2 would be smaller than pumpage for both the baseline strategy and management strategy 1, particularly after 1985. By the last 5-year simulation period (2015–19), pumpage for management strategy 2 would be only 73 percent of pumpage for the baseline strategy or management strategy 1. The total volume that would be pumped for management strategy 1 would be 4 percent less than that for the baseline strategy, whereas the total volume that would be pumped for management strategy 2 would be 22 percent less than that for the baseline strategy.

During model calibration, return flow was assumed to be a function of water applied in excess of the irrigation requirement (Luckey and others, 1986, p. 9). However, pumpage for most of the 1980 to 2020 projection would be less than the estimated irrigation requirement (Heimes and Luckey, 1982). Also, for those States that considered return flow in the Economic Development Administration study, the return flow would be small compared to the pumpage. Therefore, return flow was assumed to be negligible and was not simulated during the projection period in the southern, central, and northern High Plains models.

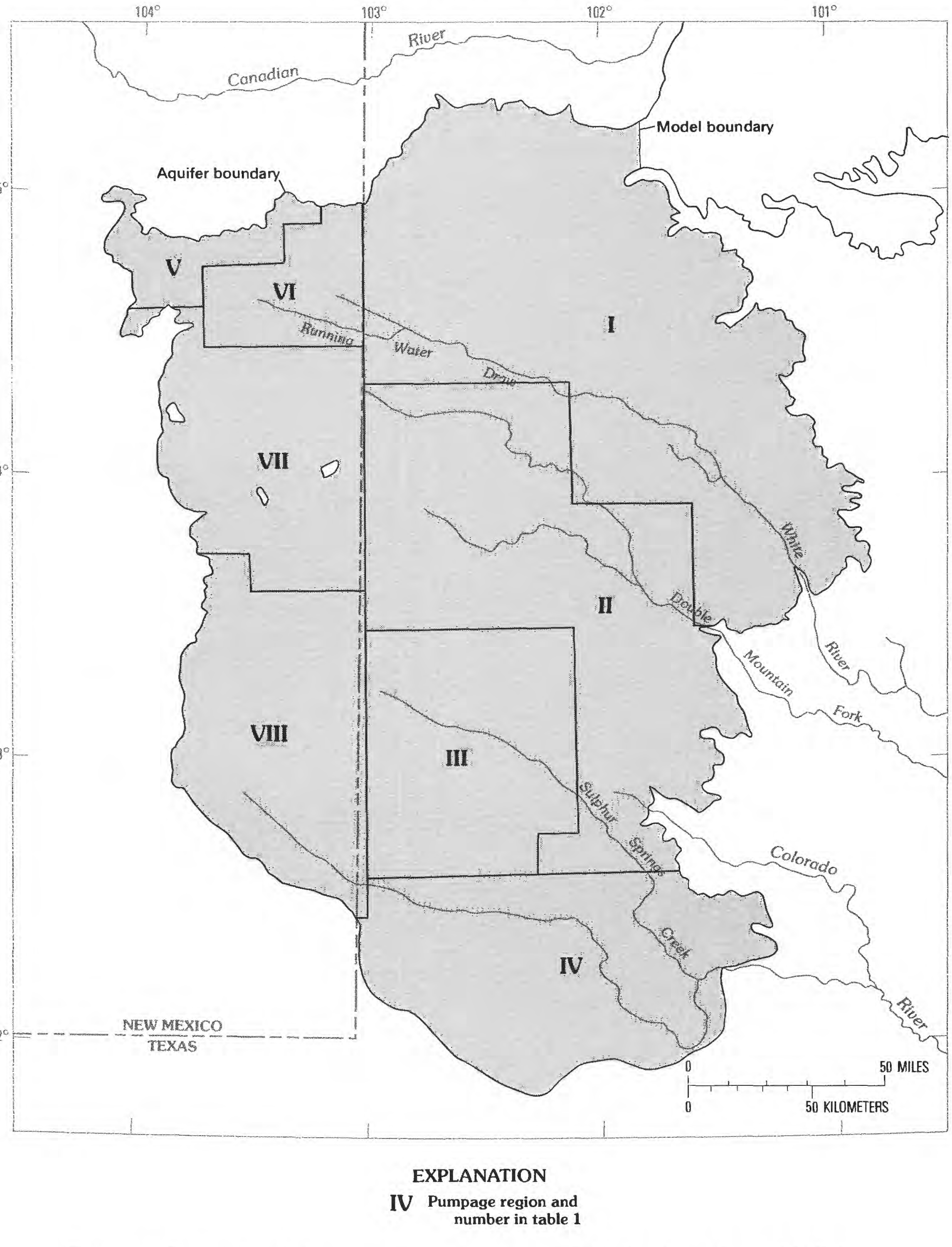

FIGURE 4.—Regions for which pumpage projections were available for the southern High Plains.

BASELINE STRATEGY

The projected water-level changes from 1980 to 2020 that would result from baseline-strategy pumpage are shown in figure 6. Much of the southern High Plains would have water-level declines in excess of 10 ft for this strategy and declines are projected to exceed 150 ft in two areas. The size of the larger area is about 700 mi². The maximum 1980 to 2020 water-level decline would be about 180 ft over one model node

TABLE 1.—*Simulated pumpage, 1980 to 2020, by strategy and region for the southern High Plains*

Region	Simulated pumpage, in thousands of acre-feet per year, for the indicated period							
	1980–1984	1985–1989	1990–1994	1995–1999	2000–2004	2005–2009	2010–2014	2015–2019
Baseline strategy								
I..........	2,610	1,710	1,290	1,210	1,160	1,120	1,080	1,030
II.........	984	685	508	469	432	397	363	331
III........	473	345	270	260	252	242	234	226
IV.........	40	32	27	27	27	28	32	42
V..........	12	11	10	12	11	8	5	2
VI.........	312	282	211	147	97	70	38	16
VII........	221	217	209	207	189	152	106	76
VIII.......	236	253	267	270	268	258	246	239
Total....	4,888	3,535	2,792	2,602	2,436	2,275	2,104	1,962
Management strategy 1								
I..........	2,558	1,574	1,389	1,285	1,221	1,163	1,109	1,057
II.........	870	563	484	443	404	367	332	299
III........	402	276	261	249	238	227	216	205
IV.........	35	26	26	25	25	26	29	41
V..........	12	10	10	11	10	7	4	2
VI.........	310	278	205	139	90	65	35	15
VII........	217	208	197	191	180	160	138	121
VIII.......	230	237	237	232	228	222	217	213
Total....	4,634	3,172	2,809	2,575	2,396	2,237	2,080	1,953
Management strategy 2								
I..........	2,558	1,356	1,084	938	855	814	776	740
II.........	870	486	378	323	283	257	232	209
III........	402	237	203	182	167	160	151	143
IV.........	35	23	20	19	18	18	20	29
V..........	11	9	8	8	8	8	8	8
VI.........	289	238	162	104	70	69	67	66
VII........	203	179	153	139	124	111	95	85
VIII.......	216	203	185	170	159	156	152	149
Total....	4,584	2,731	2,193	1,883	1,684	1,593	1,501	1,429

(100 mi^2). Water levels are projected to decline more than 100 ft in several areas of the southern High Plains that total about 2,900 mi^2. The average projected water-level decline from 1980 to 2020 for the baseline strategy in the southern High Plains would be 32 ft. The median decline would be 13 ft; this means that for the baseline strategy, one-half of the area would have water-level declines in excess of 13 ft. The median is less than the average because the average is influenced more by the larger water-level declines than is the median. The projected water-level declines from 1980 to 2020 would be in addition to the water-level declines of as much as 150 ft that have already occurred in the southern High Plains prior to 1980 (Luckey and others, 1981). The small projected water-level rises near the southern and eastern boundaries probably were due to neglecting small streams in the nodes where ground water discharges.

The total volume of water that would be removed from storage in the southern High Plains during the 40 years is projected to be 101 million acre-ft. The 12-million-acre-ft difference between the volume pumped and the volume removed from storage would be supplied by decreased seepage across the eastern boundary and decreased ground-water discharge to small streams near the eastern boundary.

The projected saturated thickness remaining in the southern High Plains by 2020 is shown in figure 7. The

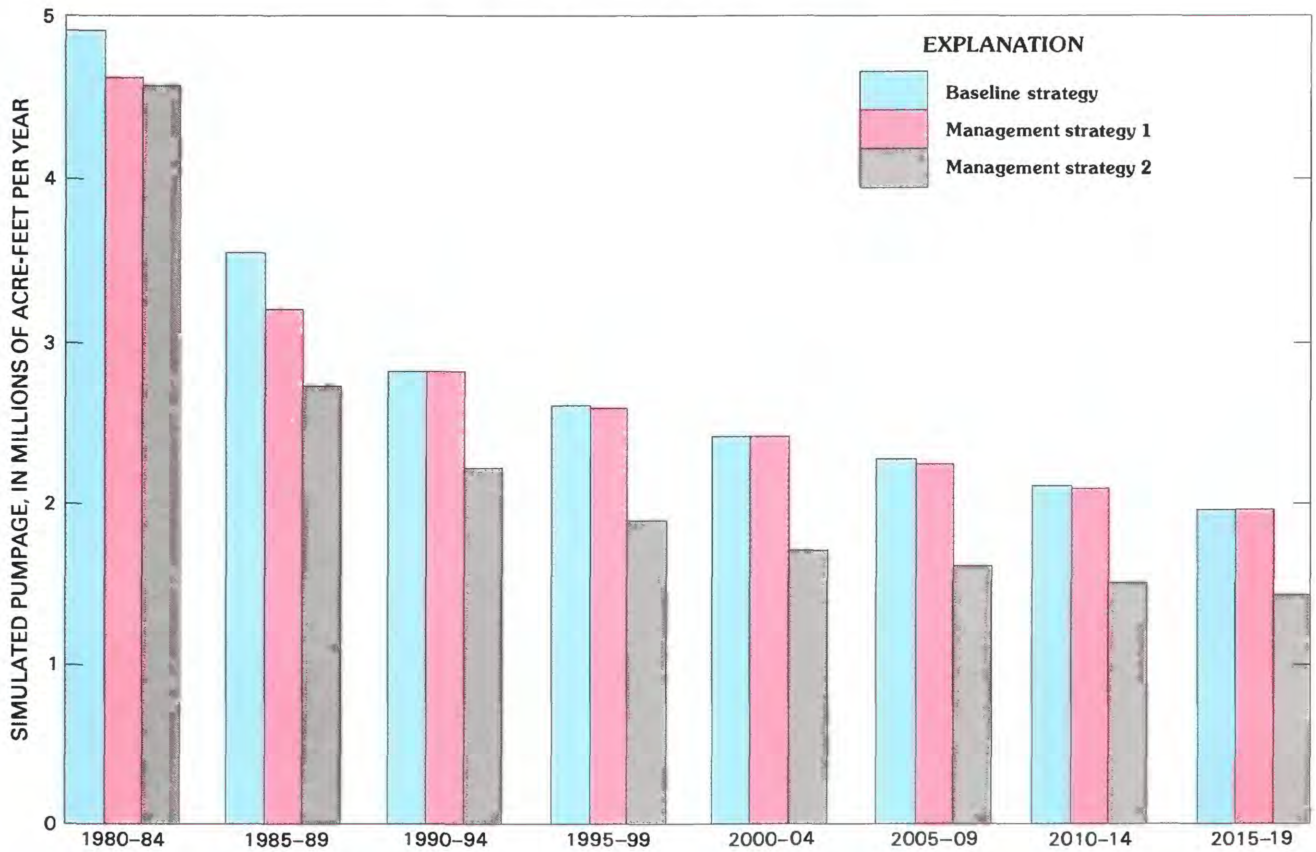

FIGURE 5.—Simulated pumpage for the southern High Plains by management strategy.

saturated thickness would exceed 100 ft in several areas that total 1,500 mi^2. The area in the east-central part of the southern High Plains represents 600 mi^2 of this total. These areas were not extensively irrigated in 1980, and they have about the same saturated thickness projected for 2020 that they had in 1980. Projected saturated thickness for 2020 for the baseline strategy would be less than 25 ft in 54 percent of the southern High Plains and less than 19 ft in 50 percent of the area. Although the average saturated thickness by 2020 in the southern High Plains for the baseline strategy would be 36 ft, figure 7 shows that this would not be distributed uniformly. Under much of the area that was intensely irrigated in 1980, the projected saturated thickness by 2020 would be less than 10 ft. By 2020, drainable water in storage is projected to be slightly more than 100 million acre-ft for the southern High Plains. Most of this water will be concentrated along the eastern, southern, and western edges of the aquifer. The aquifer contained about 200 million acre-ft of drainable water in 1980 and for the baseline strategy would contain about 140 million acre-ft in 2000.

MANAGEMENT STRATEGY 1

The projected water-level changes from 1980 to 2020 resulting from management-strategy-1 pumpage are shown in figure 8. Projected water-level declines would exceed 150 ft in two areas totaling 450 mi^2. The extent of the larger area would be 400 mi^2. By 2020, simulated 1980 to 2020 water-level declines would exceed 100 ft under 2,300 mi^2. The maximum projected water-level decline for 1980 to 2020 would be about 180 ft. Although the most severe declines would be less for management strategy 1 than for the baseline strategy, the extent of significant water-level declines (declines in excess of 10 ft) are similar for management strategy 1 and the baseline strategy. Much of the water that would be saved in the early part of the 1980 to 2020 projection period for management strategy 1 would be pumped later in the period so that total pumpage for management strategy 1 would be only 3 percent less than that for the baseline strategy. The average water-level decline for 1980 to 2020 for management strategy 1 would be 31 ft, and the median decline would be 13 ft. The average water-level decline prior to 1980 for the

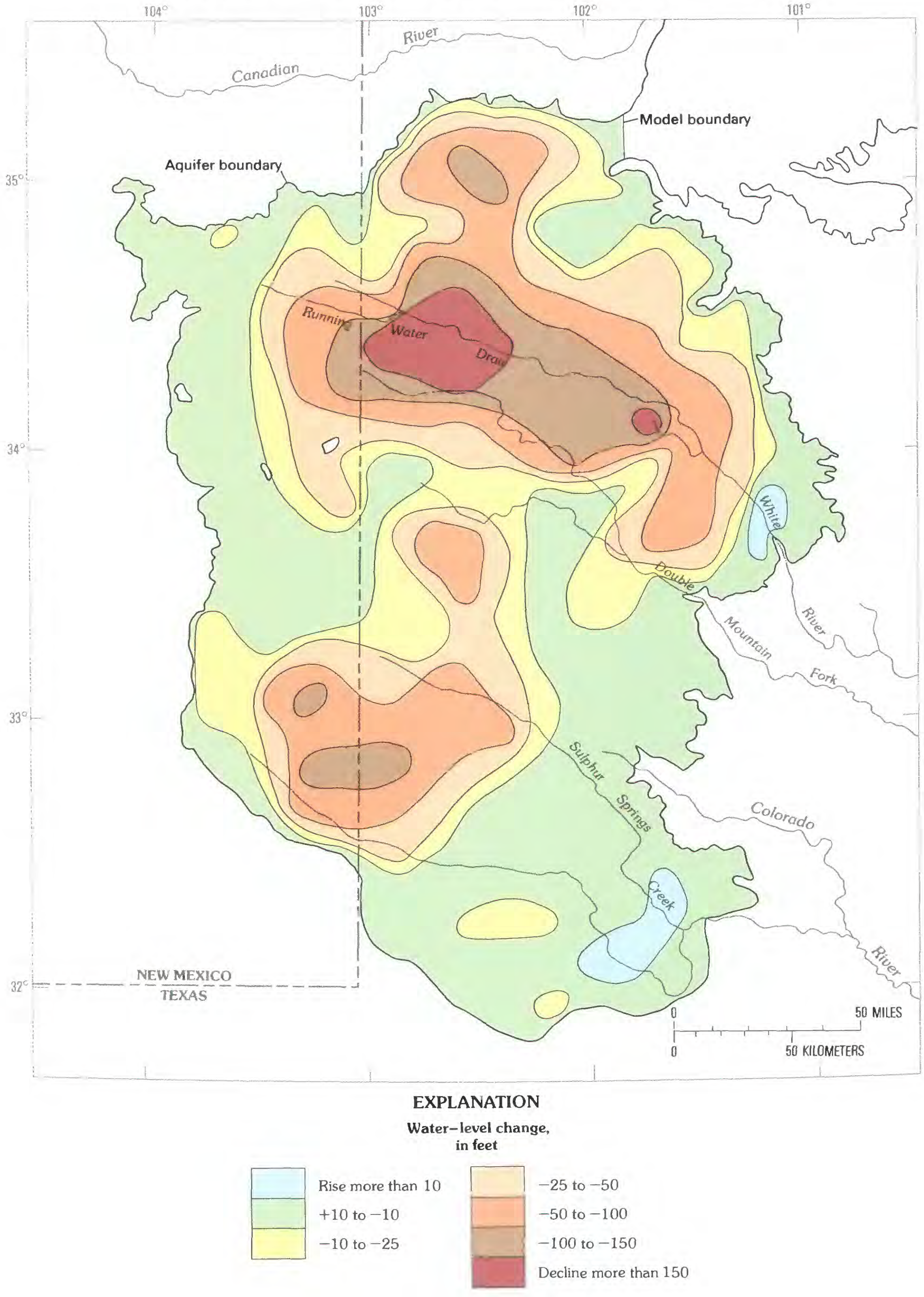

FIGURE 6.—Projected water-level changes, 1980 to 2020, for the southern High Plains resulting from pumpage for the baseline strategy.

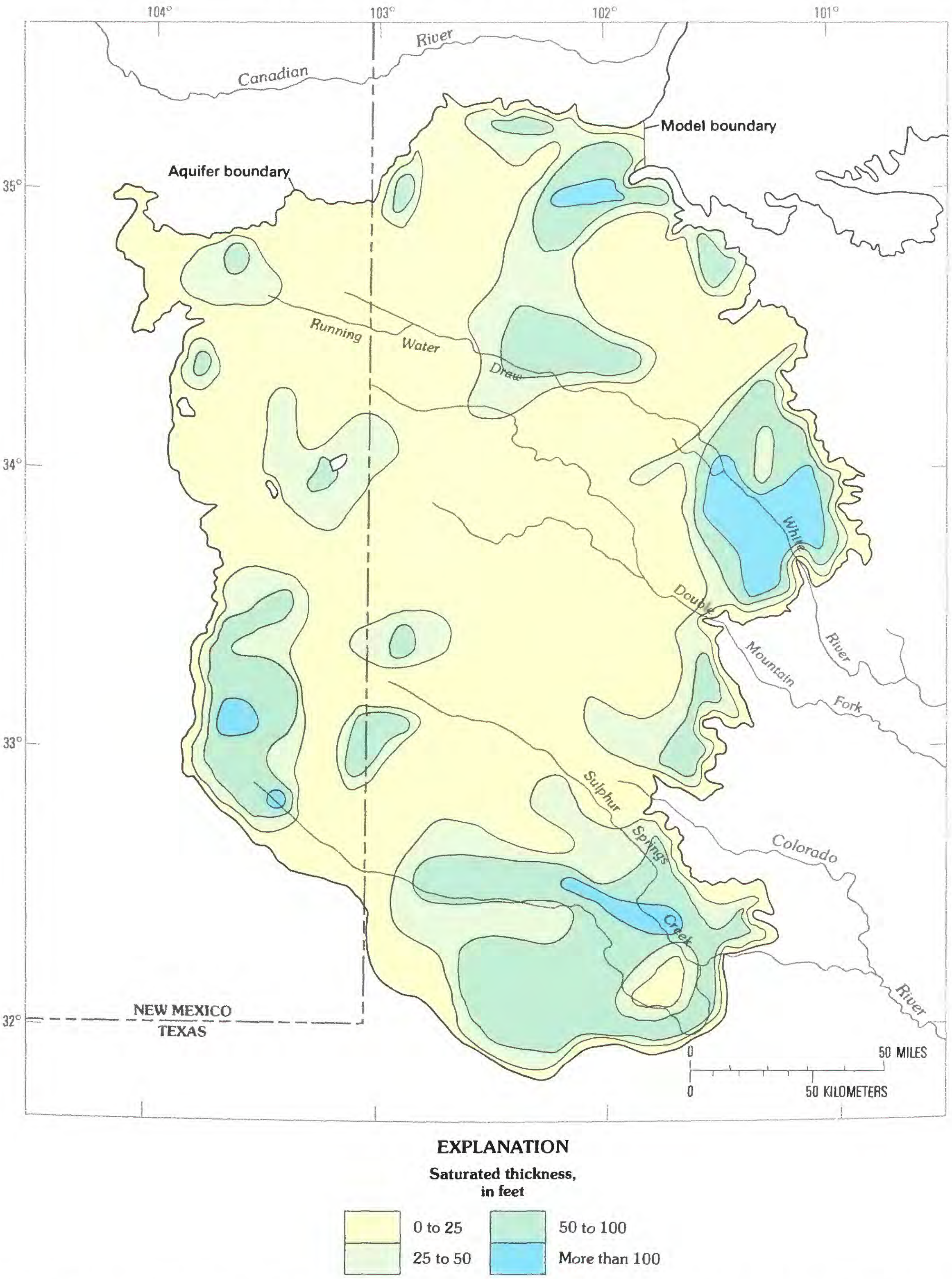

FIGURE 7.—Projected saturated thickness by 2020 in the southern High Plains resulting from pumpage for the baseline strategy.

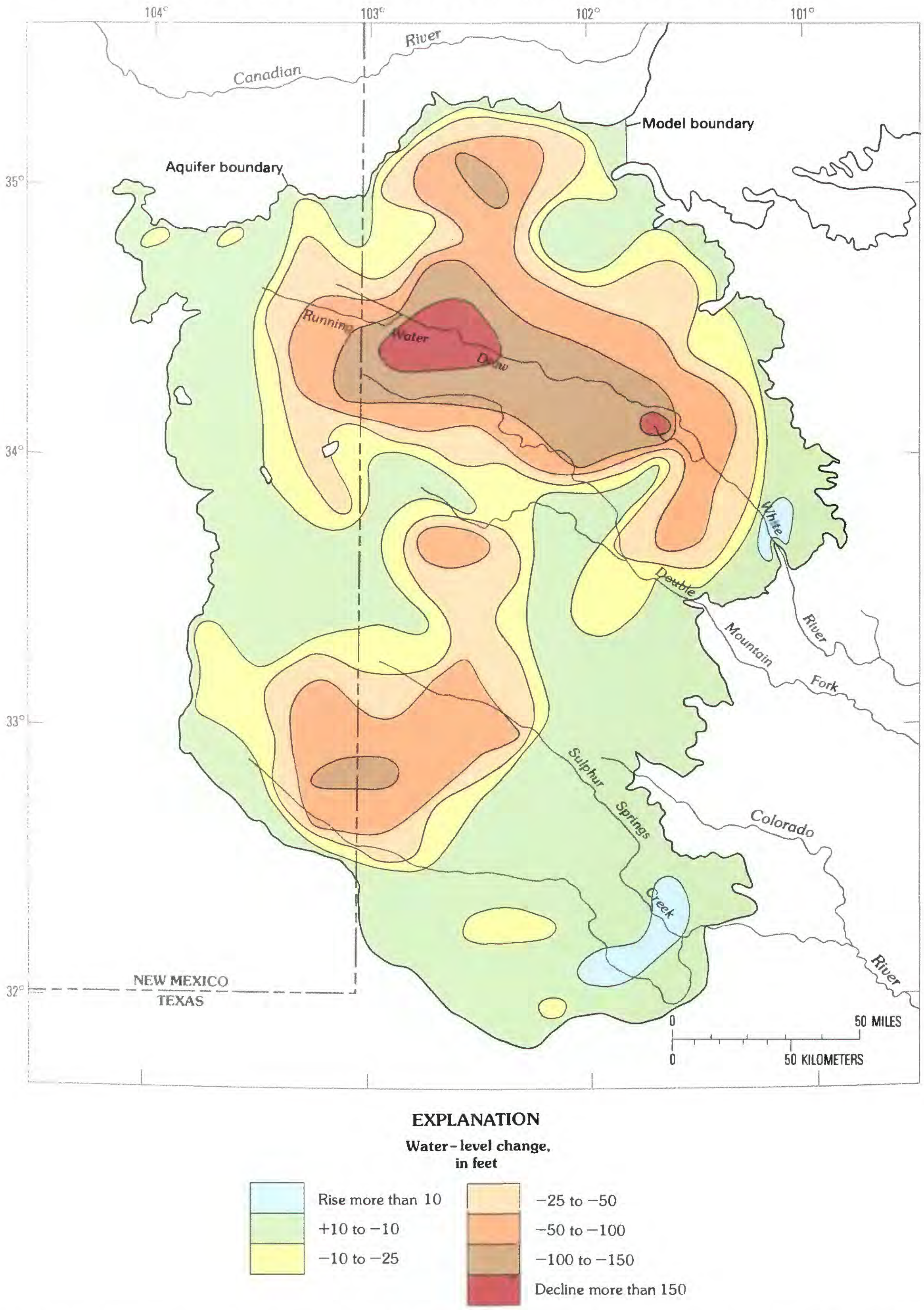

FIGURE 8.—Projected water-level changes, 1980 to 2020, for the southern High Plains resulting from pumpage for management strategy 1.

southern High Plains was about 33 ft (Luckey and others, 1981), and the median decline was 20 ft.

The total volume of water that would be removed from storage in the southern High Plains from 1980 to 2020 for management strategy 1 is projected to be 98 million acre-ft. The average saturated thickness projected for 2000 would be 48 ft and by 2020 it would be 37 ft. For management strategy 1, one-half of the southern High Plains is projected to have less than 20 ft of saturated thickness by 2020. By 2020, less than 105 million acre-ft of drainable water would remain in storage in the southern High Plains.

MANAGEMENT STRATEGY 2

The projected water-level changes from 1980 to 2020 resulting from management-strategy-2 pumpage are shown in figure 9. The large mandatory decrease in water use will have a significant effect on water-level changes. For management strategy 2, there would be only one small area (30 mi^2) where water levels are projected to decline more than 150 ft, and the maximum decline would be only slightly more than 150 ft. The two areas where management-strategy-2 water levels are projected to decline more than 100 ft total about 2,000 mi^2. For management strategy 2, about 47 percent of the area of the southern High Plains is projected to have water-level declines of less than 10 ft. The average projected water-level decline from 1980 to 2020 for this management strategy would be 26 ft.

The total volume of water that would be removed from storage in the southern High Plains from 1980 to 2020 for management strategy 2 is projected to be 80 million acre-ft. The average saturated thickness projected for 2000 would be 51 ft, and by 2020 it would be 42 ft. For management strategy 2, one-half of the area of the southern High Plains would have less than 34 ft of saturated thickness remaining by 2020. By 2020, about 125 million acre-ft of drainable water would remain in storage in the southern High Plains.

COMPARISON OF STRATEGIES

Different volumes of pumpage for the baseline strategy, management strategy 1, and management strategy 2 resulted in different projected water-level changes. Because the pumping pattern is assumed to be similar for all three strategies, the pattern of water-level change would be similar for all strategies although the magnitude of the change would be different. Compared to the baseline strategy, the projected water-level declines would be slightly less for management strategy 1 and would be much less for management strategy 2. Water-level declines are projected to exceed 100 ft under 2,900 mi^2 for the baseline strategy, 2,300 mi^2 for management strategy 1, and 2,000 mi^2 for management strategy 2. The maximum water-level decline would be about 180 ft for both the baseline strategy and management strategy 1 but would be only about 150 ft for management strategy 2. The median decline would be about 13 ft for both the baseline strategy and management strategy 1 and about 10 ft for management strategy 2. The average water-level decline for management strategy 1 would be 1 ft less than that for the baseline strategy, whereas the average water-level decline for management strategy 2 would be 7 ft less than that for the baseline strategy.

The difference in saturated thickness between management strategy 2 and the baseline strategy by 2020 is shown in figure 10. The maximum difference in the saturated thickness by 2020 between management strategy 2 and the baseline strategy would be 63 ft. In two areas, more than 50 ft of saturated thickness could be saved as a result of the mandatory decrease in water use of management strategy 2. These areas compose about 2 percent of the area of the southern High Plains. The difference in saturated thickness would exceed 25 ft in 3,200 mi^2 and 10 ft in about 6,600 mi^2 (23 percent of the southern High Plains). In areas with less than 10 ft difference in saturated thickness, the average difference is only 1.3 ft.

For the baseline strategy, ground-water storage is projected to decrease by 101 million acre-ft from 1980 to 2020. A similar decrease in storage (98 million acre-ft) is projected for management strategy 1. For management strategy 2, ground-water storage is projected to decrease by 80 million acre-ft during the 40 years.

CENTRAL HIGH PLAINS

The central High Plains consists of 48,500 mi^2 in Colorado, Kansas, New Mexico, Oklahoma, and Texas north and east of about lat 35° N., long 102° W. and south of lat 39° N. The central High Plains constitutes about 28 percent of the entire High Plains. About 24 percent of the water pumped from the High Plains aquifer prior to 1980 was from the central High Plains.

The central High Plains was divided into 12 regions (fig. 11) with different pumpage estimates for each region. Note that Region VIII has two separate parts. Projected pumpage was available for selected years (1985, 1990, 2000, and 2020) for all regions except Region IX. Actual pumpage was available for 1980 for all regions. A linear interpolation was made between years for which pumpage was available. Region II is part of Region 2 of Texas as defined by High Plains

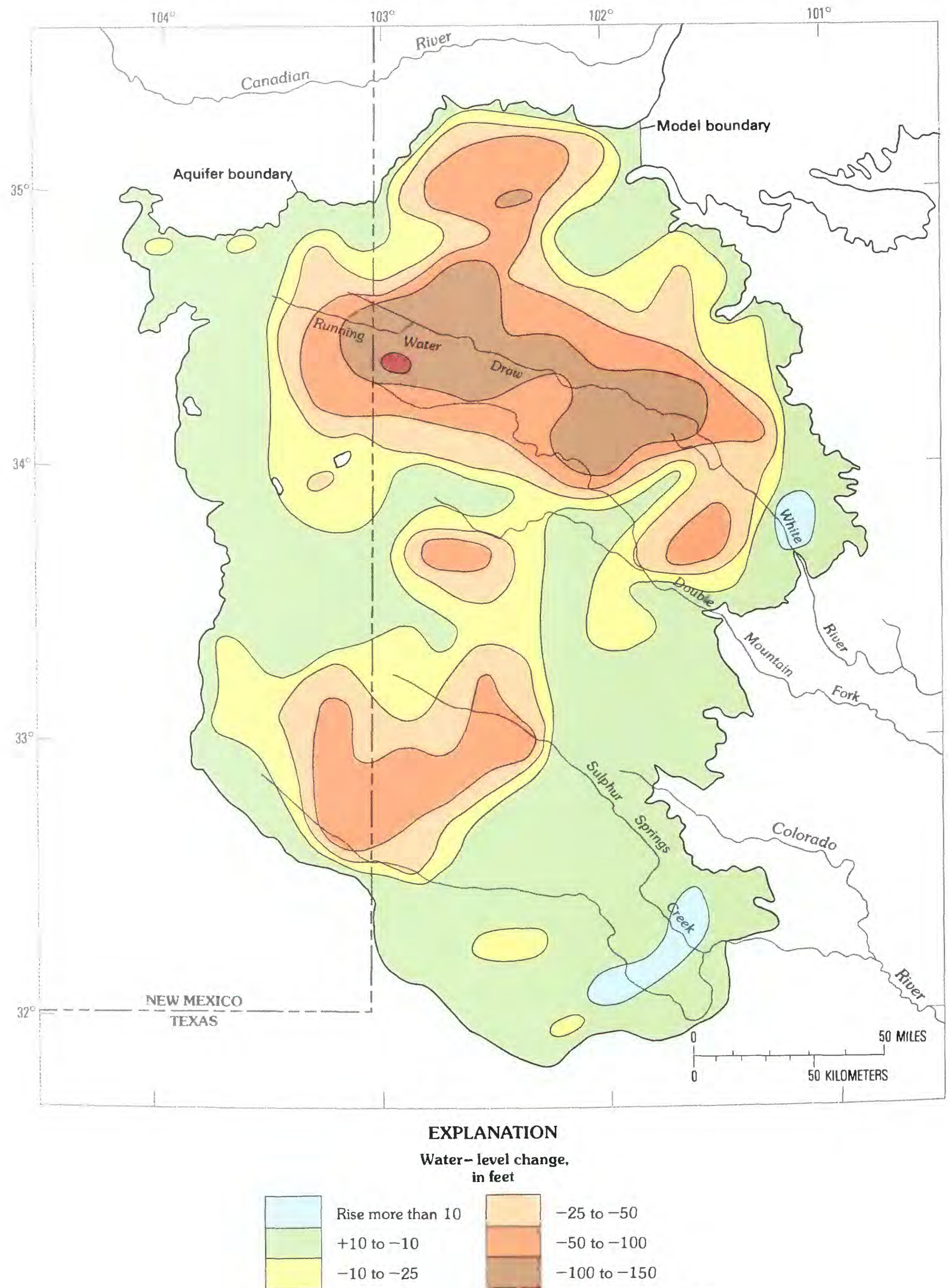

FIGURE 9.—Projected water-level changes, 1980 to 2020, for the southern High Plains resulting from pumpage for management strategy 2.

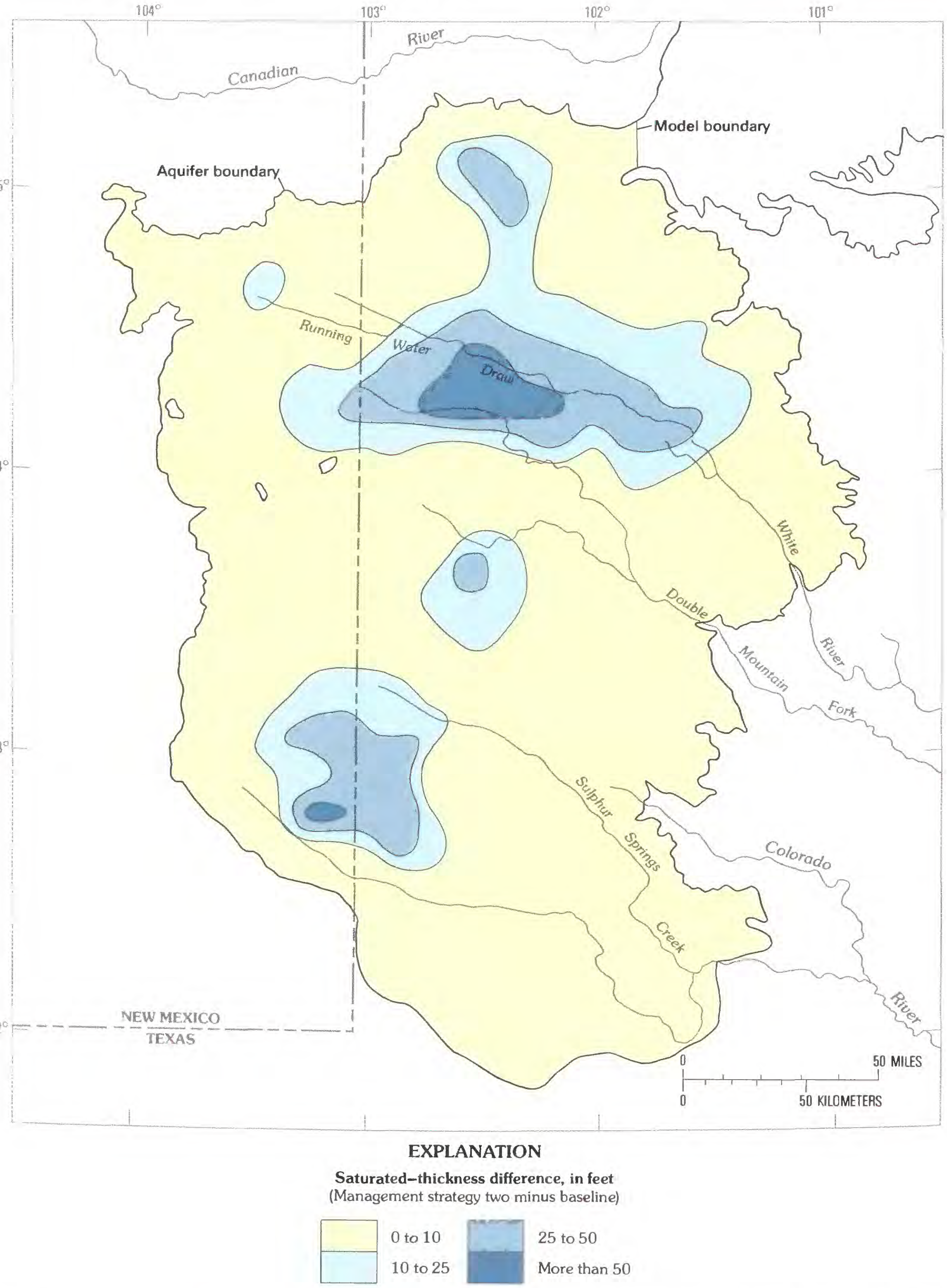

FIGURE 10.—Difference in projected saturated thickness by 2020 between management strategy 2 and the baseline strategy for the southern High Plains.

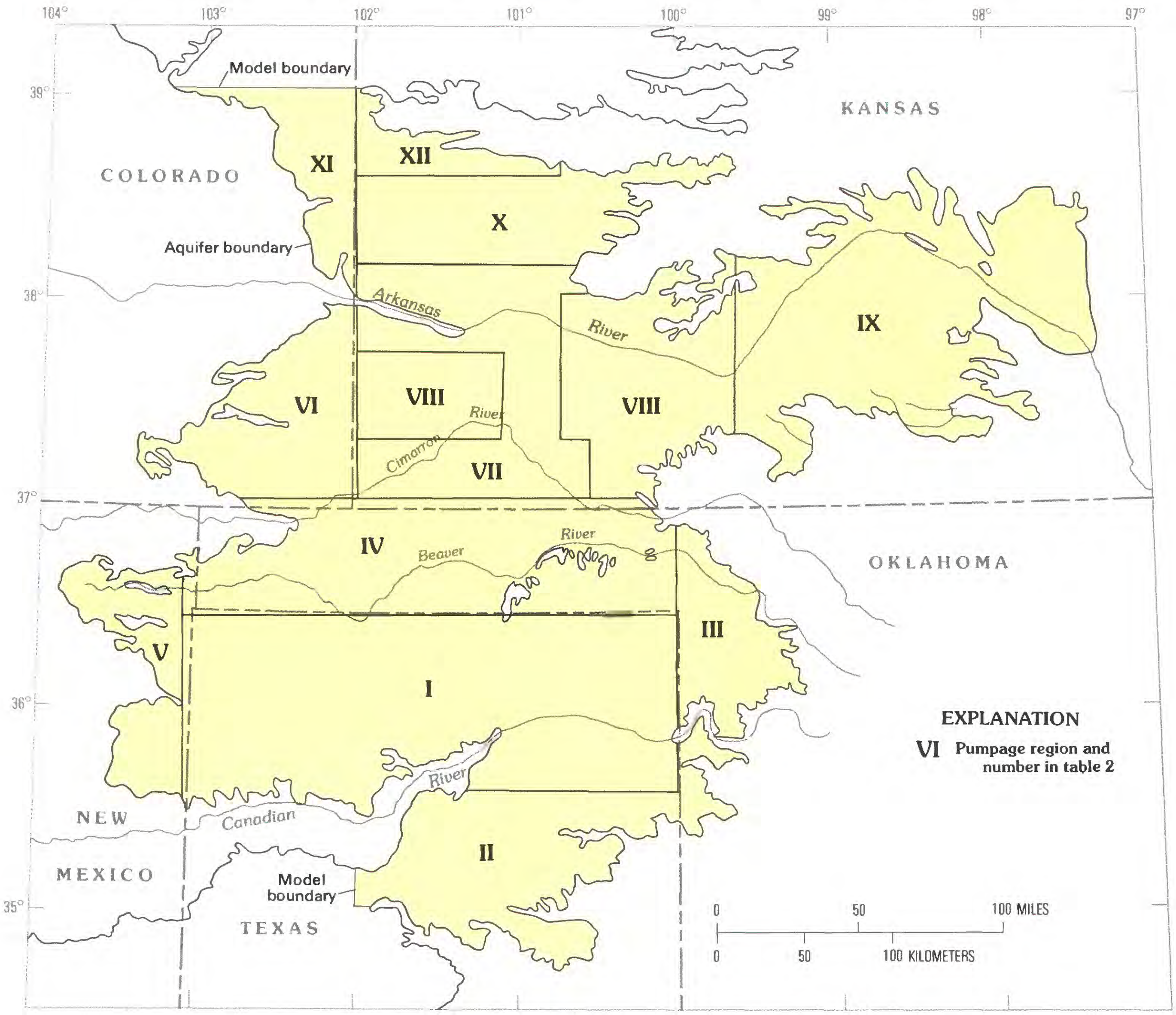

FIGURE 11.—Regions for which pumpage projections were available for the central High Plains.

Associates (1982). The pumpage estimates for this region were divided between the southern and central High Plains by assigning 10 percent of the pumpage to the central High Plains and the remainder to the southern High Plains. Region XI is composed of parts of Regions 5 and 6 of Colorado as defined by Young and others (1982). Twelve percent of Colorado Region 5 pumpage was assigned to Region XI with the remainder assigned to the northern High Plains. Colorado Region 6 contributed 96 percent of its pumpage to Region XI; the remainder was assigned to Region VI. Region XII is part of Region 2 in Kansas (Buller, 1982), and the pumpage estimates for this region were divided by assigning 25 percent to the central High Plains and the remainder to the northern High Plains. Pumpage estimates for all regions were distributed to model nodes within the regions as described for the southern model.

Region IX is outside the Economic Development Administration study area; hence, pumpage had to be estimated for that region. Pumpage for 1980, assuming normal climatic conditions, was estimated by multiplying the 1980 irrigated acreage as mapped from Landsat (Thelin and Heimes, in press) by an estimated annual application of water of 1.25 ft. This resulted in a normalized 1980 pumpage of 512,000 acre-ft. The 1.25-ft application was decreased from a measured application of 1.32 ft in 1980 (a relatively hot and dry year) for 4,000 acres in Stafford County, Kans. (Heimes and Luckey, 1983, table 2). The baseline-strategy pumpage projection was made using the percentages of the normalized 1980 pumpage listed below. The percentages approximately define the trend for the combined baseline-strategy pumpage projections for Regions VII and VIII. These regions were used to define the trend because they are adjacent to Region IX and, when combined, provide a consistent trend. The baseline-strategy pumpage projection for Region IX was as follows:

1980–1984 pumpage =85 percent of normalized 1980 pumpage
1985–1989 pumpage =60 percent of normalized 1980 pumpage
1990–1994 pumpage =40 percent of normalized 1980 pumpage
1995–2019 pumpage =30 percent of normalized 1980 pumpage.

Pumpages for management strategy 1 and management strategy 2 were estimated for Region IX using ratios between the combined pumpage in Regions VII and VIII for the baseline strategy and for management strategy 1 and management strategy 2, respectively. The baseline-strategy pumpage projection for Region IX was multiplied by the following ratios to generate management-strategy-1 and management-strategy-2 pumpage projections:

Years	Region IX pumpage ratio	
	Management strategy 1 to baseline strategy	Management strategy 2 to baseline strategy
1980–84	0.97	0.92
1985–89	.99	.87
1990–94	1.35	1.05
1995–99	2.10	1.51
2000–04	2.26	1.86
2005–09	2.38	1.67
2010–14	2.13	1.49
2015–19	1.89	1.32

The pumpage projections for the central High Plains are given in table 2. For the baseline strategy, projected pumpage is about 6.0 million acre-ft/yr for 1980–84 and decreases to about 3.4 million acre-ft/yr for 2015–19. There is a steady decrease in total pumpage throughout the central High Plains except for projected increases in Regions IV and V. For management strategy 1, pumpage is projected to decrease from about 5.7 million acre-ft/yr for 1980–84 to about 4.0 million acre-ft/yr for 2015–19. Note that the projected pumpage is greater for management strategy 1 than for the baseline strategy during later periods. The additional pumpage primarily is in Regions VII, VIII, and IX where, although less water is applied per acre for management strategy 1, the irrigated acreage is more than for the baseline strategy (Buller, 1982, p. 81–82). This additional irrigated acreage more than offsets the decreased rate of application of water. Projected pumpage for management strategy 2 ranges from about 5.5 million acre-ft/yr in 1980–84 to about 2.8 million acre-ft/yr in 2015–19.

The pumpage projections for the central High Plains are summarized in figure 12. This figure shows that, compared to the baseline strategy, projected pumpage is larger for management strategy 1 and smaller for management strategy 2 starting in 1990. These pumpages were used to project future water levels and saturated thickness for each of the three strategies. The total simulated pumpage for 1980 to 2020 is 158 million acre-ft for the baseline strategy, 178 million acre-ft for management strategy 1, and 138 million acre-ft for management strategy 2.

BASELINE STRATEGY

The projected water-level declines from 1980 to 2020 resulting from baseline-strategy pumpage are shown in figure 13. Much of the central High Plains will have water-level declines in excess of 10 ft under this strategy. The projected water-level declines would exceed 200 ft for the 40 years in 150 mi^2 in Texas north of the Canadian River. The maximum water-level decline from 1980 to 2020 would be about 250 ft. Water levels are projected to decline more than 100 ft in 2,950 mi^2 of Texas, Oklahoma, and Kansas. Water levels are projected to decline more than 25 ft in 15,700 mi^2 in parts of all States in the central High Plains except New Mexico. For the baseline strategy, the average projected water-level decline from 1980 to 2020 in the central High Plains would be 26 ft; the median projected decline would be 11 ft. The median decline indicates that one-half of the area of the central High Plains is projected to have water-level declines of more than 11 ft. The average decline is larger than the median decline because the average is influenced more by the large water-level declines than is the median. These projected declines are in addition to the declines, in excess of 50 ft, that had already occurred in the area by 1980 (Luckey and others, 1981).

The total volume of water that would be removed from storage during the 40 years is projected to be 138 million acre-ft. This is about 87 percent of the total volume of the simulated pumpage. The 13-percent difference

TABLE 2.—*Simulated pumpage, 1980 to 2020, by strategy and region for the central High Plains*

Region	Simulated pumpage, in thousands of acre-feet per year, for the indicated period							
	1980–1984	1985–1989	1990–1994	1995–1999	2000–2004	2005–2009	2010–2014	2015–2019
Baseline strategy								
I..........	2,029	1,802	1,356	1,360	1,426	1,421	1,418	1,416
II.........	290	190	144	134	129	125	120	115
III........	75	71	53	56	58	59	60	61
IV.........	566	545	519	599	649	654	658	663
V..........	137	146	154	159	165	173	180	187
VI.........	141	111	78	71	64	57	50	43
VII........	1132	848	512	408	357	386	416	445
VIII.......	884	674	442	349	289	280	270	261
IX.........	435	310	205	155	155	155	155	155
X..........	248	146	91	94	86	62	38	14
XI.........	44	41	37	34	30	25	21	16
XII........	36	30	24	19	15	13	10	7
Total....	6,017	4,914	3,615	3,438	3,423	3,410	3,396	3,383
Management strategy 1								
I..........	1,845	1,646	1,379	1,305	1,353	1,332	1,312	1,294
II.........	256	157	139	128	122	116	111	106
III........	73	67	46	47	47	46	46	46
IV.........	544	501	447	496	521	511	501	491
V..........	136	143	146	148	151	156	160	192
VI.........	141	120	98	85	81	90	99	108
VII........	1,057	833	792	1,038	1,150	1,061	971	882
VIII.......	897	686	499	549	564	527	491	454
IX.........	422	307	277	326	350	369	330	293
X..........	234	128	82	93	100	98	96	95
XI.........	44	42	41	37	33	29	26	22
XII........	35	28	26	23	22	21	21	20
Total....	5,684	4,658	3,972	4,275	4,494	4,356	4,164	4,003
Management strategy 2								
I..........	1,845	1,418	1,076	953	947	932	918	906
II.........	256	136	108	94	86	81	78	74
III........	69	60	36	34	33	32	32	31
IV.........	515	445	355	348	339	331	322	313
V..........	132	123	115	109	107	110	113	116
VI.........	137	107	80	64	57	64	71	78
VII........	999	722	610	747	805	742	680	617
VIII.......	846	598	388	398	395	369	343	318
IX.........	400	270	215	234	288	259	231	205
X..........	223	112	64	68	70	69	68	66
XI.........	42	36	30	25	22	20	19	17
XII........	33	25	20	17	15	15	15	14
Total....	5,497	4,052	3,097	3,091	3,164	3,024	2,890	2,755

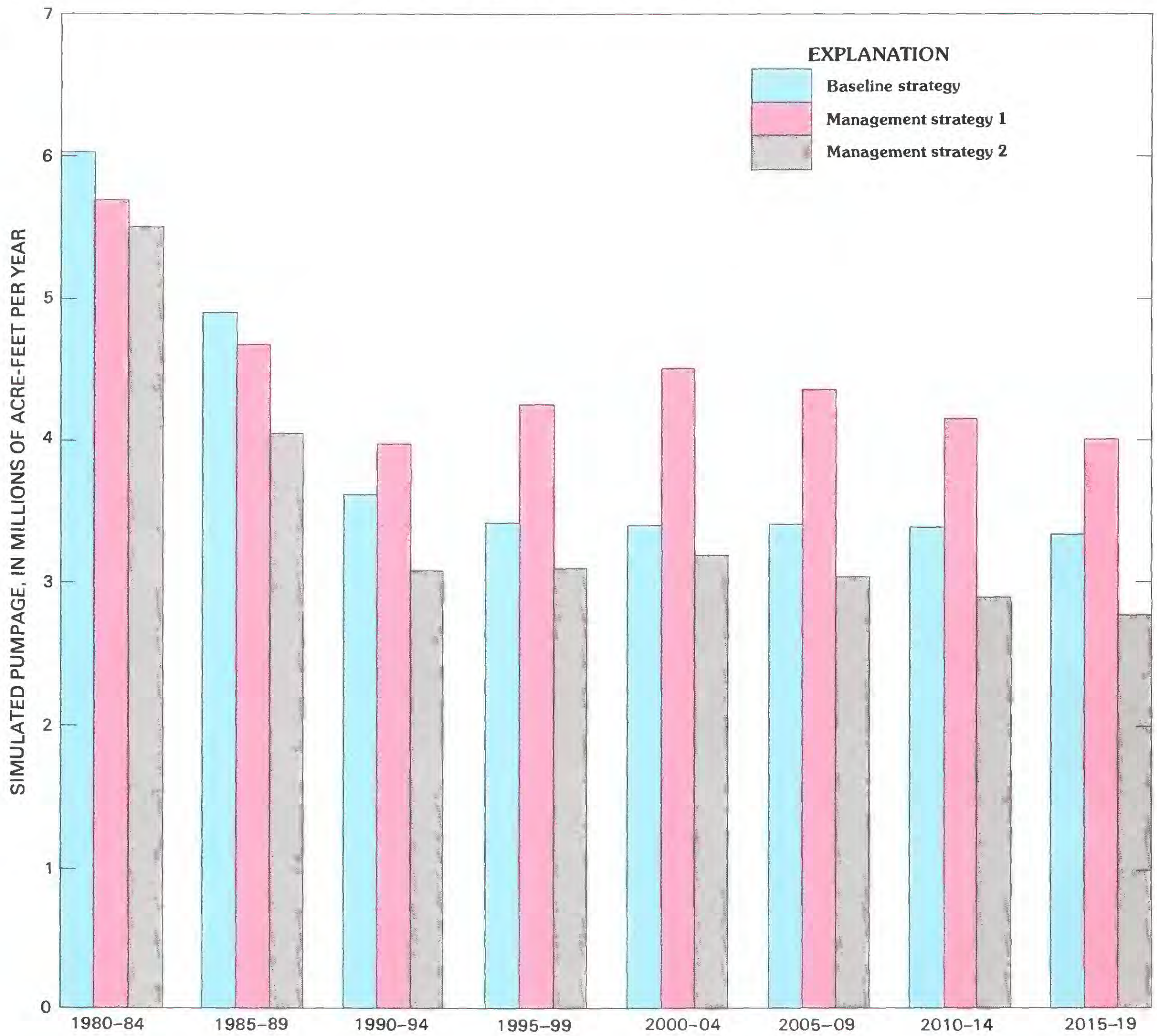

FIGURE 12.—Simulated pumpage for the central High Plains by management strategy.

between the simulated pumpage and the projected volume removed from storage would be supplied primarily by decreased seepage to streams.

The projected saturated thickness remaining in the central High Plains by 2020 is shown in figure 14. There would be two small areas totaling 400 mi^2 that are projected to have more than 400 ft of saturated thickness remaining by 2020. There would be one large area (3,150 mi^2) and a few small areas projected to have more than 200 ft of saturated thickness remaining by 2020. There would be 21,600 mi^2 of the central High Plains that are projected to have less than 50 ft of saturated thickness remaining by 2020 as a result of baseline-strategy pumpage. Although the average saturated thickness was 104 ft during 1980, some areas, particularly in the western part of the central High Plains, are projected to have almost zero saturated thickness by 2020. The median saturated thickness by 2020 in the central High Plains for the baseline strategy is projected to be 82 ft.

MANAGEMENT STRATEGY 1

The projected water-level declines from 1980 to 2020 resulting from management-strategy-1 pumpage are shown in figure 15. Two areas would have declines

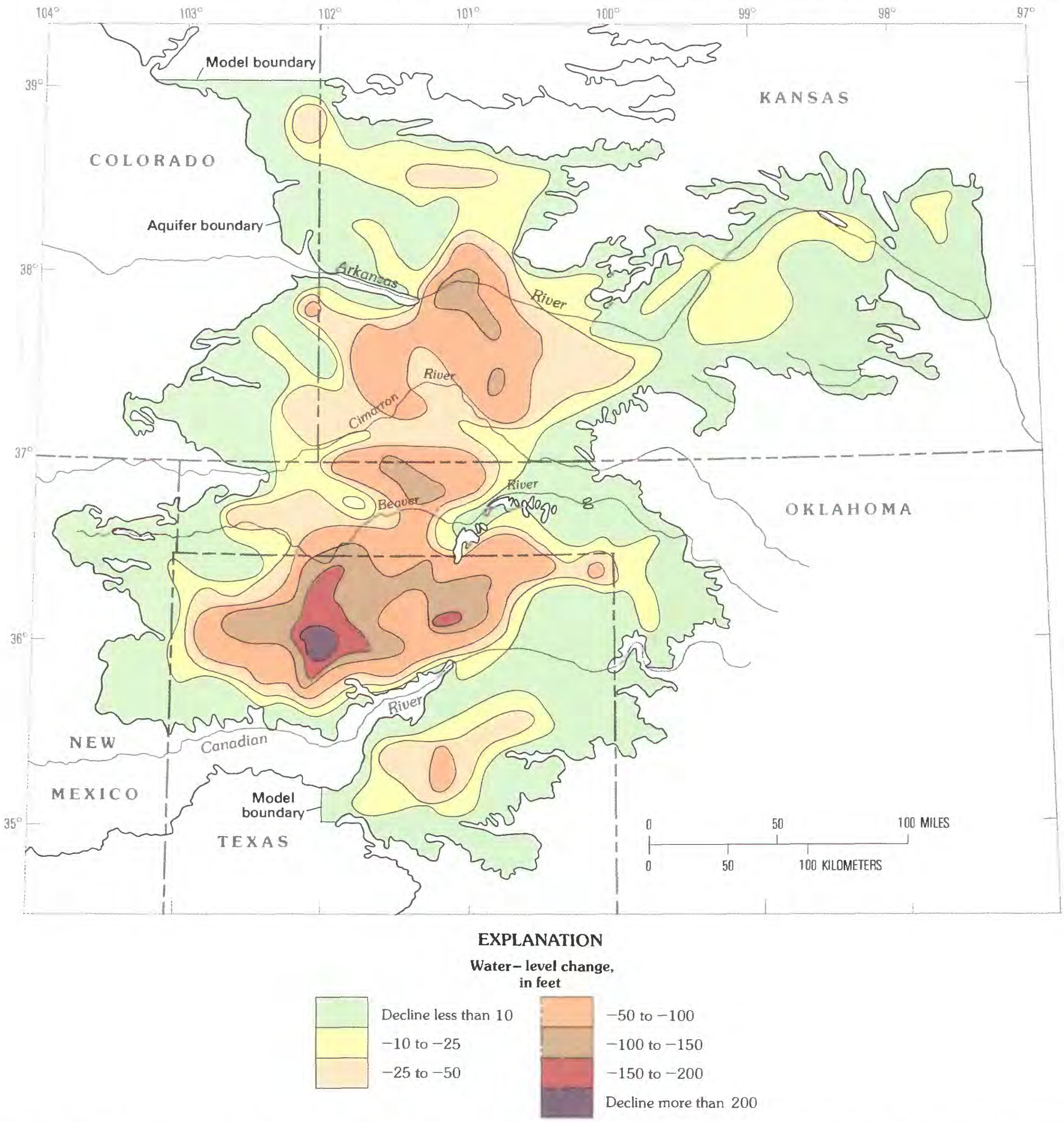

FIGURE 13.—Projected water-level declines, 1980 to 2020, for the central High Plains resulting from pumpage for the baseline strategy.

exceeding 200 ft, one in Texas and one in Kansas. The maximum projected water-level decline from 1980 to 2020 would be about 230 ft. There would be large areas totaling 3,850 mi^2 where projected water-level declines would exceed 100 ft for the 40 years. Water-level declines would exceed 10 ft in 55 percent of the central High Plains as a result of management-strategy-1 pumpage. Those areas with projected declines of less than 10 ft were only sparsely irrigated in 1980 and are projected to have little irrigation in the future. The average decline from 1980 to 2020 for this strategy would be 29 ft, and the median decline would be 12 ft.

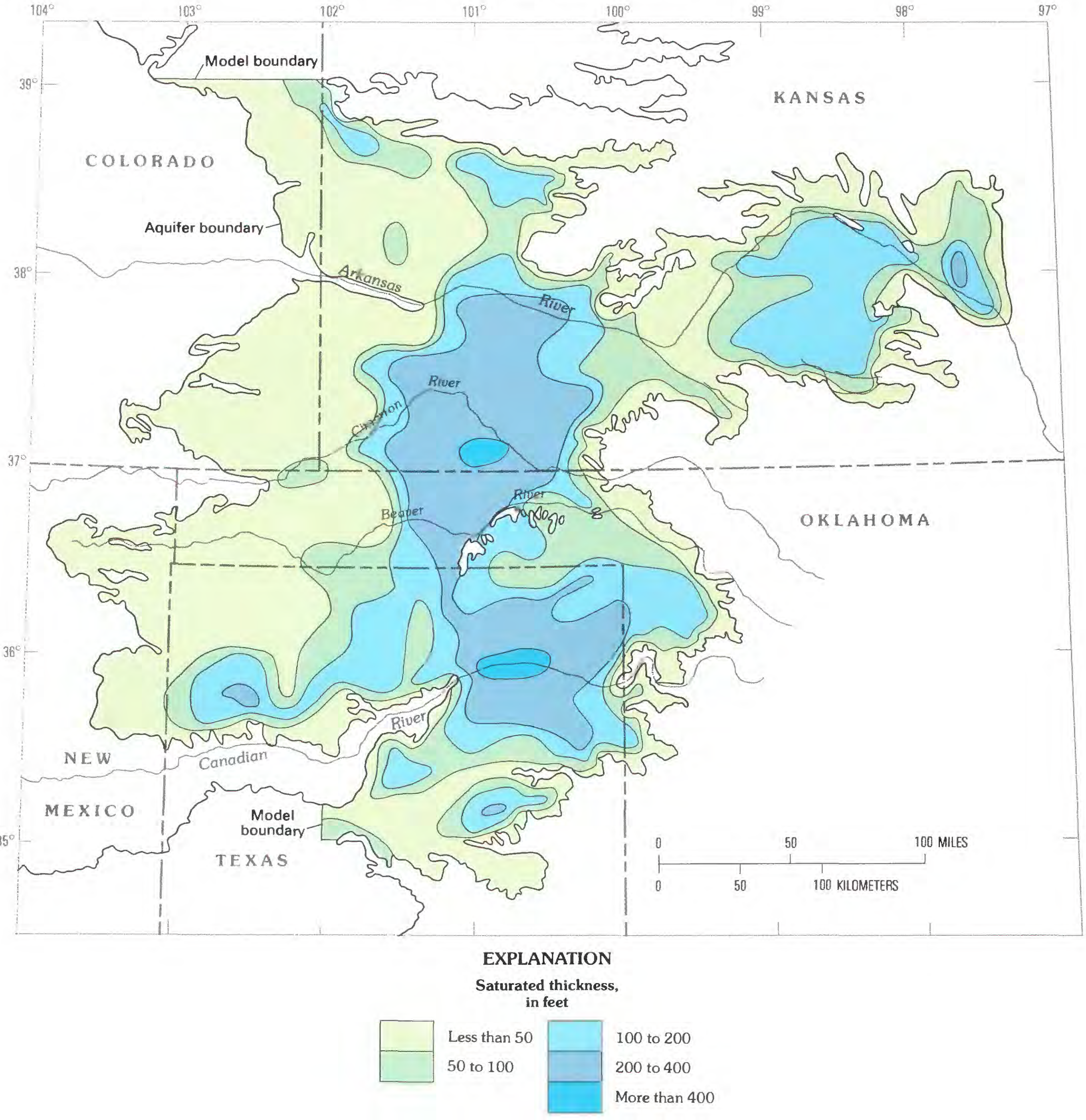

FIGURE 14.—Projected saturated thickness by 2020 in the central High Plains resulting from pumpage for the baseline strategy.

The average water-level decline prior to 1980 for the area was about 15 ft (Luckey and others, 1981).

The total volume of water that would be removed from storage in the central High Plains from 1980 to 2020 for management strategy 1 is projected to be 157 million acre-ft compared to 178 million acre-ft of pumpage. The 12-percent difference between the simulated pumpage and the projected volume removed from storage would be supplied primarily by decreased seepage to streams. The average projected saturated thickness would be 114 ft by 2000 and 100 ft by 2020; the median projected saturated thickness would be 94 ft by 2000 and 78 ft by 2020.

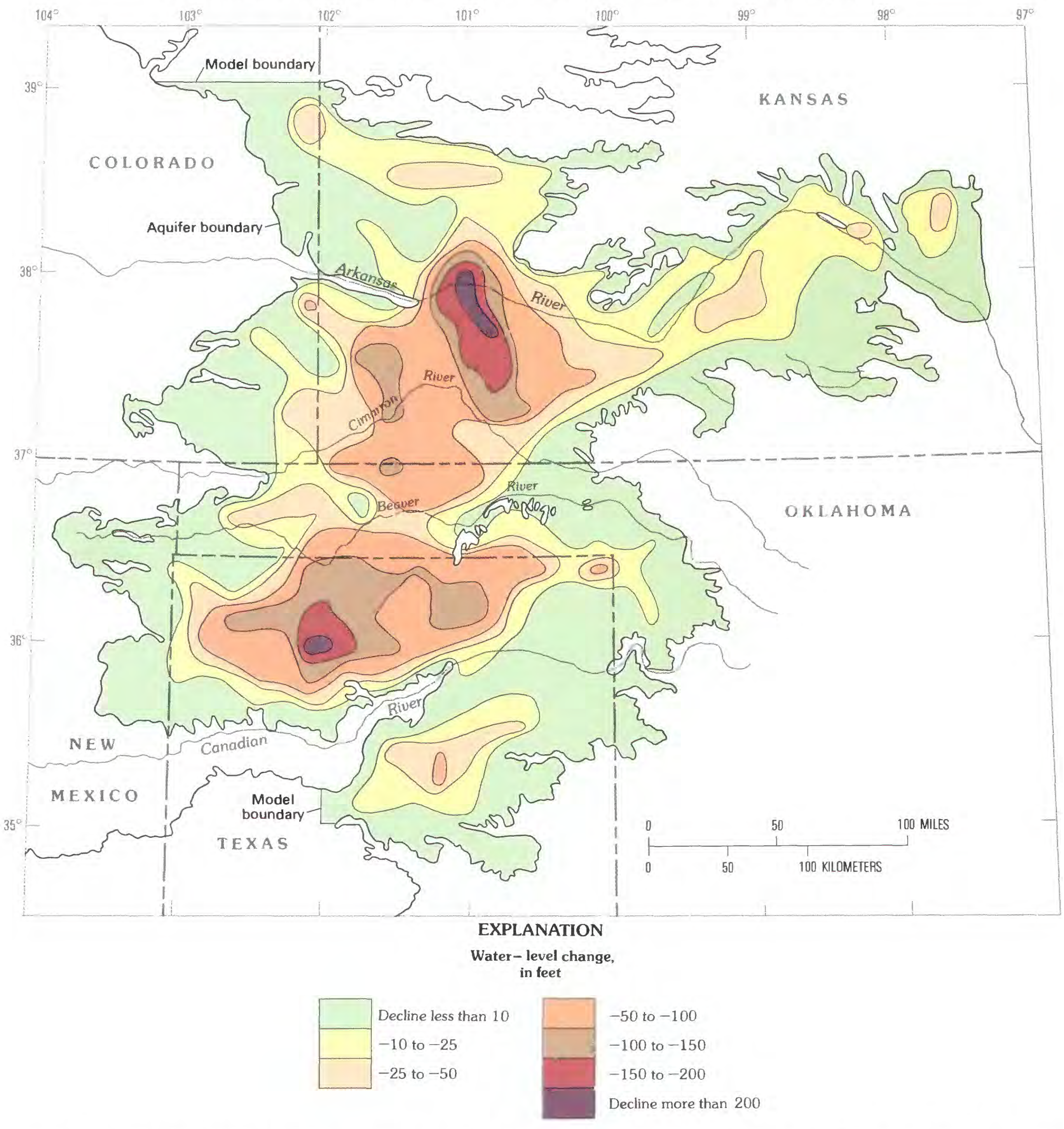

FIGURE 15.—Projected water-level declines, 1980 to 2020, for the central High Plains resulting from pumpage for management strategy 1.

MANAGEMENT STRATEGY 2

The projected water-level declines from 1980 to 2020 resulting from management-strategy-2 pumpage are shown in figure 16. Even with significant mandatory decreases in water use, the central High Plains will continue to have large water-level declines between 1980 and 2020. No areas are projected to have declines in excess of 200 ft; the maximum projected water-level decline for 1980 to 2020 for management strategy 2 is

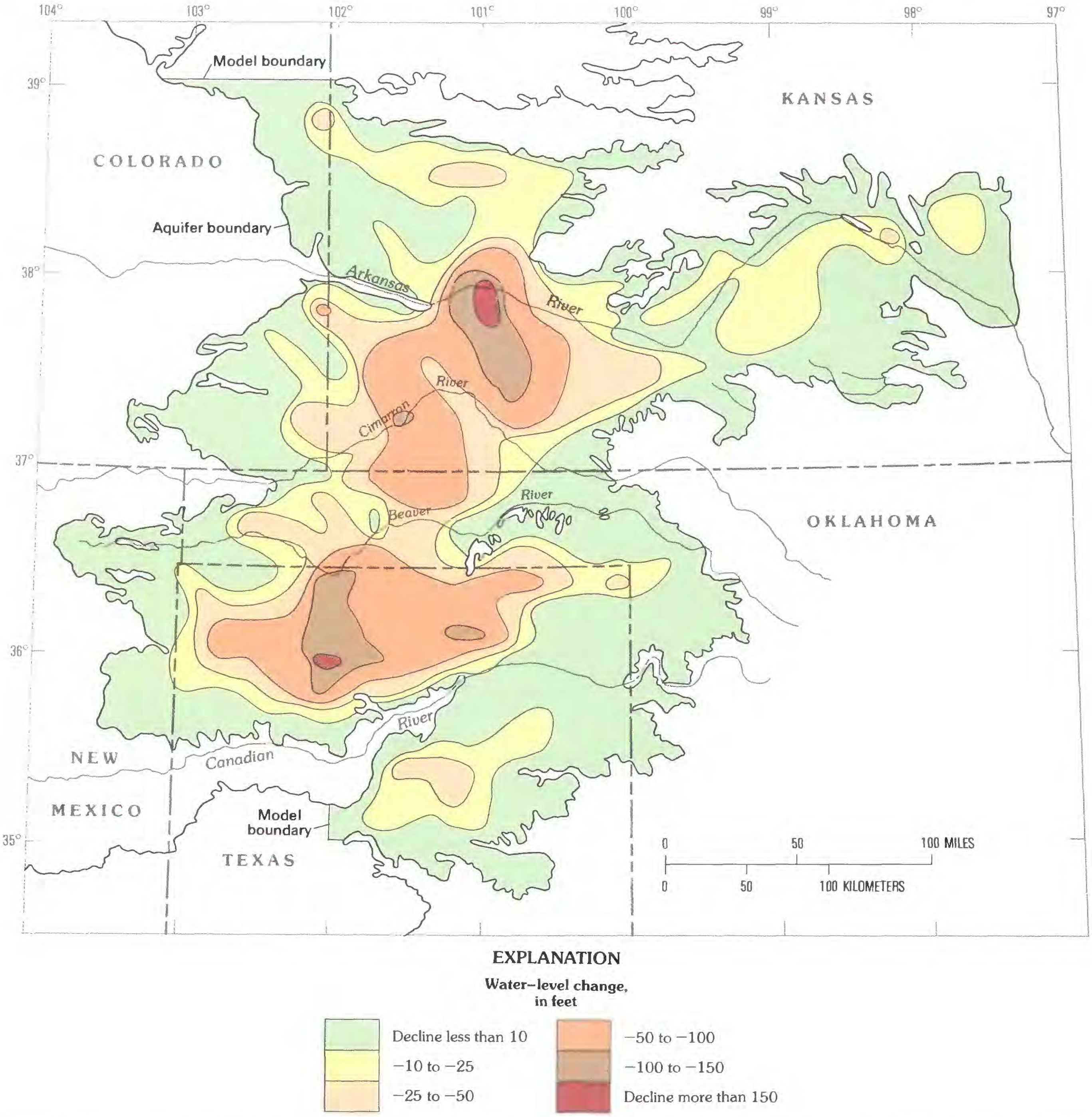

FIGURE 16.—Projected water-level declines, 1980 to 2020, for the central High Plains resulting from pumpage for management strategy 2.

about 180 ft. Water levels are projected to decline more than 100 ft in 1,700 mi². About one-half (24,000 mi²) of the central High Plains is projected to have declines of more than 10 ft. The average water-level decline for management strategy 2 would be 22 ft.

The total volume of water projected to be removed from storage in the central High Plains from 1980 to 2020 under management strategy 2 would be 121 million acre-ft. This would be 88 percent of the simulated pumpage. The remaining 12 percent of the pumpage would be supplied primarily by decreased discharge to or increased recharge from streams. The average saturated thickness for management strategy 2 is projected to be 116 ft by 2000 and 107 ft by 2020. The median saturated thickness is projected to be 96 ft by 2000 and 87 ft by 2020.

COMPARISON OF STRATEGIES

Projected water-level declines generally would be smallest for management strategy 2. South of the Kansas-Oklahoma State line, the projected water-level declines would be largest for the baseline strategy (fig. 13). North of this line, projected water-level declines would be largest for management strategy 1 (fig. 15). The greater water-level declines for management strategy 1 compared to the baseline strategy north of the Kansas-Oklahoma State line would be due to more pumpage resulting from increased irrigated acreage. Throughout the central High Plains, the projected water-level declines resulting from management-strategy-2 pumpage (fig. 16) would be considerably less than those resulting from management-strategy-1 pumpage (fig. 15). A decrease in pumpage between management strategy 1 and management strategy 2 was simulated for all pumping periods from 1980 to 2020; this resulted in a uniform decrease in projected water-level declines.

The difference in saturated thickness by 2020 between management strategy 2 and the baseline strategy is shown in figure 17. In Texas and Oklahoma, there would be three areas totaling 500 mi^2 where more than 50 ft of saturated thickness would be saved as a result of the mandatory decrease in water use in management strategy 2. The maximum difference in saturated thickness between management strategy 2 and the baseline strategy would be 68 ft. The difference in saturated thickness would exceed 25 ft in 4,250 mi^2 and 10 ft in 6,800 mi^2. In Kansas, there would be an area where saturated thickness would be greater for the baseline strategy than for management strategy 2. The maximum such difference between management strategy 2 and the baseline strategy would be 46 ft. The decreased saturated thickness between management strategy 2 and the baseline strategy would exceed 25 ft in 1,000 mi^2 and 10 ft in 2,300 mi^2. The area where saturated thickness would be greater for the baseline strategy corresponds to pumpage Region VII and would be the result of larger simulated pumpage for management strategy 2 than for the baseline strategy. Total management-strategy-2 pumpage in Region VII would be 7.1 million acre-ft more than the baseline-strategy pumpage (table 2). Much of the map shows less than 10 ft difference in 2020 saturated thickness between strategies; the average difference in this area is only 0.11 ft.

The average projected saturated thickness by 2020 resulting from baseline-strategy pumpage would be 104 ft with 550 million acre-ft of drainable water remaining in storage. During the projection period, 1980 to 2020, 138 million acre-ft of water would be removed from storage. With management-strategy-1 pumpage, the average projected saturated thickness by 2020 would be 100 ft, and 530 million acre-ft of drainable water would remain in storage. This would be a 157-million acre-ft decrease in storage from 1980. The projected change in storage from 1980 to 2020 resulting from management-strategy-2 pumpage would be 121 million acre-ft. With management strategy 2, 560 million acre-ft of drainable water is projected to remain in storage by 2020 with an average saturated thickness of 107 ft. The difference in storage between management strategy 2 and the baseline strategy would be about 17 million acre-ft.

NORTHERN HIGH PLAINS

The northern High Plains consists of 96,500 mi^2 in Colorado, Kansas, Nebraska, South Dakota, and Wyoming north about lat 39° N. The northern High Plains constitutes 55 percent of the entire High Plains. From predevelopment to 1980, 26 percent of the total ground water pumped from the High Plains aquifer was pumped from the northern High Plains.

The northern High Plains was divided into 16 regions with different pumpage estimates as shown in figure 18. Note that Region VII has two parts. Pumpage estimates for 1980 to 2020 are shown in table 3. Pumpage estimates were available for 1985, 1990, 2000, and 2020 for all three management strategies for Regions I through VII (Young and others, 1982; Buller, 1982) and all years from 1980 to 2020 for the baseline strategy for Regions XII through XVI (Dayle Williamson, Nebraska Natural Resources Commission, written commun., August 1983). A linear interpolation was made between years for which pumpage was available. Pumpage projections were made during this study for Regions VIII through XI. Baseline-strategy pumpage estimates for Regions VIII through XI were the product of assumed water application and irrigated acreage for selected years. For each region, the 1980 irrigated acreage and application were based on actual data (Heimes and Luckey, 1983; Thelin and Heimes, in press). The projected water application, acreage, and baseline-strategy pumpage for Regions VIII–XI are summarized in table 4. Projections of pumpage were made for 2000 and 2020 for all four regions (VIII–XI). In addition, projections of pumpage were also made for 1985 and 1990 for Region XI to provide more detail. A linear interpolation was done between the years for which pumpage was projected.

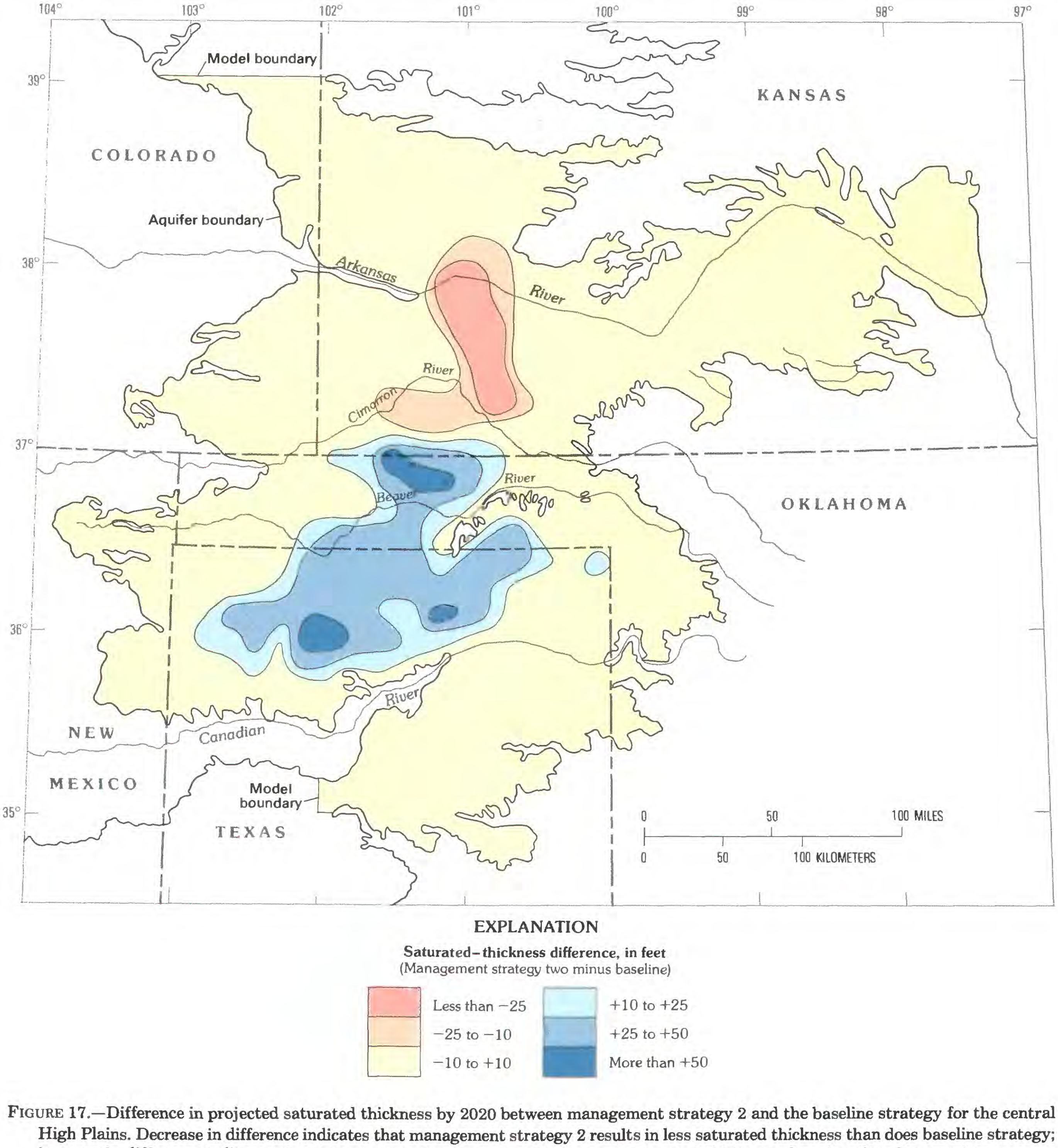

FIGURE 17.—Difference in projected saturated thickness by 2020 between management strategy 2 and the baseline strategy for the central High Plains. Decrease in difference indicates that management strategy 2 results in less saturated thickness than does baseline strategy; increase in difference indicates that management strategy 2 results in more saturated thickness than does baseline strategy.

Pumpage for 1980, 1985, 1990, 2000, and 2020 for regions VIII through XI also was estimated for management strategy 1 and management strategy 2. Management-strategy-1 pumpage was assumed to be the same as the baseline-strategy pumpage. Management-strategy-2 pumpage was assumed to be equal to baseline-strategy pumpage for 1980, 90 percent of baseline-strategy pumpage for 1985, 80 percent of baseline-strategy pumpage for 1990, and 70 percent of the baseline-strategy pumpage for 2000 and 2020.

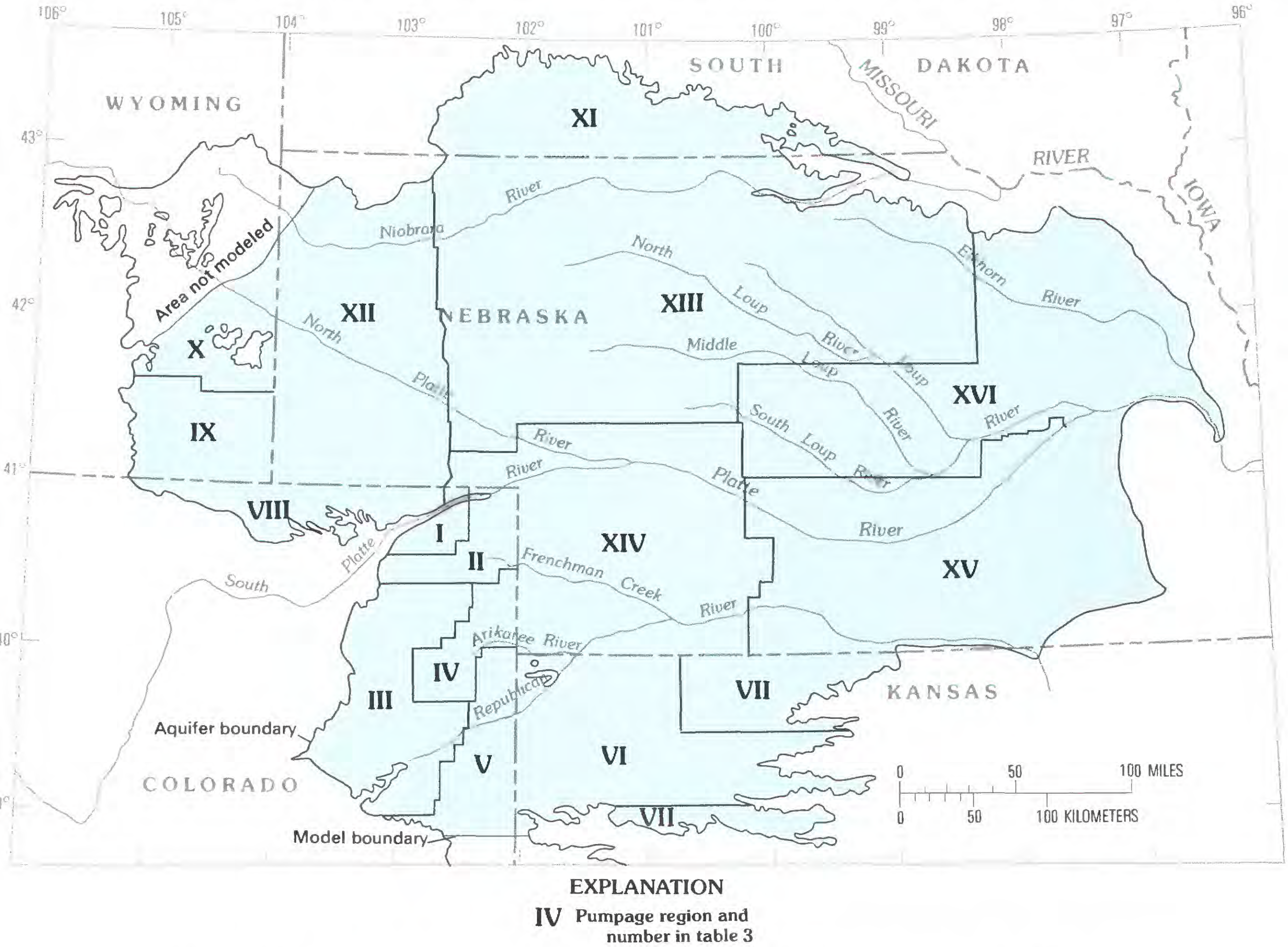

FIGURE 18.—Regions for which pumpage projections were available for the northern High Plains.

Much more detailed pumpage projections were available for the High Plains in Nebraska (Dayle Williamson, Nebraska Natural Resources Commission, written commun., August 1983) than were available for the other States. Annual pumpage estimates were made to 2020 by the Economic Development Administration study investigators for several ground-water flow models which together covered most of the High Plains aquifer in Nebraska. The nodes in these models ranged in size from 1 to 25 mi^2. The pumpage estimates from these models were aggregated to the 100-mi^2 nodes during this study. Pumpage estimates for the Regions outside of Nebraska were distributed to model nodes as described in the section on the southern High Plains.

Regions XII through XVI are Nebraska economic regions defined in the Economic Development Administration study (High Plains Associates, 1982; High Plains Study Council, 1982) and are used here for summary purposes only. As noted above, detailed projections of pumpage were available for Nebraska; the data presented in table 3 are a summary of that information. The projected pumpage for Regions XII through XVI would be identical for the baseline strategy and management strategy 1 because "***projected demand for Strategy 1 did not differ significantly from the Baseline" (Nebraska Natural Resources Commission, 1981, p. 29). For management strategy 2, the projected pumpage for Nebraska was assumed to be equal to management-strategy-1 pumpage for 1980, 90 percent of management-strategy-1 pumpage for 1985, 80 percent of management-strategy-1 pumpage for 1990, and 70 percent of management-strategy-1 pumpage for 2000 and 2020. The percentages varied linearly between the specified years. These decreases are comparable to management-strategy-2 pumpage decreases in regions outside of Nebraska.

The projected pumpage by management strategy is summarized in figure 19. There would be a slight increase in pumpage between the baseline strategy and management strategy 1 for all time periods except 2005

TABLE 3.—*Simulated pumpage, 1980 to 2020, by strategy and region for the northern High Plains*

Region	Simulated pumpage, in thousands of acre-feet per year, for the indicated period							
	1980–1984	1985–1989	1990–1994	1995–1999	2000–2004	2005–2009	2010–2014	2015–2019
Baseline strategy								
I..........	31	31	31	31	31	31	30	30
II.........	128	128	127	128	123	111	100	88
III........	194	178	172	171	163	148	132	116
IV.........	283	293	304	315	320	513	311	307
V..........	202	184	161	127	114	114	103	103
VI.........	440	381	291	242	200	169	137	105
VII........	109	90	73	58	46	38	30	22
VIII.......	14	14	14	13	12	11	11	11
IX.........	24	27	28	27	26	25	25	24
X..........	7	8	8	8	7	7	7	7
XI.........	17	19	22	22	22	23	23	24
XII........	204	242	264	295	324	356	391	424
XIII.......	591	902	1,069	1,269	1,472	1,582	1,682	1,766
XIV........	1,060	1,381	1,621	1,833	1,017	813	905	974
XV.........	2,050	2,278	2,492	2,765	2,836	2,994	3,122	3,202
XVI........	1,340	1,566	1,897	2,216	2,417	2,670	2,898	3,036
Total....	6,694	7,722	8,574	9,520	9,130	9,605	9,907	10,239
Management strategy 1								
I..........	32	31	31	30	29	29	29	28
II.........	129	127	124	121	117	110	103	95
III........	194	185	187	182	175	165	154	144
IV.........	284	290	294	300	301	296	290	285
V..........	280	275	267	242	216	186	157	128
VI.........	419	354	280	243	209	181	152	124
VII........	104	86	77	69	65	63	62	61
VIII.......	14	14	14	13	12	12	11	11
IX.........	24	27	28	27	26	25	25	24
X..........	7	8	8	8	7	7	7	7
XI.........	17	19	22	22	22	23	23	24
XII........	204	242	264	295	324	356	391	424
XIII.......	591	902	1,069	1,269	1,472	1,582	1,682	1,766
XIV........	1,060	1,381	1,621	1,833	1,017	813	905	974
XV.........	2,050	2,278	2,492	2,765	2,836	2,994	3,126	3,202
XVI........	1,340	1,566	1,897	2,216	2,417	2,670	2,898	3,036
Total....	6,749	7,785	8,675	9,635	9,245	9,512	10,015	10,333
Management strategy 2								
I..........	30	27	24	23	22	21	21	20
II.........	120	109	97	89	83	79	76	73
III........	183	155	135	124	116	113	111	109
IV.........	266	249	229	217	209	206	204	202
V..........	263	229	192	166	144	130	115	100
VI.........	394	307	220	179	146	127	107	87
VII........	99	74	60	51	45	44	44	43
VIII.......	13	12	11	9	8	8	8	8
IX.........	23	23	22	20	18	18	17	17
X..........	7	7	7	6	5	5	5	5
XI.........	16	17	17	16	15	16	16	17
XII........	190	207	206	215	227	249	274	297
XIII.......	552	771	834	927	1,031	1,108	1,178	1,236
XIV........	992	1,181	1,265	1,338	712	569	633	682
XV.........	1,916	1,947	1,944	2,018	1,985	2,096	2,188	2,242
XVI........	1,253	1,339	1,479	1,617	1,692	1,869	2,028	2,125
Total....	6,317	6,654	6,742	7,015	6,458	6,658	7,025	7,263

TABLE 4.—*Projected acreage, water application, and pumpage for northern High Plains Regions VIII through XI for the baseline strategy*

Region	Year	Irrigated acres	Water application, in feet	Pumpage, in acre-feet
VIII..........	1980	10,800	1.30	14,000
	2000	10,800	1.20	13,000
	2020	10,800	1.10	12,000
IX............	1980	17,900	1.20	21,500
	2000	23,600	1.10	26,000
	2020	23,600	1.00	23,600
X.............	1980	5,100	1.25	6,400
	2000	6,700	1.15	7,700
	2020	6,700	1.05	7,000
XI............	1980	11,500	1.30	15,000
	1985	13,800	1.30	17,900
	1990	16,600	1.30	21,600
	2000	18,200	1.20	21,800
	2020	21,900	1.10	24,100

to 2009. The total volume pumped for the baseline strategy would be 357 million acre-ft, whereas the total volume pumped for management strategy 1 would be 360 million acre-ft. There would be less than a 1-percent difference in pumpage between the two strategies. The total volume pumped for management strategy 2 would be 271 million acre-ft. This would be about 76 percent of the volume pumped for the baseline strategy. Management-strategy-2 pumpage would be significantly less than the baseline-strategy pumpage for all periods.

The water levels in the northern High Plains aquifer are largely controlled by streams (Luckey and others, 1986, p. 37–38). Future pumpage could change the relation between streams and aquifer to the extent that streams will no longer control the water levels. Simulations were made to see if streams would cease flowing with the pumpage projected for the northern High Plains. Simulated pumpage would be sufficient near the South Loup River and parts of the Elkhorn and Republican Rivers to deplete the base flow of parts of these streams after 1990. To properly simulate the hydrologic conditions, the parts of the streams where base flow would be depleted were removed from the model in 1990 and then the simulations were continued to 2020. The South Loup River was removed from the model upstream from its confluence with the Middle Loup River, the Republican River and its tributaries were removed from the model west of long 101° W., and the Elkhorn River was removed from the model west of long 98° W.

The model, which was developed to compute water levels within large areas, cannot provide detailed information about streamflow capture within small areas. Streamflow capture, defined as decreased streamflow caused by pumping from wells, may include both direct depletion from the stream and decrease in ground-water flow to the stream. To provide more quantitative information about streamflow capture, the ground-water flow equation was solved directly for streamflow capture (Jenkins, 1970) using assumptions that are reasonable for the northern High Plains.

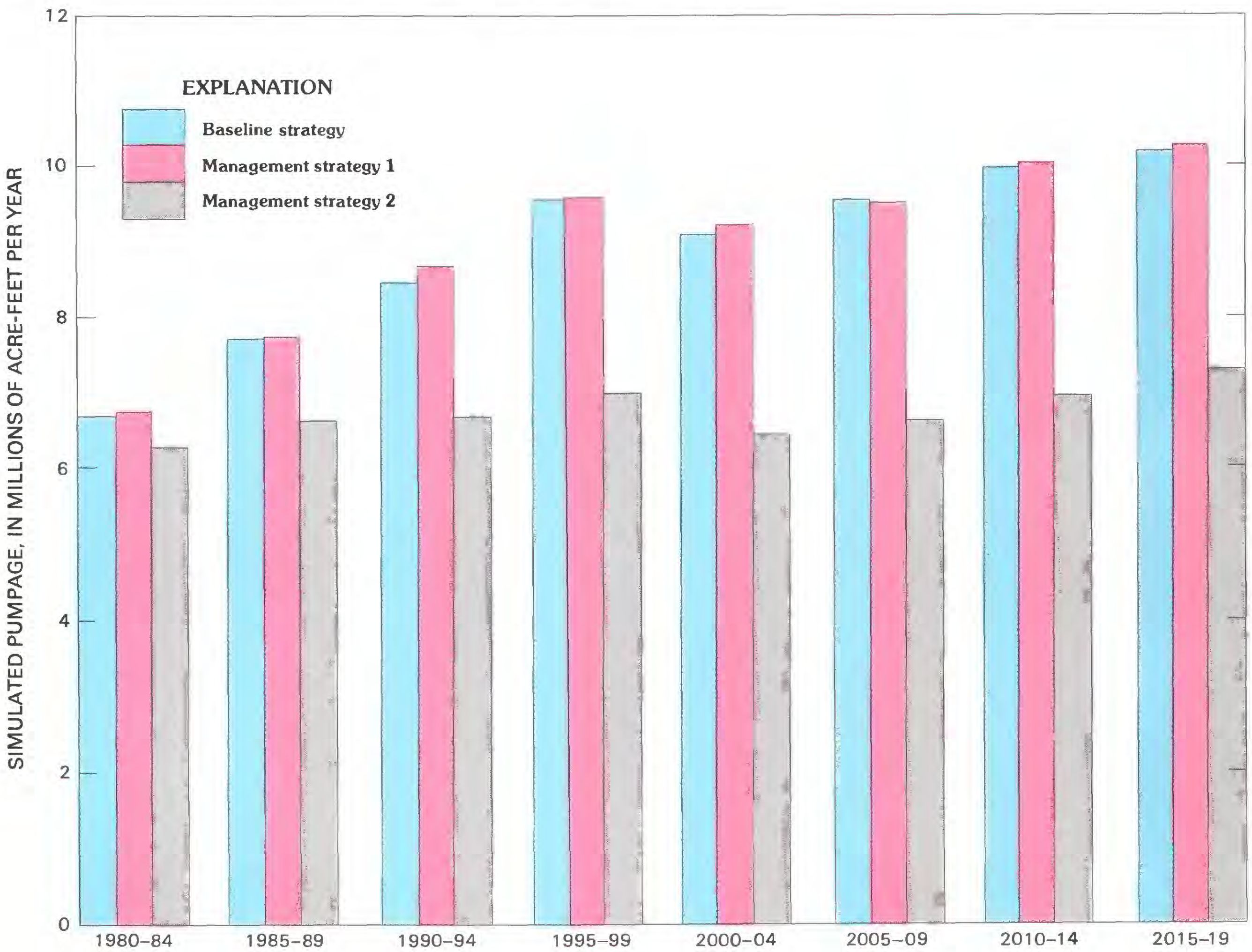

FIGURE 19.—Simulated pumpage for the northern High Plains by management strategy.

Streamflow capture was calculated on the basis of the average aquifer-parameter estimates for the northern High Plains aquifer determined by model calibration (Luckey and others, 1986). Values of the aquifer parameters were hydraulic conductivity, 53 ft/d; saturated thickness, 340 ft; and specific yield, 0.152. The calculated streamflow capture shown in figure 20 assumes one well pumping 130 acre-ft/yr on every other quarter section (two wells per square mile). This assumed density of irrigation is not an average for the entire northern High Plains, but is typical of the more intensely irrigated areas. The data in figure 20 represent the calculated streamflow capture, per mile of stream, at the end of 40 years of pumping. Most of the streamflow capture would be caused by pumpage from wells within 10 mi of the stream and virtually all the streamflow capture would be caused by pumpage from wells within 20 mi of the stream. The difference between streamflow capture at the end of the 3-month irrigation

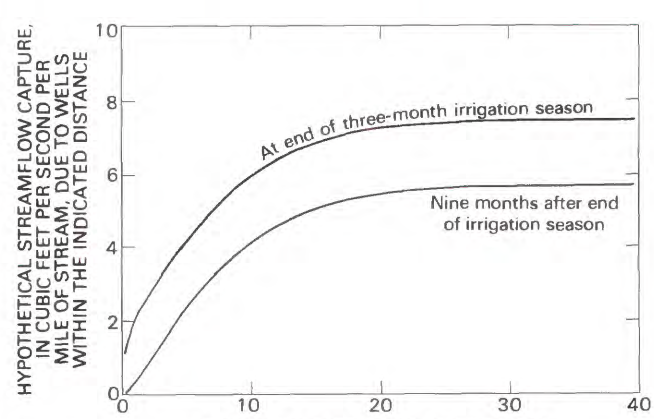

FIGURE 20.—Hypothetical streamflow capture for the northern High Plains computed based on estimated average aquifer parameters and two irrigation wells per square mile withdrawing 130 acre-ft of water per year.

season and 9 months later would be caused by pumpage from wells within 3 mi of the stream. Streamflow capture would be directly related to pumpage, particularly within a few miles from the stream. Because the model described here has 10-mi grid spacing, a more detailed model would be needed to simulate management strategies to regulate streamflow capture.

BASELINE STRATEGY

The projected water-level declines from 1980 to 2020 resulting from baseline-strategy pumpage are shown in figure 21. The projected water-level declines for the northern High Plains would range from less than 10 ft in about one-half of the northern High Plains to more than 200 ft in two isolated areas. The maximum water-level decline from 1980 to 2020 would be 230 ft over one model node (100 mi²). Water levels are projected to decline more than 100 ft in several areas of Nebraska and Colorado totaling 9,700 mi². Water levels are projected to decline more than 25 ft in parts of all States in the northern High Plains by 2020. The median projected water-level decline from 1980 to 2020 for the baseline strategy would be 14 ft. This means that one-half of the area of the northern High Plains is projected to have water-level declines of more than 14 ft from 1980 to 2020. The average water-level decline from 1980 to 2020 for the baseline strategy would be 36 ft. The

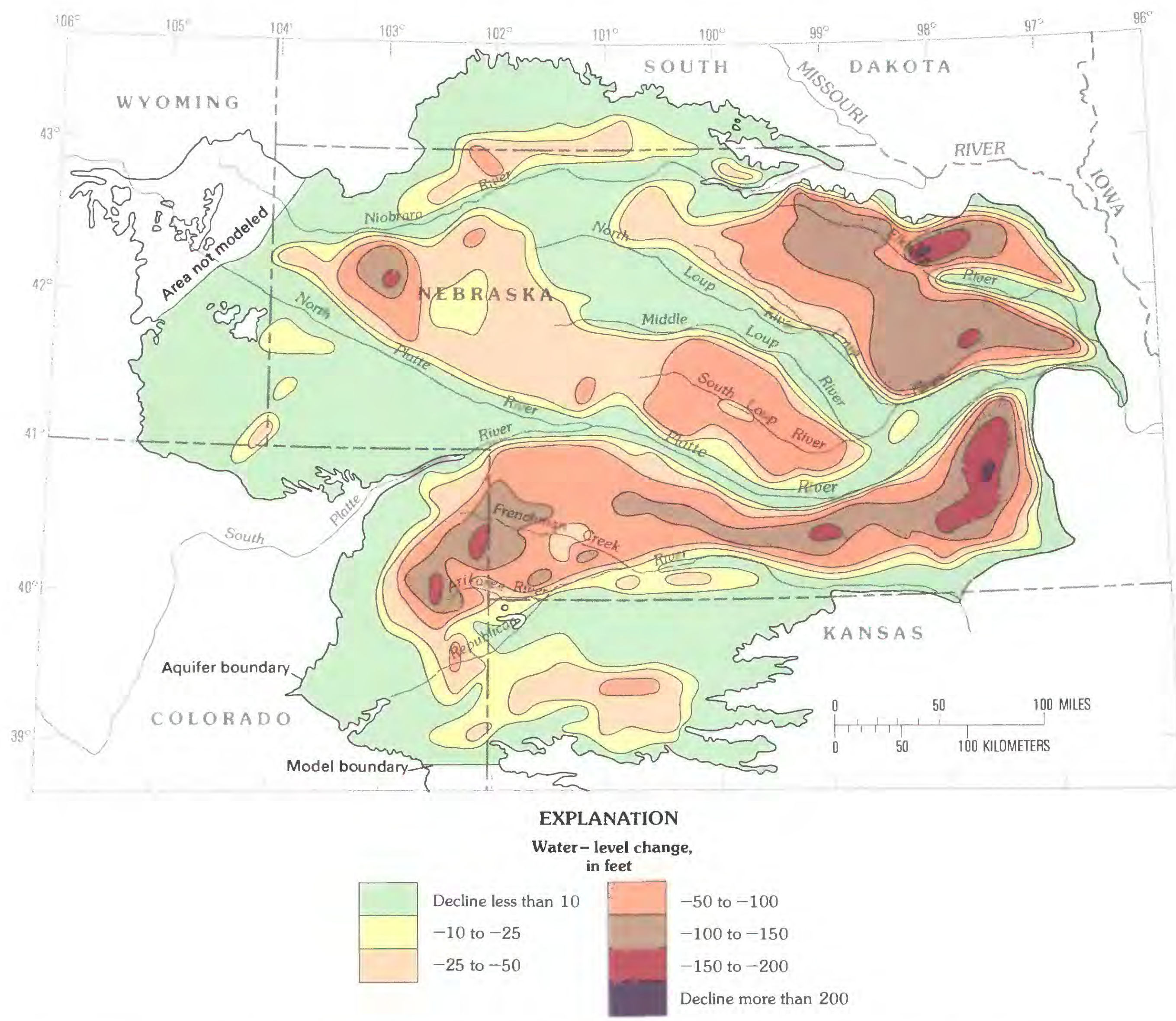

FIGURE 21.—Projected water-level declines, 1980 to 2020, for the northern High Plains resulting from pumpage for the baseline strategy.

average water-level decline is larger than the median decline because the average is influenced more by the larger water-level declines than is the median. The projected water-level declines from 1980 to 2020 would be in addition to the declines, in excess of 25 ft, that had already occurred in the northern High Plains by 1980 (Luckey and others, 1981).

Large water-level declines are projected near parts of the Elkhorn, South Loup, and Republican Rivers. These water-level declines would occur because projected pumpage in these areas would be large enough to deplete the normal base flow of these streams early in the projection period (1980–2020). Along the rest of the major streams, water-levels are projected to decline by less than 10 ft because pumpage near the streams would be supplied mostly by streamflow capture. The total volume of water that would be removed from storage during this 40-year simulation is projected to be 291 million acre-ft. The difference between the volume of water that would be removed from storage (291 million acre-ft) and the volume of water that would be pumped (357 million acre-ft) would come primarily from decreased discharge to or increased recharge from the streams. By 2020, the total projected rate of streamflow capture estimated by the model for the entire northern High Plains would be 2,750 ft^3/s. By 2020, the estimated maximum streamflow capture would be about 18 ft^3/s per mile of stream and the average would be about 1.4 ft^3/s per mile. The maximum streamflow capture calculated by the model would be more than the hypothetical streamflow capture shown in figure 20, and the average would be much less than that shown in figure 20. However, figure 20 is based on the average estimated aquifer parameters and about 40-percent density of irrigation (two 130-acre center-pivot systems per 640 acres). As shown in figure 3, the maximum density of irrigation in the northern High Plains is considerably more than 40 percent and the average is much less than 40 percent. Hence, the streamflow capture calculated by the model appears to be consistent with that calculated by directly solving the ground-water flow equation for streamflow capture.

The projected saturated thickness remaining in the northern High Plains by 2020 is shown in figure 22. There would be a large area (1,650 mi^2) in central Nebraska where the projected saturated thickness would exceed 800 ft. The projected saturated thickness would exceed 200 ft in 34,400 mi^2 in parts of Nebraska, South Dakota, and Wyoming. In 40 percent of the northern High Plains, the saturated thickness is projected to be less than 100 ft by 2020. The median saturated thickness projected by 2020 for the baseline strategy would be 138 ft. The average saturated thickness is projected to be 217 ft by 2020, but this average is influenced by the large saturated-thickness area of central Nebraska. The average saturated thickness in the areas with less than 200 ft of saturated thickness would be 77 ft.

MANAGEMENT STRATEGY 1

The projected pumpage from 1980 to 2020 for management strategy 1 would be 3 million acre-ft (1 percent) greater than that for the baseline strategy. Management-strategy-1 pumpage would be greater than baseline-strategy pumpage in parts of Colorado and Kansas; management-strategy-1 pumpage would be identical to baseline-strategy pumpage in Nebraska, South Dakota, and Wyoming. Simulated water-level declines from 1980 to 2020 would be virtually identical for management strategy 1 and the baseline strategy; thus, simulated declines for management strategy 1 are not shown. The average water-level decline from 1980 to 2020 would be 36 ft for management strategy 1, and the median decline would be 14 ft. For the 159 nodes (17 percent of the area of the model) where the water levels would be different between the baseline strategy and management strategy 1, the water-level declines would average 0.2 ft more for management strategy 1 than for the baseline strategy.

MANAGEMENT STRATEGY 2

The projected water-level declines from 1980 to 2020 resulting from management-strategy-2 pumpage are shown in figure 23. Even with large mandatory decreases in water use, significant water-level declines would still occur in the northern High Plains from 1980 to 2020. The maxiumum water-level decline for management strategy 2 would be 168 ft. There would be numerous areas totaling 5,400 mi^2 where water levels are projected to decline more than 100 ft from 1980 to 2020. Water levels are projected to decline more than 10 ft in 47,000 mi^2 in parts of all five States. The average water-level decline from 1980 to 2020 in the northern High Plains for management strategy 2 is projected to be 28 ft and the median water-level decline is projected to be 11 ft.

The total volume of water that would be removed from storage from 1980 to 2020 for management strategy 2 is projected to be 228 million acre-ft. Most (83 percent) of the 43-million-acre-ft difference between pumpage and water removed from storage would come from streamflow capture. The total projected streamflow capture for the northern High Plains by 2020 for management strategy 2 would be 1,700 ft^3/s.

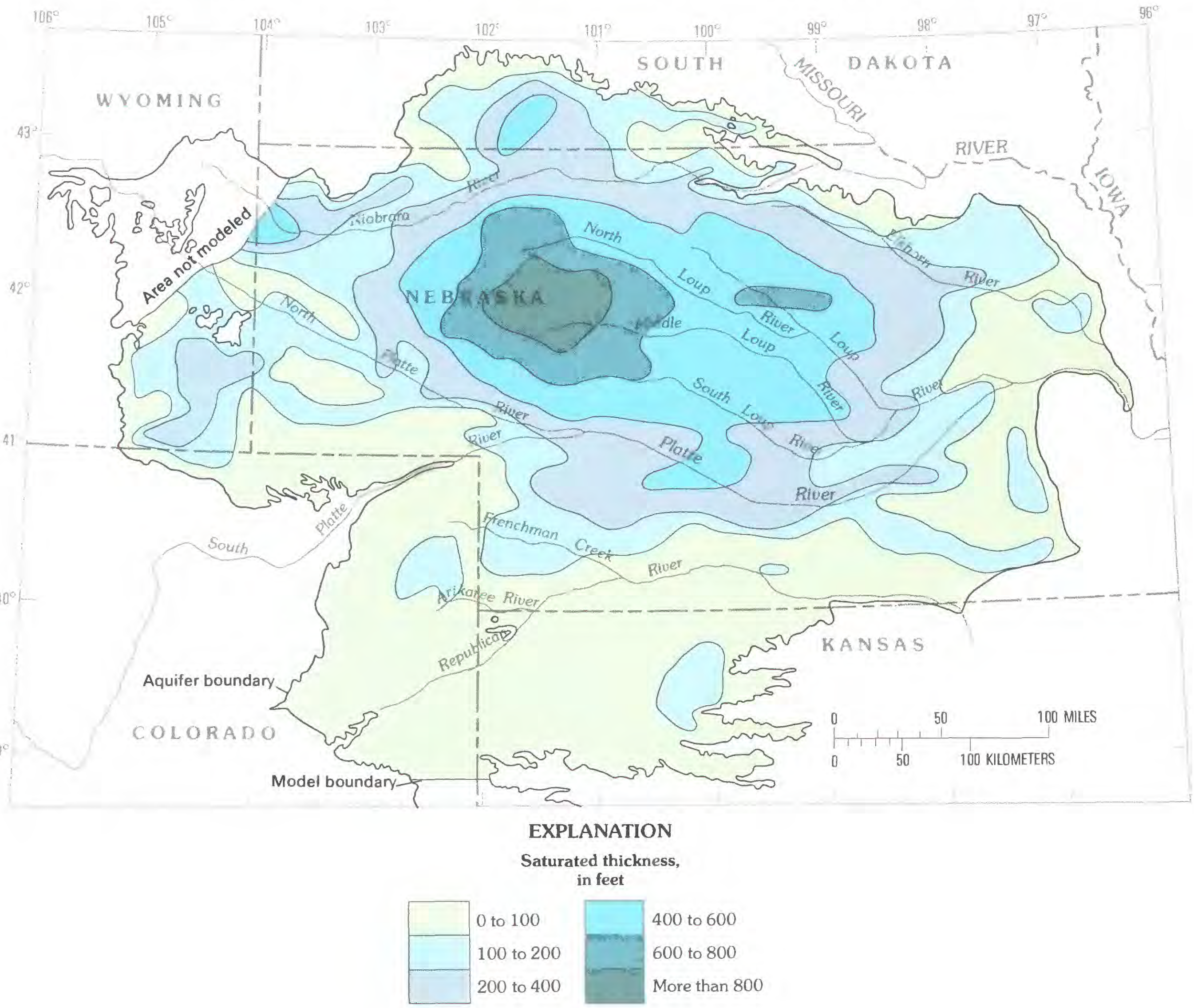

FIGURE 22.—Projected saturated thickness by 2020 in the northern High Plains resulting from pumpage for the baseline strategy.

The average streamflow capture would be 0.86 ft^3/s per mile of stream, and the maximum would be 18 ft^3/s per mile.

The average projected saturated thickness by 2020 for management strategy 2 would be 225 ft, but this is influenced by the large saturated thickness in central Nebraska where the projected saturated thickness would exceed 800 ft in places. The median simulated saturated thickness projected by 2020 for management strategy 2 would be 152 ft.

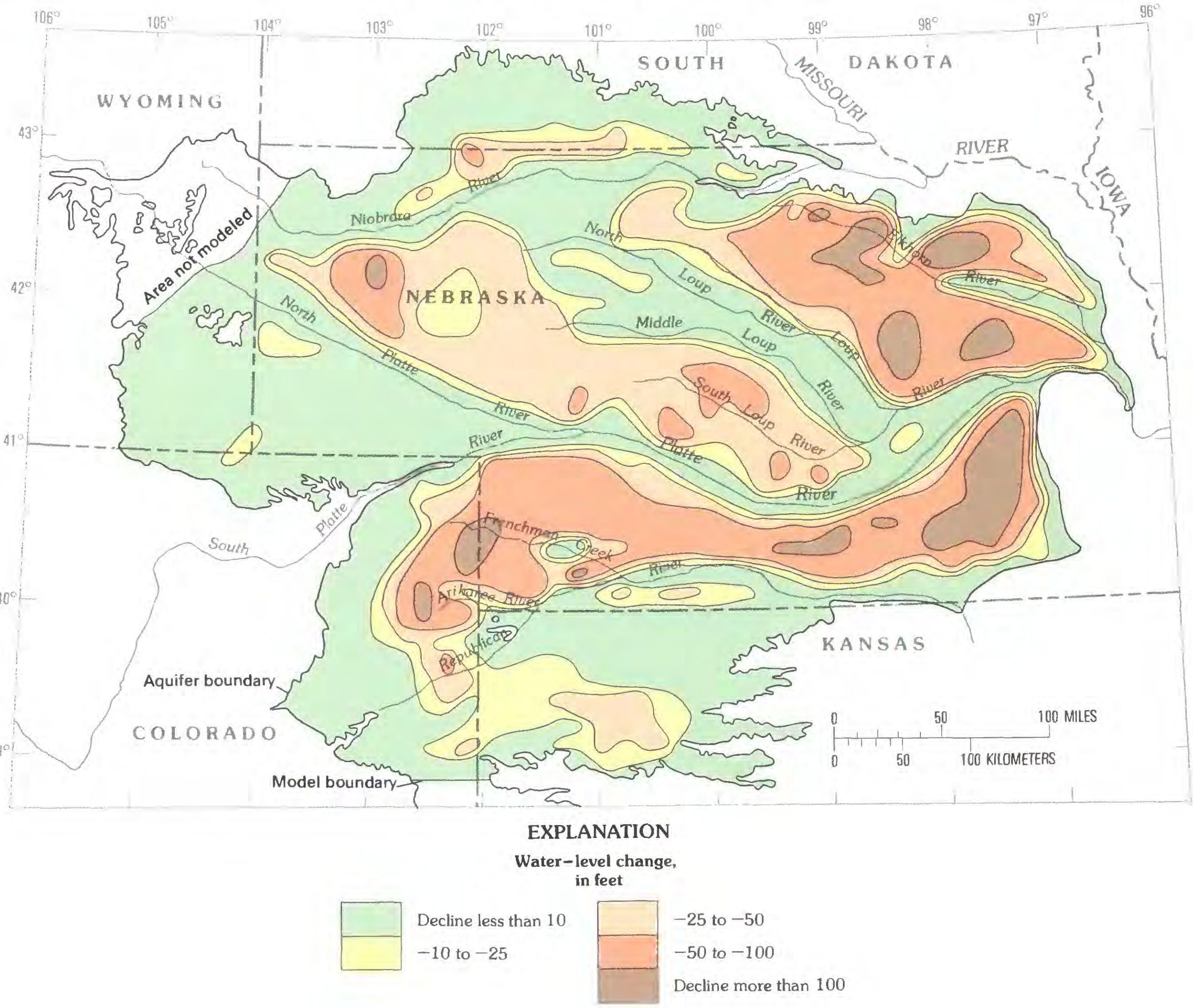

FIGURE 23.—Projected water-level declines, 1980 to 2020, for the northern High Plains resulting from pumpage for management strategy 2.

COMPARISON OF STRATEGIES

The water-level declines projected for the baseline strategy and management strategy 1 would be virtually identical for the entire northern High Plains, but declines resulting from management-strategy-2 pumpage would be much less. The average water-level decline from 1980 to 2020 for the baseline strategy would be 36 ft, and the average decline for management strategy 2 would be 28 ft. The median water-level declines for the same period would be 14 ft for the baseline strategy and 11 ft for management strategy 2.

The difference in saturated thickness between management strategy 2 and the baseline strategy is shown in figure 24. More than 50 ft of saturated thickness would be saved in several areas totaling 750 mi^2 in eastern Colorado and eastern Nebraska as a result of the mandatory decrease in water use in management strategy 2. The maximum difference in saturated thickness by 2020 between management strategy 2 and the baseline strategy would be 67 ft. The difference in saturated thickness would exceed 10 ft in 27 percent of the northern High Plains. Most of this area is between the Republican and Platte Rivers and north of the Loup River system. Although the average difference in saturated thickness between management strategy 2 and the baseline strategy by 2020 would be almost 8 ft, the median difference only would be slightly more than 1 ft. In areas with differences in saturated thickness of less than 10 ft, the average difference is 1.34 ft.

In addition to the difference in saturated thickness, streamflow capture also would be decreased. The decrease in streamflow capture between the baseline strategy and management strategy 2 would be 19 million acre-ft during the 40 years, and by 2020, streamflow for management strategy 2 would be 1,050 ft^3/s more than that for the baseline strategy.

As a result of baseline-strategy pumpage, the volume of drainable water in storage in the northern High Plains is projected to be 1,810 million acre-ft in 2020. Virtually the same volume of water would remain in storage assuming management-strategy-1 pumpage. About 63 million acre-ft more water would remain in storage by 2020 for management strategy 2 than for

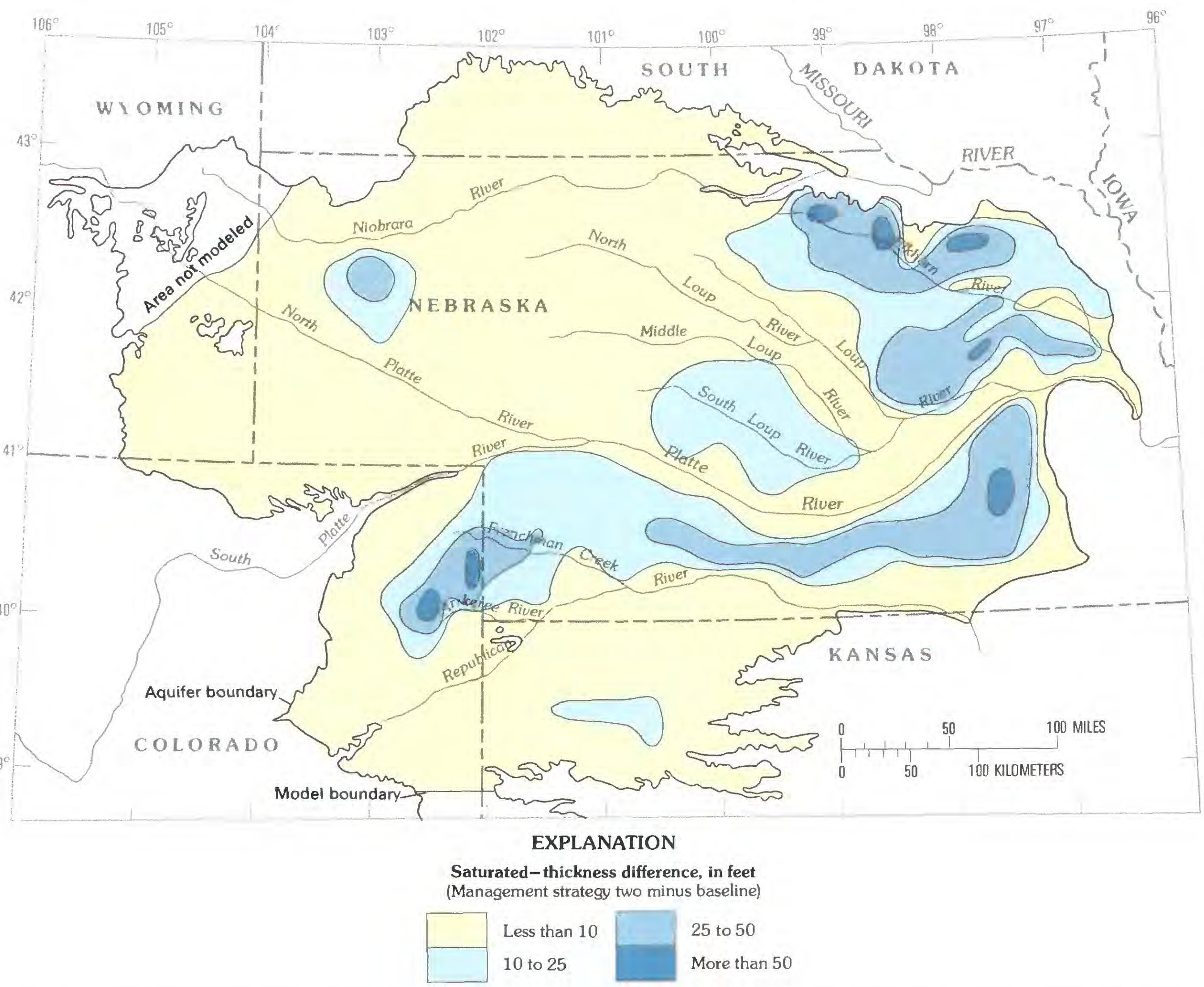

FIGURE 24.—Difference in projected saturated thickness by 2020 between management strategy 2 and the baseline strategy for the northern High Plains.

the baseline strategy. Although this is only 3.5 percent of the water projected to remain in storage by 2020, it represents an 8.7-year supply of water at the 2015–2019 management-strategy-2 withdrawal rate.

PROJECTED WELL YIELDS

Water-level declines increase the cost of pumping and decrease well yields. Gutentag and others (1984, p. 47) reported that well yield

> "***required to irrigate a specific number of acres will depend on the crop and soil type, climate, and irrigation system. Typically, one well capable of producing 250 gal/min can irrigate 40 acres; one well capable of producing 750 gal/min can irrigate 160 acres and effectively operate a quarter-section center-pivot system. Of course, it is possible to use several wells operated as a unit to obtain the desired yield. But, at some point, well yields will become a constraint to irrigation development because of the costs associated with drilling, operating, and maintaining additional wells."

Determining potential well yields was the first step in calculating the probable well yields. Potential well yields in the High Plains were calculated by solving the Theis (1935) equation with the water-table correction (Jacob, 1963). The hypothetical well used in the calculation was assumed to be pumped continuously for 90 days (irrigation season). The well was assumed to have an effective radius of 1.25 ft because irrigation wells commonly are constructed by gravel packing a 16-in. screen in a 30-in. hole. The water level in the aquifer adjacent to the well at the end of the 90-day pumping period was assumed to be 15 ft above the base of the aquifer. Interference from nearby wells was neglected in the calculation, because well spacing in the High Plains normally is about 0.5 mi and interference usually is small. These assumptions are the same as those used by Lindner-Lunsford and Borman (1985) for the High Plains in Colorado but are somewhat different from those used by Gutentag and others (1984, p. 47). The potential well yield was calculated by the following equation based on the above described assumptions.

$$Q_p = \frac{0.0326K(m^2-225)}{\log_e(mK/Sy)+4.8626} \qquad (1)$$

where Q_p is the potential well yield in gallons per minute;
K is the hydraulic conductivity, in feet per day;
m is the saturated thickness, in feet; and
Sy is the specific yield (dimensionless).

Probable well yield was then calculated by multiplying the potential well yield by 0.65 to account for the inherent inefficiencies of constructed wells. The probable well yield is given by

$$Q = \frac{0.0212K(m^2-225)}{\log_e(mK/Sy)+4.8626} \qquad (2)$$

where Q is the probable well yield in gallons per minute and the other symbols are as defined above. The probable well yield was calculated for each model node of the southern, central, and northern High Plains models using equation 2.

Probable well yields for the High Plains by 2020, based on projected saturated thickness resulting from baseline-strategy pumpage, are shown in figure 25. Probable well yields in 2020 would be greatest in the northern High Plains and least in the southern High Plains.

The percentage change in probable well yields from 1980 to 2020 for the High Plains is shown in figure 26. The change-in-yield map is based on the difference in probable well yields in 1980 and that projected by 2020 as a result of baseline-strategy pumpage. As expected, the largest percentage changes would occur where the projected water-level change from 1980 to 2020 is large and the 1980 saturated thickness was small. Decreases in probable well yields are projected to be greatest in the southern High Plains and least in the northern High Plains.

SOUTHERN HIGH PLAINS

Throughout 80 percent of the southern High Plains, the probable well yields by 2020 (fig. 25) are projected to be less than 250 gal/min although there would be several areas totaling 2,050 mi^2 where the probable well yields are projected to exceed 750 gal/min. The largest of these areas, in the east-central part of the southern High Plains, had significant saturated thickness in 1980 (Weeks and Gutentag, 1981) and very little projected water-level decline from 1980 to 2020, so the probable well yields by 2020 would be similar to those in 1980. The average probable well yield by 2020 for the southern High Plains on the basis of projected pumpage for the baseline strategy would be 230 gal/min, but the median would be much less. The average for the area with probable well yields of less than 250 gal/min would be only 32 gal/min. Similar results were obtained for management strategy 1. For management strategy 2, the average probable well yield for the southern High Plains by 2020 is projected to be 290 gal/min.

In about 38 percent of the southern High Plains, probable well yields are projected to decrease by more than 75 percent from 1980 to 2020 as a result of baseline-strategy pumpage (fig. 26). In about 56 percent of the area, well yields are projected to decrease by more than

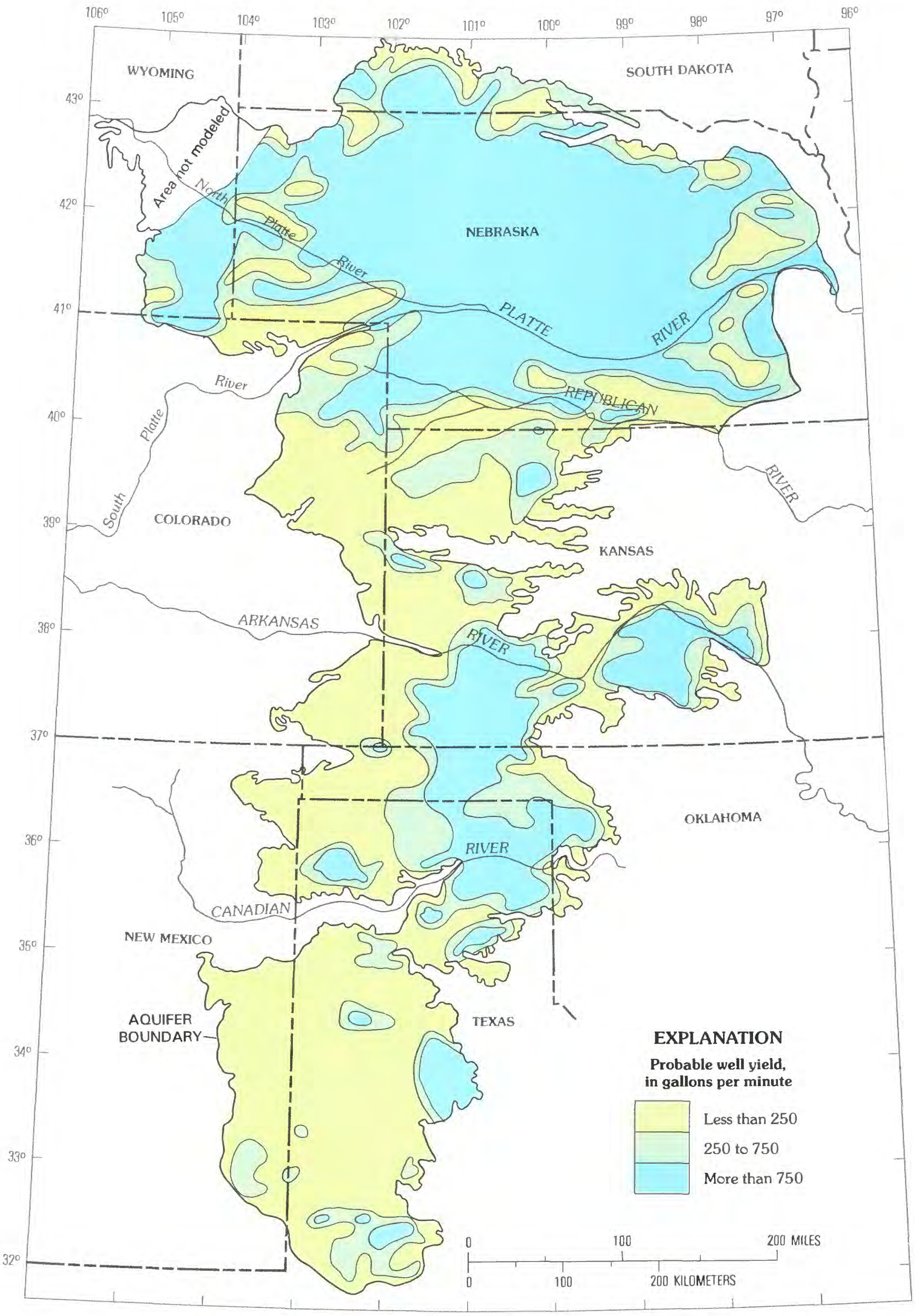

FIGURE 25.—Probable well yields by 2020 for the High Plains resulting from pumpage for the baseline strategy.

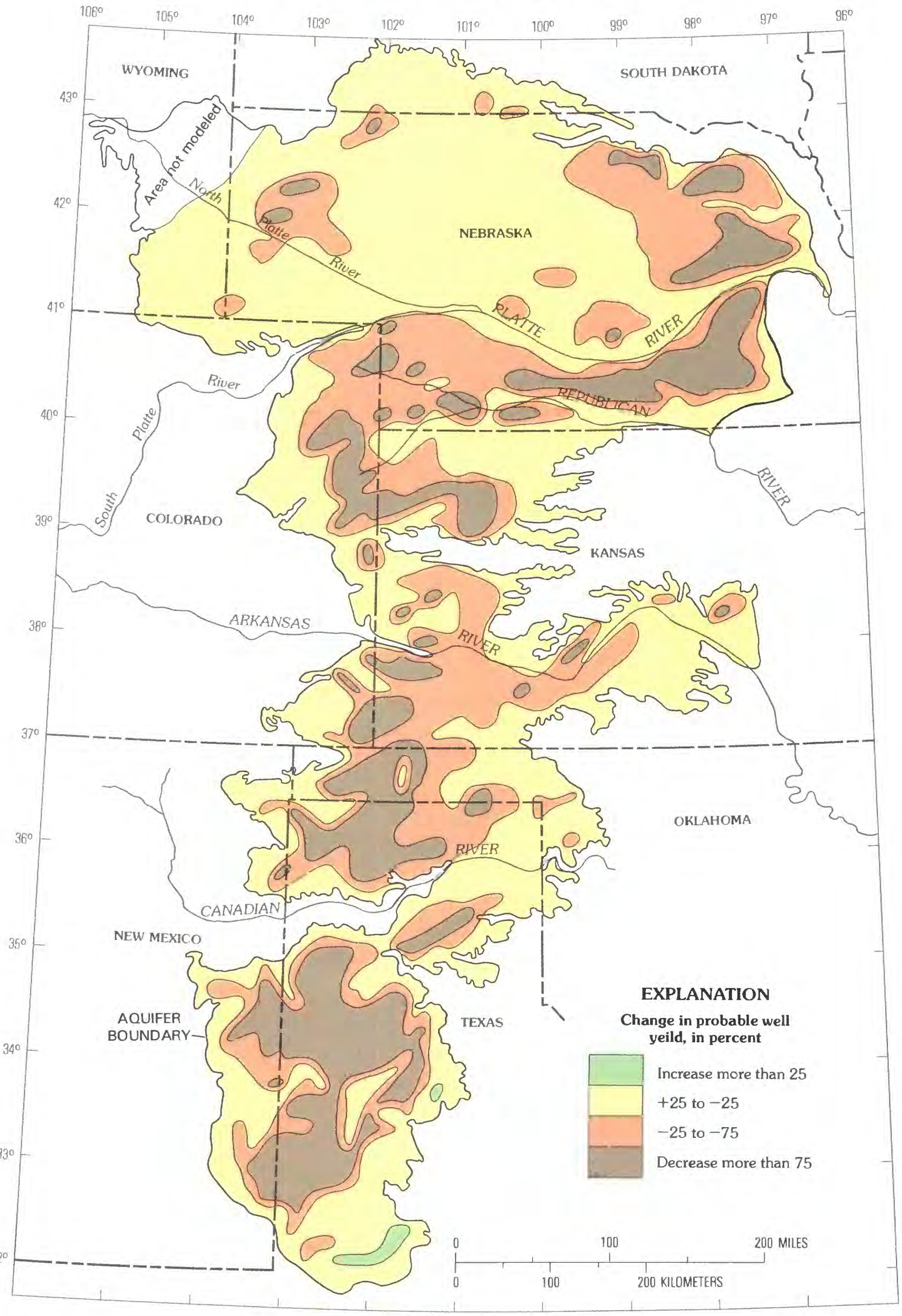

FIGURE 26.—Percentage changes in probable well yields, 1980 to 2020, for the High Plains resulting from pumpage for the baseline strategy.

25 percent by 2020. In two areas totaling 620 mi², the probable well yields are projected to increase by more than 25 percent by 2020 because water levels are projected to rise in these areas (fig. 6).

CENTRAL HIGH PLAINS

Most of the western part of the central High Plains is projected to have well yields of less than 250 gal/min by 2020 as a result of baseline-strategy pumpage (fig. 25). Significant water-level declines from 1980 to 2020 are projected for this area (fig. 13), and these declines, combined with small saturated thickness in 1980 (Weeks and Gutentag, 1981), are projected to decrease probable well yields to less than 250 gal/min. East of about long 101°30′ W., projected well yields by 2020 generally would be greater than 750 gal/min. Although this area is projected to have significant water-level declines from 1980 to 2020, the saturated thickness in 1980 generally was more than 200 ft and the well yields are projected to remain greater than 750 gal/min by 2020. Wells in the central High Plains are projected to yield less than 250 gal/min in about 47 percent of the area and more than 750 gal/min in 32 percent of the area. For the baseline strategy, the median probable well yield by 2020 is projected to be 370 gal/min. For management strategy 1, the median is projected to be 350 gal/min, whereas for management strategy 2, the median is projected to be 430 gal/min.

Probable well yields in the central High Plains as a result of baseline-strategy pumpage are projected to decrease by more than 75 percent from 1980 to 2020 in several areas (fig. 26), most of which are west of long 101° W. Probable well yields are projected to decrease by 25–75 percent in about 15,000 mi² and by more than 75 percent in 7,050 mi². Many of the largest percentage changes in probable well yield are projected to occur in those areas which had less than 100 ft of saturated thickness in 1980.

NORTHERN HIGH PLAINS

In the northern High Plains, well yields are projected to be greater than 750 gal/min in 58 percent of the area by 2020 (fig. 25). The only large areas in the northern High Plains with projected well yields of less than 250 gal/min would be south of lat 40°30′ N. and between the North and South Platte Rivers in Colorado and Nebraska. In the northern High Plains, significant decreases in probable well yields are projected south of the Platte Rivers (fig. 26). North of the Platte Rivers, significant decreases are projected east of long 99° W. and in the vicinity of long 103° W. These changes are in areas that had substantial irrigation in 1978 (fig. 3). The saturated thickness is so large throughout much of the northern High Plains that even with large projected water-level declines from 1980 to 2020, well yields will still exceed 750 gal/min by 2020 (fig. 25).

SUMMARY AND CONCLUSIONS

The High Plains is one of the major irrigated agricultural areas of the United States and in 1980 accounted for more than 20 percent of the irrigated land and about 30 percent of the ground water pumped for irrigation in the Nation. Throughout much of the High Plains, the rate of withdrawal of ground water for irrigation exceeds the natural rate of replenishment and, as a consequence, water-level declines have occurred. The U.S. Geological Survey began a regional geohydrologic study of the 174,000-mi² High Plains aquifer in 1978. One of the objectives of the study was to evaluate the effects of future pumpage on the High Plains aquifer.

The High Plains aquifer system was divided into three parts: the southern High Plains, the central High Plains, and the northern High Plains; each part was simulated separately. The models of each part were first calibrated so that they could adequately simulate historical hydrologic conditions. The models were calibrated by comparing simulated and measured water levels or water-level changes for predevelopment and development periods. The predevelopment-period models simulated the system prior to large-scale irrigation development; the development-period models simulated the system after the beginning of large-scale irrigation development. Once the models were calibrated, they were used to project the hydrologic effects of estimated future ground-water pumpage.

Three different water-management strategies, as defined by an economic study of the High Plains region (High Plains Associates, 1982), were simulated. The baseline strategy assumed continuation of current (1980) economic trends and governmental policies. Management strategy 1 assumed voluntary adoption of new techniques to decrease irrigation water use. Management strategy 2 assumed an additional mandatory decrease in water use from management strategy 1. The total pumpage simulated for 1980 to 2020 was 628 million acre-ft for the baseline strategy, 647 million acre-ft for management strategy 1, and 497 million acre-ft for management strategy 2. Pumpage increased between the baseline strategy and management strategy 1 because increased irrigated acreage in management strategy 1 more than offset the decreased per-acre water use for this strategy. The simulated

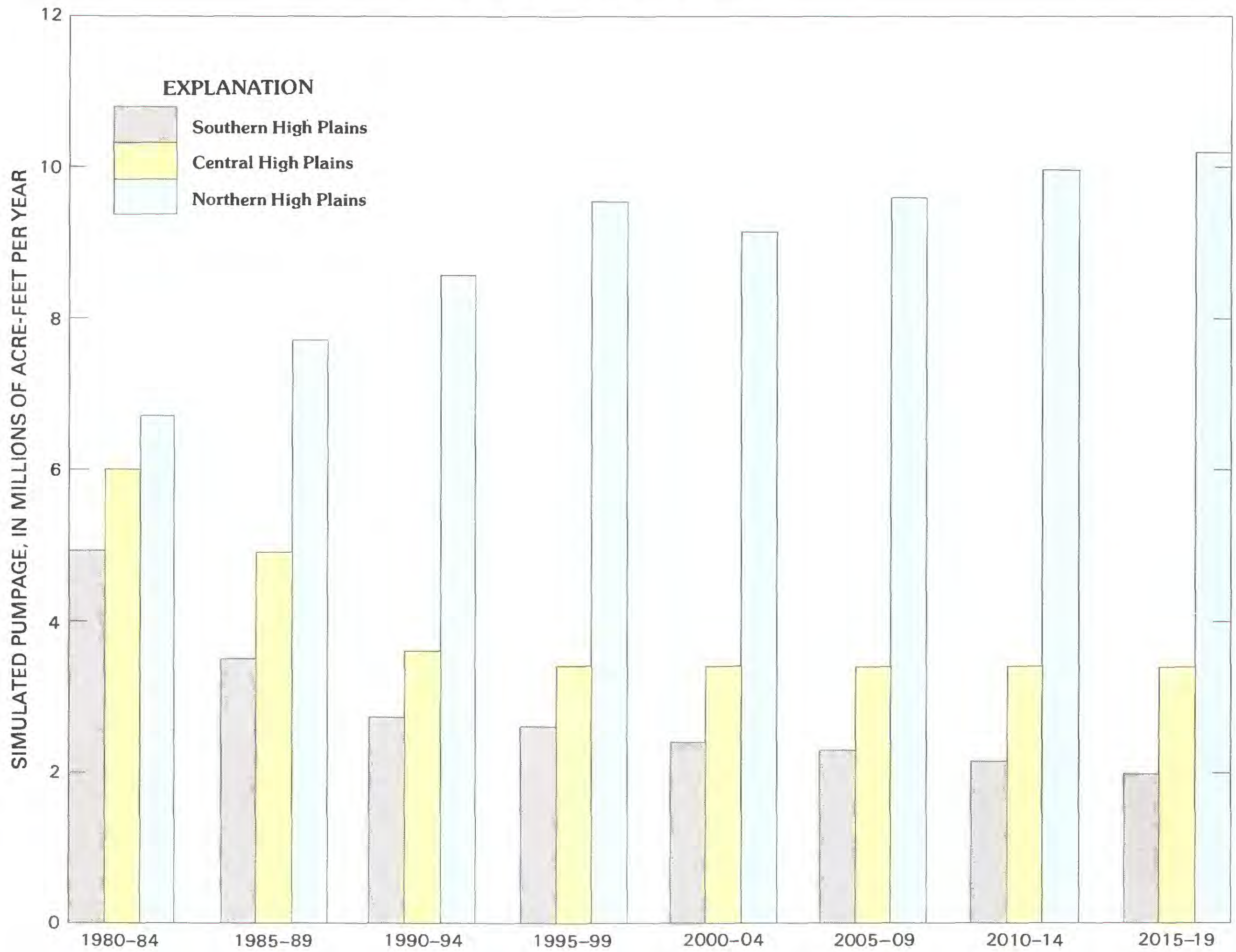

FIGURE 27.—Simulated pumpage for the baseline strategy by High Plains model region.

pumpage for the baseline strategy by High Plains model region is shown in figure 27.

In the southern High Plains, the total simulated pumpage from 1980 to 2020 would be 113 million acre-ft for the baseline strategy, 109 million acre-ft for management strategy 1, and 88 million acre-ft for management strategy 2. Projected water-level declines from 1980 to 2020 resulting from baseline-strategy pumpage would exceed 150 ft in parts (700 mi^2) and exceed 10 ft throughout much of the southern High Plains. During the 40 years from 1980 to 2020, 101 million acre-ft of water are projected to be removed from the southern High Plains aquifer, and by 2020, more than one-half of the area would have less than 25 ft of saturated thickness remaining. Slightly more than 100 million acre-ft of drainable water would remain in storage compared to about 200 million acre-ft during 1980. By 2020, probable well yields throughout most (80 percent) of the southern High Plains would be less than 250 gal/min.

Projected water-level declines for the southern High Plains resulting from management-strategy-1 pumpage are similar to those projected for the baseline strategy. The average water-level decline would be only 1 ft less for management strategy 1 than for the baseline strategy.

Projected water-level declines from 1980 to 2020 resulting from management-strategy-2 pumpage are significantly less than those for the baseline strategy. Water levels in only one small area (30 mi^2) are projected to decline more than 150 ft. The average water-level decline from 1980 to 2020 is projected to be 7 ft less for management strategy 2 than for the baseline strategy, and saturated thickness is projected to be 25 ft greater in 3,200 mi^2 (11 percent of the area) as a result of the decreased water use between the baseline strategy and management strategy 2.

In the central High Plains, simulated pumpage from 1980 to 2020 would be 158 million acre-ft for the baseline strategy, 178 million acre-ft for management strategy

1, and 138 million acre-ft for management strategy 2. Projected water-level declines from 1980 to 2020 resulting from baseline-strategy pumpage would exceed 200 ft in about 150 mi^2 (less than 1 percent of the area) and 25 ft in about one-third of the area. About 138 million acre-ft of water are projected to be removed from storage as a result of 40 years of baseline-strategy pumpage; the average saturated thickness will be about 100 ft by 2020. About 550 million acre-ft of drainable water would remain in storage in 2020 assuming baseline-strategy pumpage. Probable well yields in the central High Plains would decrease by more than 25 percent from 1980 to 2020 in 47 percent of the area, but would be more than 750 gal/min in 32 percent of the area.

Total management-strategy-1 pumpage in the central High Plains would be 13 percent greater than total baseline-strategy pumpage. Consequently, water-level declines would be greater assuming management strategy 1.

Projected water-level declines from 1980 to 2020 resulting from management-strategy-2 pumpage would be everywhere less than those resulting from management-strategy-1 pumpage. There are areas in Kansas where water-level declines projected for management strategy 2 exceed those projected for the baseline strategy due to an increase in irrigated acreage. For management strategy 2, water-level declines of more than 100 ft from 1980 to 2020 are projected in about 1,700 mi^2 (4 percent of the area).

In the northern High Plains, simulated pumpage from 1980 to 2020 would be 357 million acre-ft for the baseline strategy, 360 million acre-ft for management strategy 1, and 271 million acre-ft for management strategy 2. Projected water-level declines from 1980 to 2020 for the baseline strategy would exceed 200 ft in a few isolated areas and exceed 100 ft throughout more than 9,700 mi^2 (10 percent of the area). The average water-level decline from 1980 to 2020 for the baseline strategy would be 36 ft, and the average saturated thickness by 2020 would be 217 ft. About 1,810 million acre-ft of drainable water would remain in storage in 2020 assuming baseline-strategy pumpage. Probable well yields are projected to decline by more than 75 percent from 1980 to 2020 in parts of the northern High Plains. However, probable well yields of more than 750 gal/min by 2020 are projected for 58 percent of the area.

Management-strategy-1 pumpage in the northern High Plains would be nearly identical to baseline-strategy pumpage. Consequently, the water-level declines from 1980 to 2020 as a result of management-strategy-1 pumpage would be almost identical to those projected for the baseline.

For management strategy 2, water-level declines of more than 100 ft from 1980 to 2020 would occur in about 5,400 mi^2 (6 percent of the area). The average water-level decline from 1980 to 2020 as a result of management-strategy-2 pumpage would be 8 ft less than that for the baseline strategy. Water-level declines for management strategy 2 would be at least 10 ft less than those for the baseline strategy in more than one-fourth of the northern High Plains and at least 50 ft less in about 750 mi^2 (less than 1 percent of the area). For all strategies, more than 800 ft of saturated thickness are projected to remain in the central part of Nebraska by 2020.

Streamflow capture is important in the northern High Plains aquifer. For all three strategies, the base flow of the South Loup River and parts of the Elkhorn and Republican Rivers were projected to be depleted after 1990. For the baseline strategy, projected streamflow capture would be about 60 million acre-ft from 1980 to 2020. By 2020, the baseline-strategy projected rate of streamflow capture would be 2,750 ft^3/s. For management strategy 2, projected streamflow capture would be about 36 million acre-ft from 1980 to 2020. Most of the streamflow capture would be caused by wells within 10 mi of the streams.

From 1980 to 2020 for all three strategies, pumpage will decrease in the southern and central High Plains, but will increase in the northern High Plains. Water levels will continue to decline during the 40 years as a result of the pumpage. Water-level declines resulting from baseline-strategy pumpage will exceed 200 ft in a few small areas of the High Plains, and water-level declines will exceed 100 ft in more than 15,500 mi^2. More than one-half of the 174,000-mi^2 High Plains area will have water-level declines of more than 10 ft from 1980 to 2020.

Declining water levels will decrease the rate at which water can be pumped. Probable well yields by 2020 are projected to exceed 750 gal/min in small areas of the southern High Plains, large parts of the central High Plains, and most of the northern High Plains. Probable well yields by 2020 are projected to be less than 250 gal/min in most of the southern High Plains, in about one-half of the central High Plains, and in small parts of the northern High Plains.

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