High Plains Aquifer Water-Level Changes, Predicted and Actual

Several reports are included here that related to predicted or actual water level changes and time to depletion of groundwater in the High Plains Aquifer.

Predicted Water-Level Changes, 1988 USGS Report

This report describes a modeling analysis that evaluated three scenarios over the period 1980-2020 for the entire High Plains Aquifer: continuing the same growth and water management policies that were in place in 1980, voluntary decreased irrigation water use, and mandatory decreased irrigation water use. A summary of the results of these analyses predicting future water-level declines for the Nebraska portion of the aquifer begins on page 2. The full report is available as Appendix A.

Actual Water-Level Changes, 2014 USGS Report

This report presents water-level changes in the High Plains Aquifer from predevelopment (generally before 1950) to 2013, and from 2011 to 2013, as well as change in water storage in the High Plains Aquifer for these same time periods. For comparison with the predicted water-level changes from the 1988 report, a summary of actual water-level changes from predevelopment to 2013 is shown on page 4. The full report is available as Appendix B.

Comparison of Predicted and Actual Water-Level Changes

The actual water-level declines within the Nebraska portion of the Republican River Basin from predevelopment to 2013 were lower than the modeled declines that were predicted for the period 1980-2020. This comparison is explored in greater depth on page 5.

Analysis of Risk: Time to Depletion

The Department of Homeland Security Office of Cyber and Infrastructure Analysis (OCIA) produced a report on High Plains Aquifer risk and associated impacts in 2015. One aspect of this report is an estimation of time to depletion of the groundwater resource at current pumping rates. A summary of the report's findings is shown on page 7. The full report is available as Appendix C.

Predicted Water-Level Changes, 1988 USGS Report

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, 1988).

This USGS Report summarizes the results of a modeling analysis that evaluated three scenarios over the period 1980-2020 for the entire High Plains Aquifer: baseline strategy (i.e., continuing the same growth and water management policies that were in place in 1980), voluntary decreased irrigation water use, and mandatory decreased irrigation water use.

In the Nebraska portion of the Republican Basin, the baseline scenario and the first management scenario (i.e., voluntary decreased irrigation water use) predicted declines ranging from less than 10 feet to 150 feet (Figure 1), and the second management scenario (i.e., mandatory decreased irrigation water use) predicted decline ranging from less than 10 feet to 100 feet in most of the basin (Figure 2). The figures below summarize the analysis results for the Nebraska portion of the aquifer.

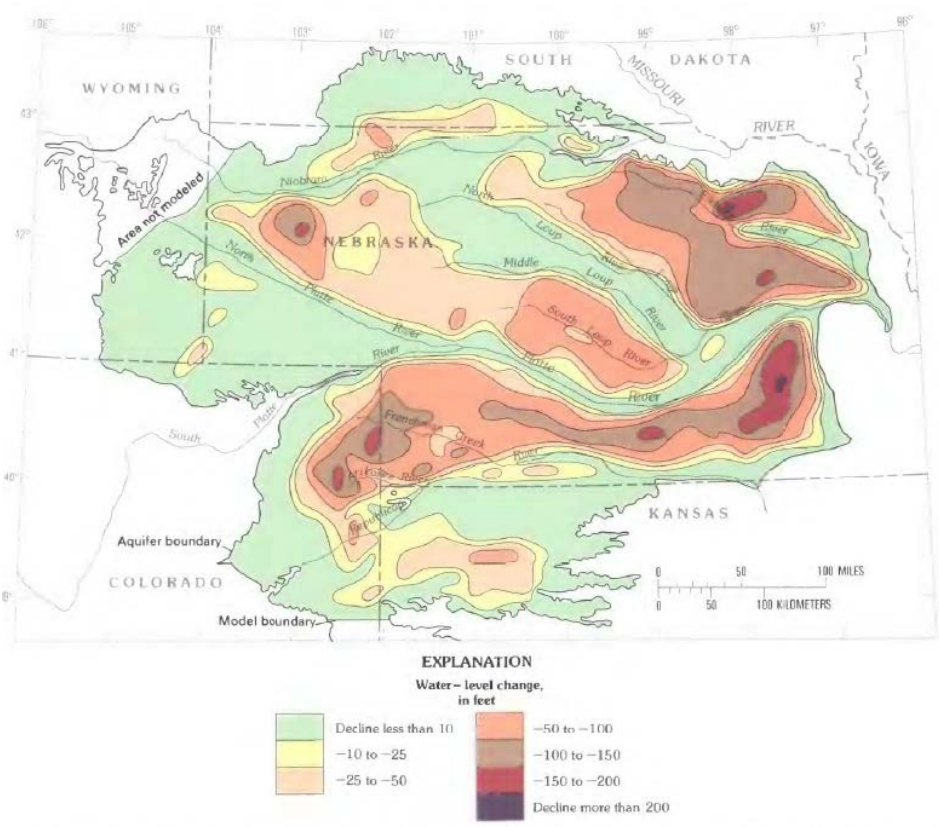


Figure 1. Projected water-level declines, 1980 to 2020, for the northern High Plains resulting from the baseline strategy of continuing the same growth and water management policies that were in place in 1980 (U.S. Geological Survey Professional Paper 1400-E, 1988).

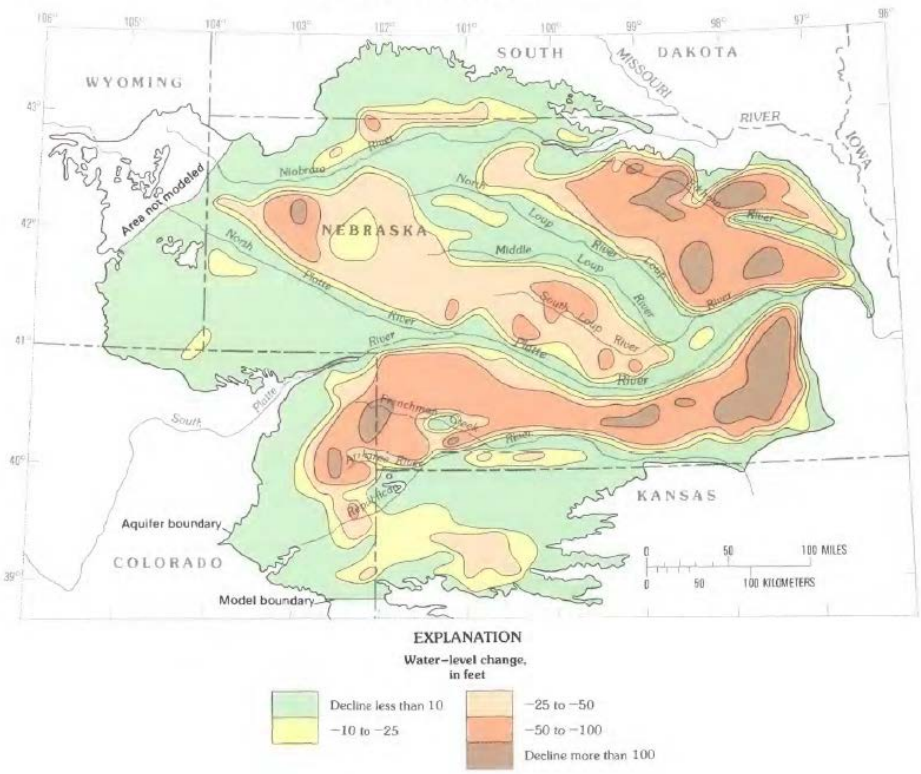


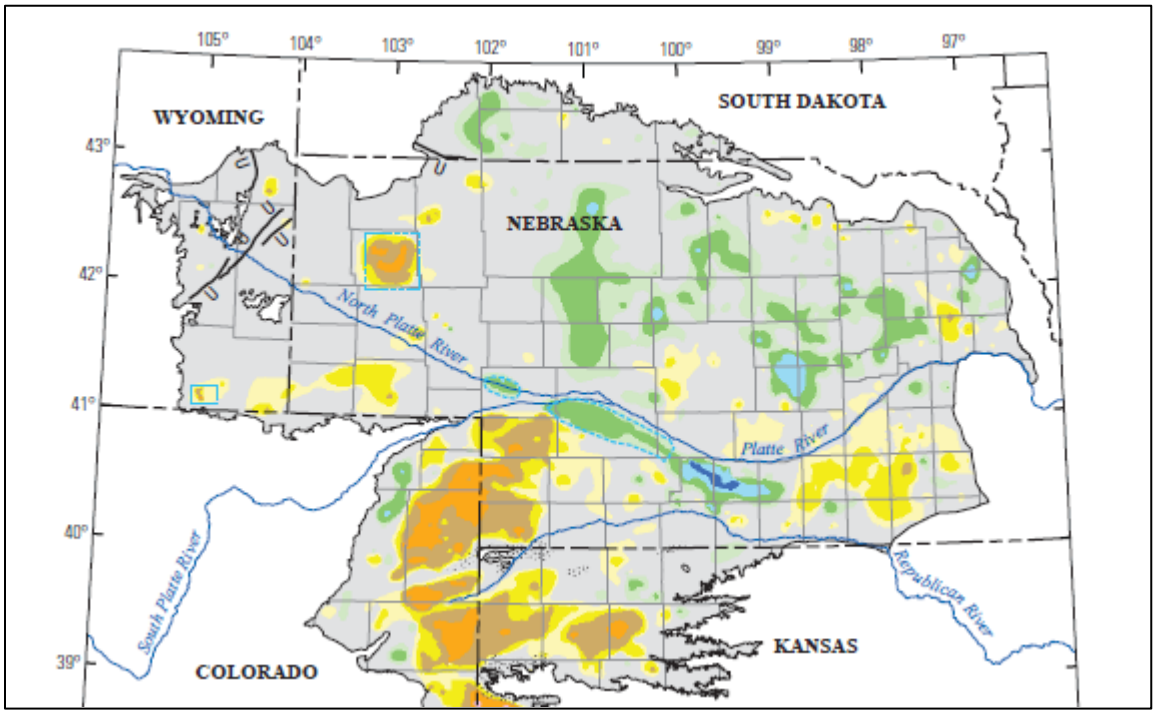
Figure 2. Projected water-level declines, 1980 to 2020, for the northern High Plains resulting from pumpage for management strategy 2, instituting a mandatory decrease in irrigation water use (U.S. Geological Survey Professional Paper 1400-E, 1988).

The full report is available as Appendix A.

Actual Water-Level Changes, 2014 USGS Report

Water-Level Changes and Change in Water in Storage in the High Plains Aquifer, Predevelopment to 2013 and 2011-13 (U.S. Geological Survey Scientific Investigations Report 2014-5218).

According to this report, groundwater declines (predevelopment to 2013) in the Nebraska portion of the Republican River Basin ranged from less than 5 feet to 50-100 feet, with water-levels in much of the basin being identified as having experienced no substantial change, and a few areas experiencing water-level rises. The full report is available as Appendix B.



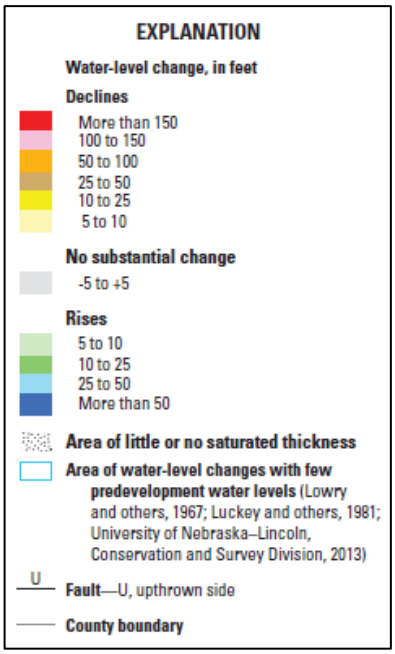


Figure 3. Water-level changes in the High Plains aquifer, predevelopment (about 1950) to 2013. Modified from U.S. Geological Survey Scientific Investigations Report 2014-5218 by cropping the image to focus only on the northern portion of the High Plains Aquifer.

Comparison of Predicted and Actual Water-Level Changes

The model used for the 1988 USGS report (page 2 and Appendix A) predicted that, with mandatory decreases in irrigation water use, water-level declines from 1980 to 2020 would range from less than 10 feet up to 100 feet for most of the Republican River Basin in Nebraska. Without mandatory decreases in irrigation water use, the predicted declines were even higher for this area, ranging from less than 10 feet up to 150 feet.

Mandatory decreases in irrigation groundwater uses were implemented by the NRDs in the form of allocations, starting in 1980 in the Upper Republican Natural Resources District and 2005 for the Lower and Middle Republican Natural Resources Districts.

The actual water-level declines reported in the 2014 USGS Report (page 4 and Appendix B) for the Republican River Basin in Nebraska from predevelopment (approximately 1950) to 2013 ranged from less than 5 feet to 50-100 feet, with water-levels in much of the basin being identified as having experienced no substantial change, and a few areas experiencing water-level rises.

While it is difficult to compare what was modeled to what actually occurred, because the models are for such large areas and the two analyses do not cover exactly the same time period, assumptions underlying the model-simulated water-level declines clearly predicted greater declines than what actually occurred in most of the Republican River Basin in Nebraska (Figures 4-6).

This comparison differs from what has occurred in the southern and central High Plains Aquifers (Appendices A and B). In general, the declines predicted in the 1988 report have occurred as predicted, according to the 2014 report. In contrast, while there are some areas of decline in the northern High Plains Aquifer, such as in the Upper Republican Natural Resources District, they are generally on the order of one-third of the declines observed in southwest Kansas and Texas, where no groundwater management occurs.

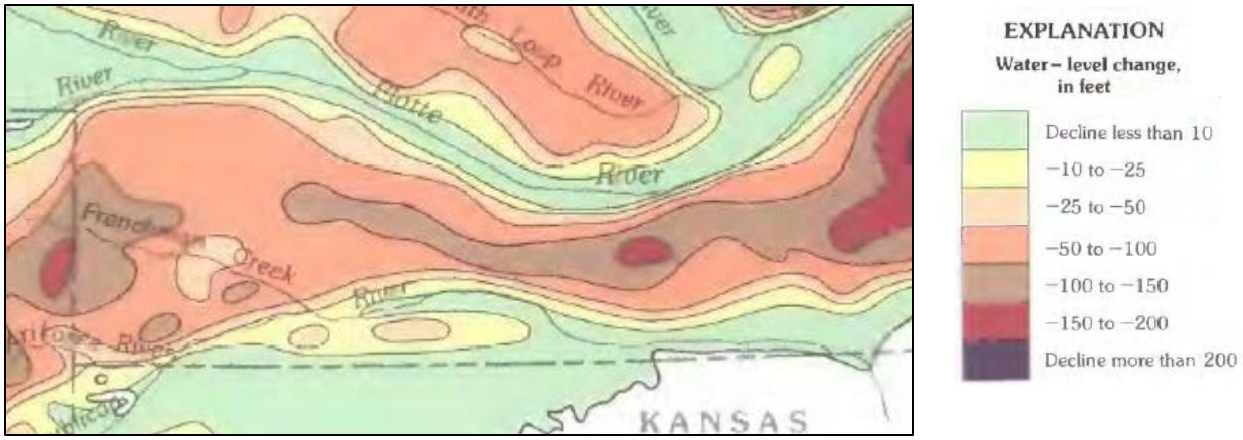


Figure 4. Predicted groundwater level-change 1980-2020 assuming continuation of 1980 growth and management practices. Modified from U.S. Geological Survey Professional Paper 1400-E (1988) by cropping image to focus on the Republican River Basin in Nebraska.

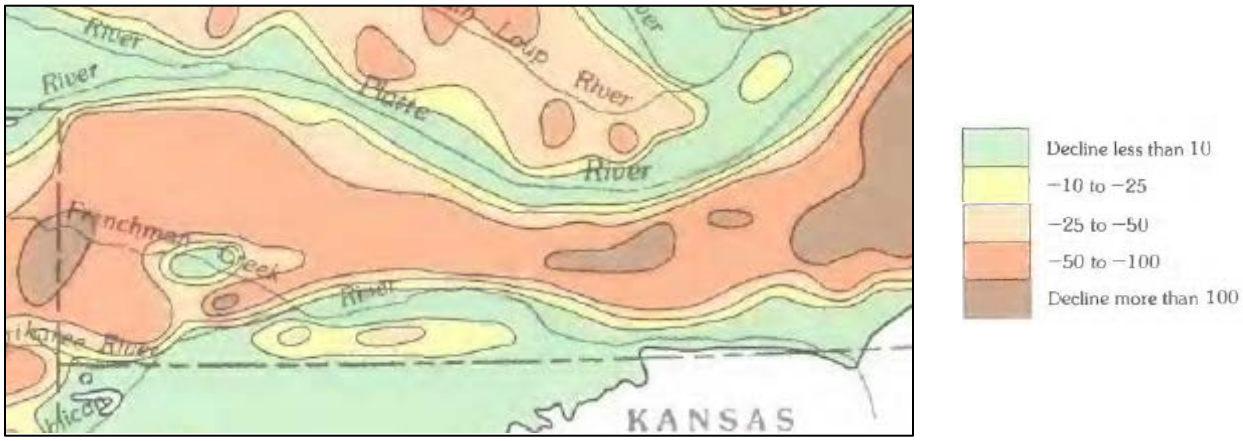


Figure 5. Predicted groundwater level-change 1980-2020 assuming mandatory decrease in irrigation water use. Modified from U.S. Geological Survey Professional Paper 1400-E (1988) by cropping image to focus on the Republican River Basin in Nebraska.

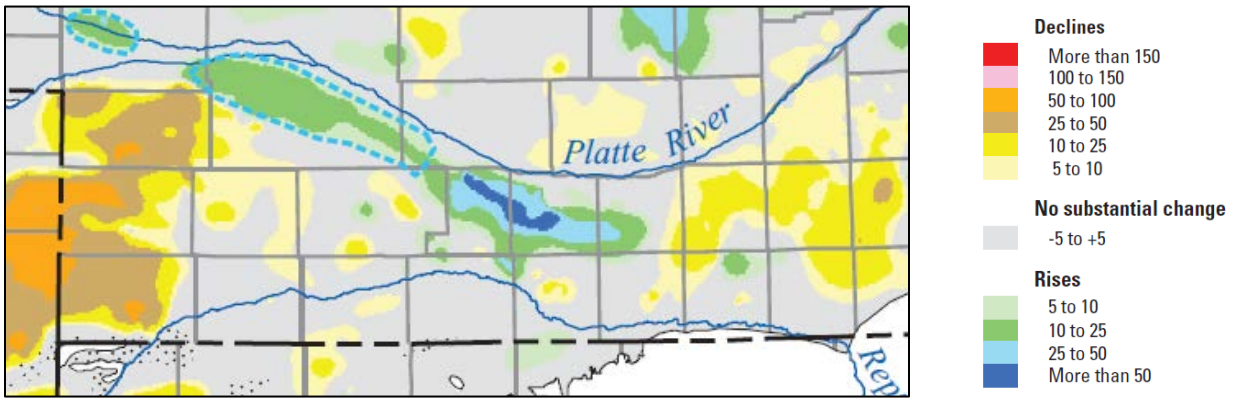


Figure 6. Water-level changes in the High Plains aquifer, predevelopment (about 1950) to 2013. Modified from U.S. Geological Survey Scientific Investigations Report 2014-5218 by cropping the image to focus on the Republican River Basin in Nebraska.

Analysis of Risk: Time to Depletion

Analysis of High Plains Resource Risk and Economic Impacts (U.S. Department of Homeland Security Office of Cyber and Infrastructure Analysis, 2015)

The Department of Homeland Security Office of Cyber and Infrastructure Analysis (OCIA) produced a report on High Plains Aquifer risk and associated impacts in 2015. One aspect of this report is an estimation of time to depletion of the groundwater resource at current pumping rates. The time to depletion for the portion of the High Plains Aquifer underlying the Republican River Basin in Nebraska ranges from 50-100 years to greater than 200 years. These results are summarized in Figure 7. The full report is available as Appendix C.

The OCIA report's estimate of time to depletion relies on several assumptions. First, due to data limitations, this study used a county-level analysis, which aggregates variability occurring below the county scale, and so does not capture the detailed aquifer response at a particular location. Second, the analysis projected "current pumping rates" forward in time in order to calculate the time to aquifer exhaustion; however, these "current pumping rates" were based on the USGS's county-level water use estimates for the year 2010. Thus, the analysis does not reflect more recent management actions or changes in groundwater withdrawals.

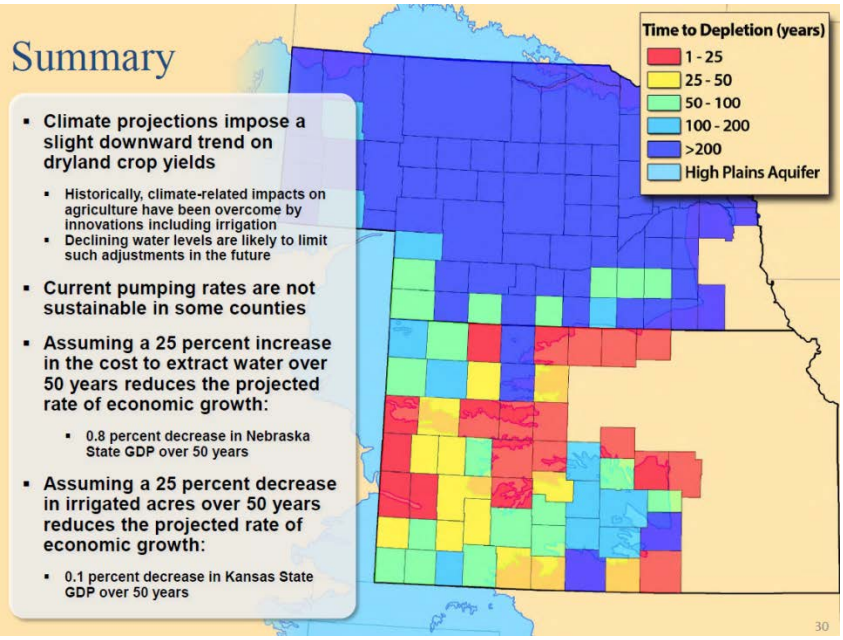


Figure 7. This figure summarizing the results of the OCIA's analysis of High Plains Aquifer risk and associated impacts is from a presentation given by OCIA during an August 31, 2015, briefing on the report. This summary slide was previously shared with the Republican River Basin-Wide Plan's stakeholder committee at a stakeholder meeting in August 2015. A figure showing the same time to depletion values is included in the full report (Appendix C).

Appendix A

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, 1988).

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

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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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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

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.

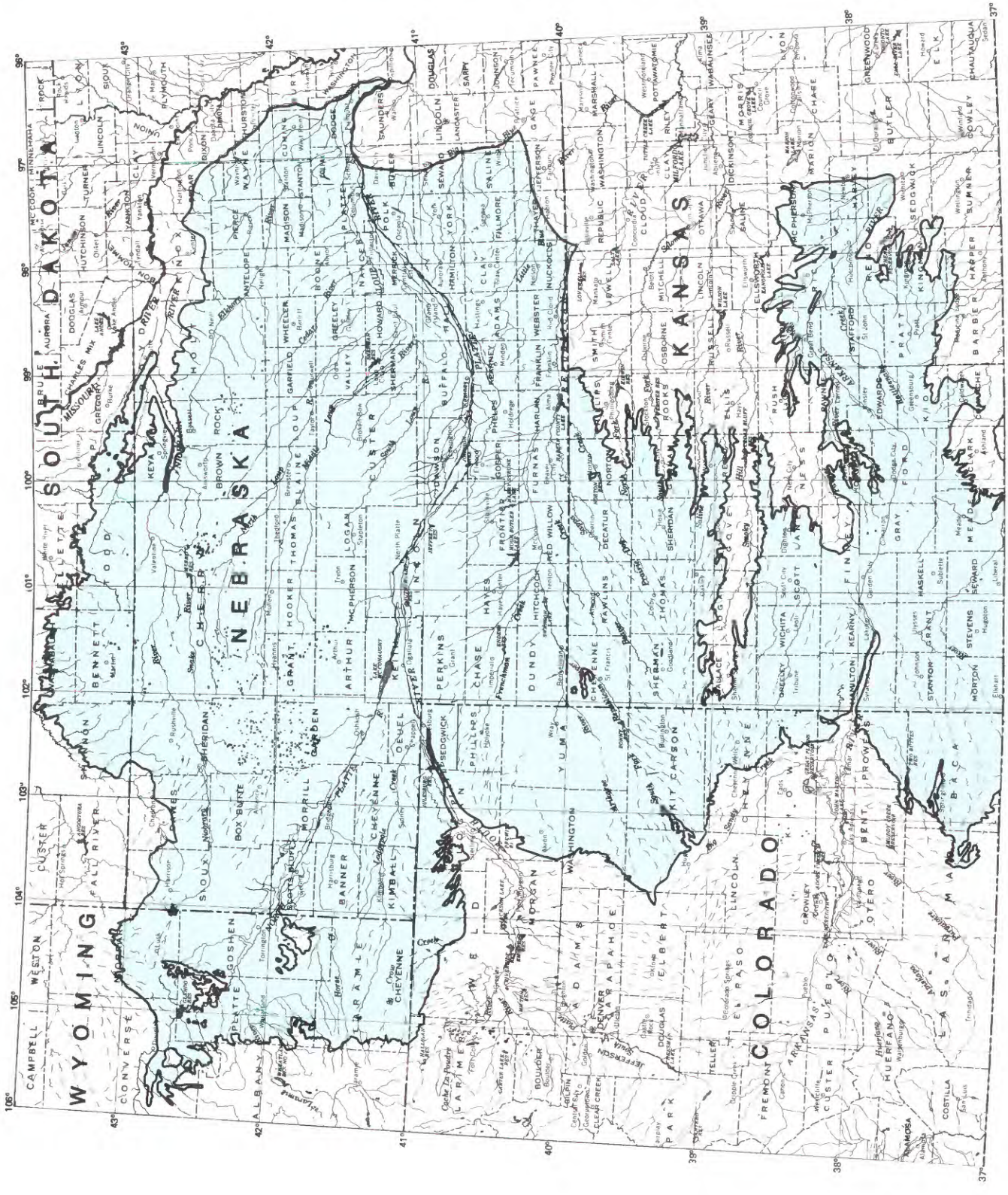
In the central High Plains, simulated pumpage from 1980 to 2020 would be 158 million acre-feet for the baseline strategy, 178 million acre-feet for management strategy 1, and 138 million acre-feet for management strategy 2. For the baseline strategy, water levels in the central High Plains are projected 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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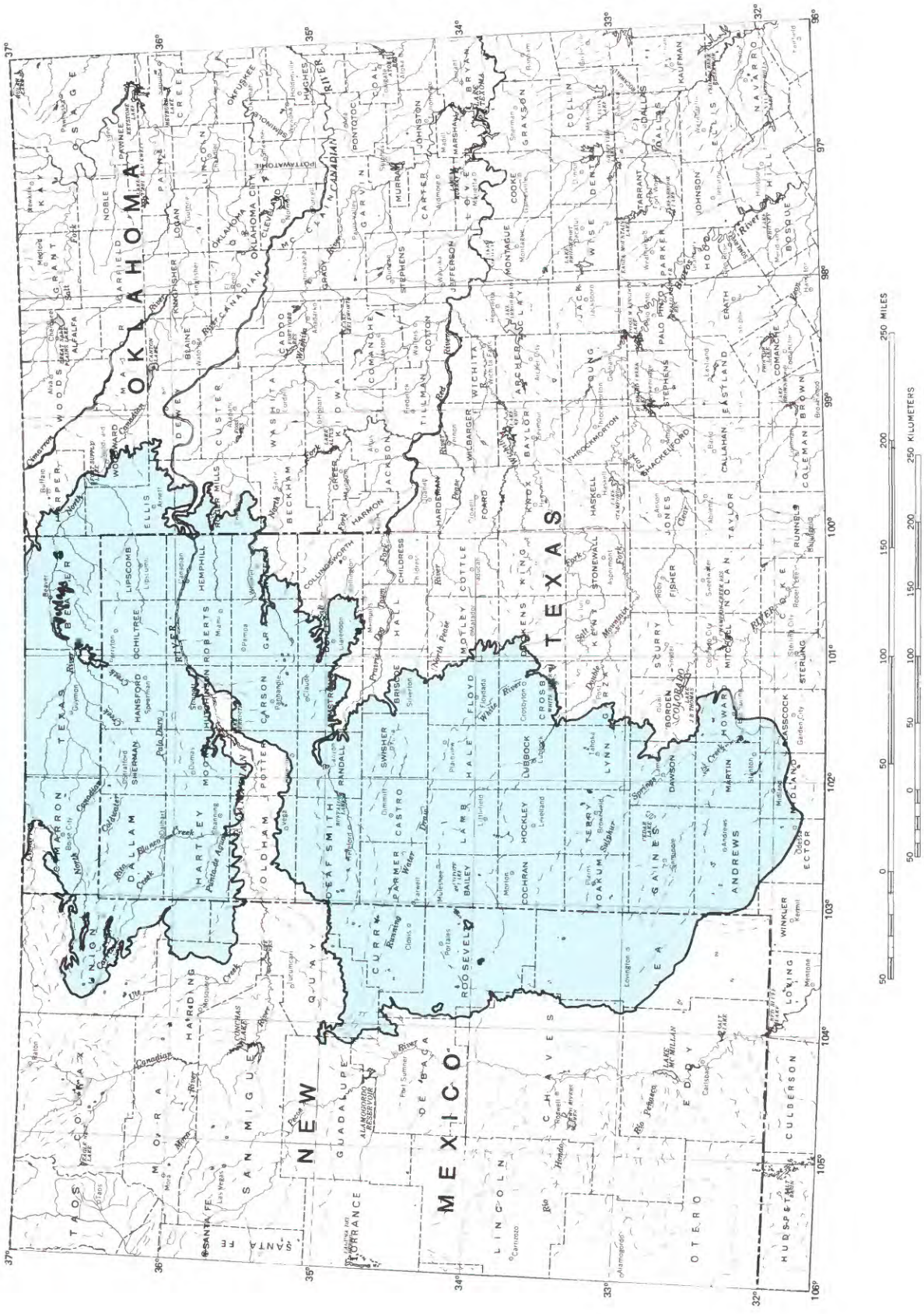


FIGURE 1.—Location of High Plains aquifer.

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

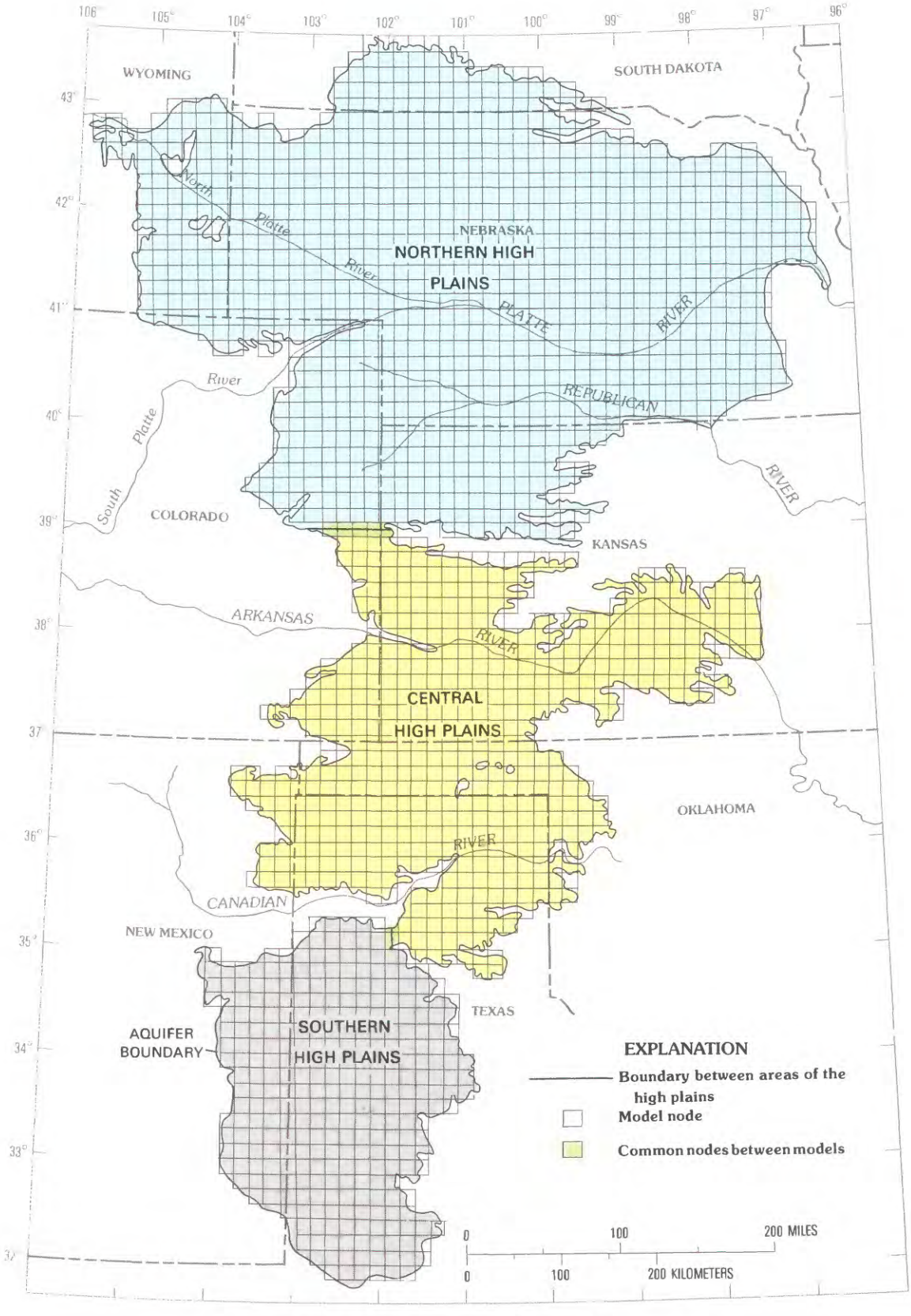


FIGURE 2.—Division of the High Plains and grids for the models.

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

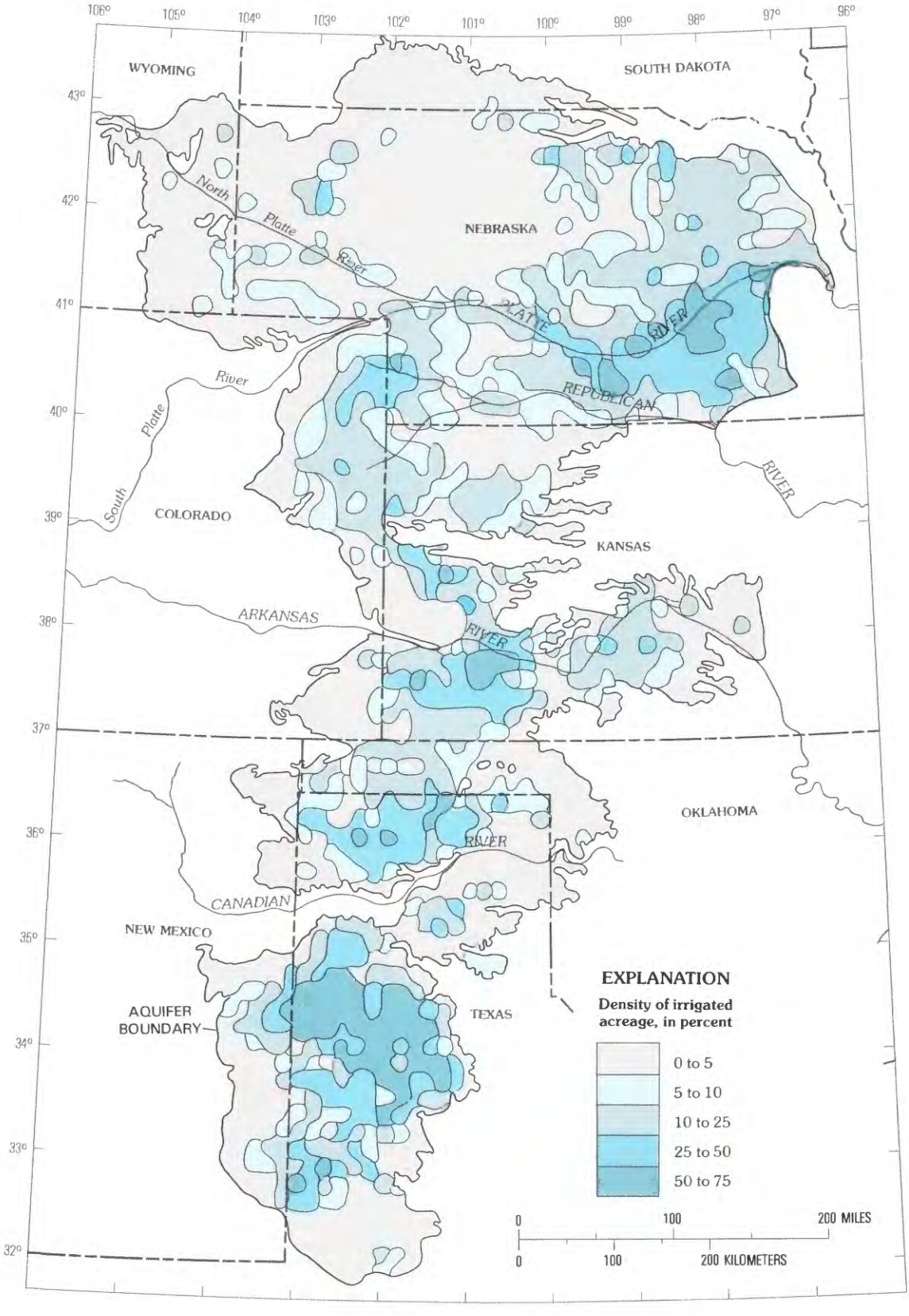


FIGURE 3.—Density of acreage irrigated by ground water in the High Plains, 1978.

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.

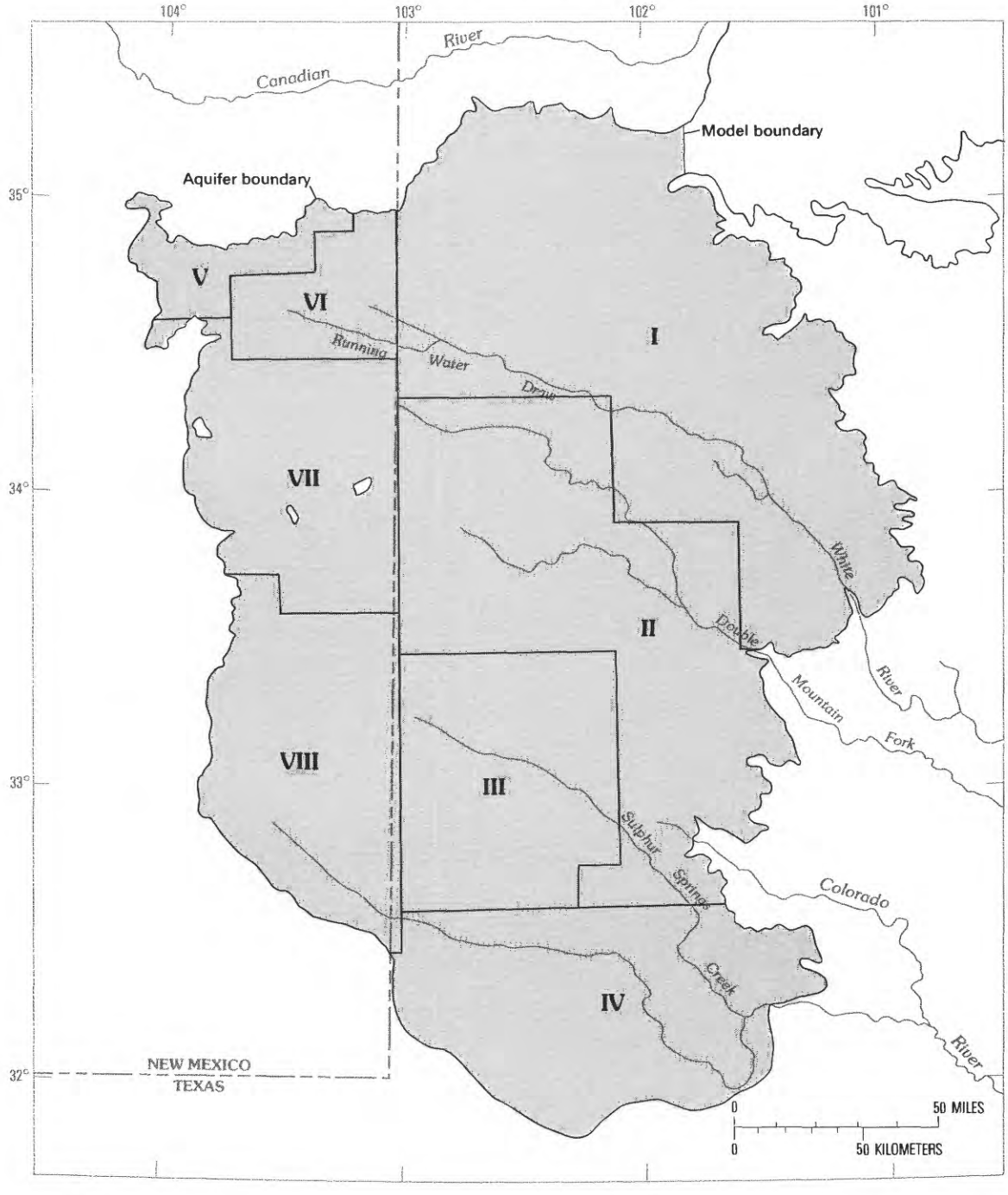
Pumpage projections were available for the eight regions in the southern High Plains shown in figure 4. Four of the regions are in Texas, and four are in New Mexico. The regions in Texas correspond to the subregions defined by High Plains Associates (1982, fig. II-1), and the regions in New Mexico correspond 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.



EXPLANATION

IV Pumpage region and number in table 1

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 mi^2. 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 mi²). Water levels are projected to decline more than 100 ft in several areas of the southern High Plains that total about 2,900 mi². 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

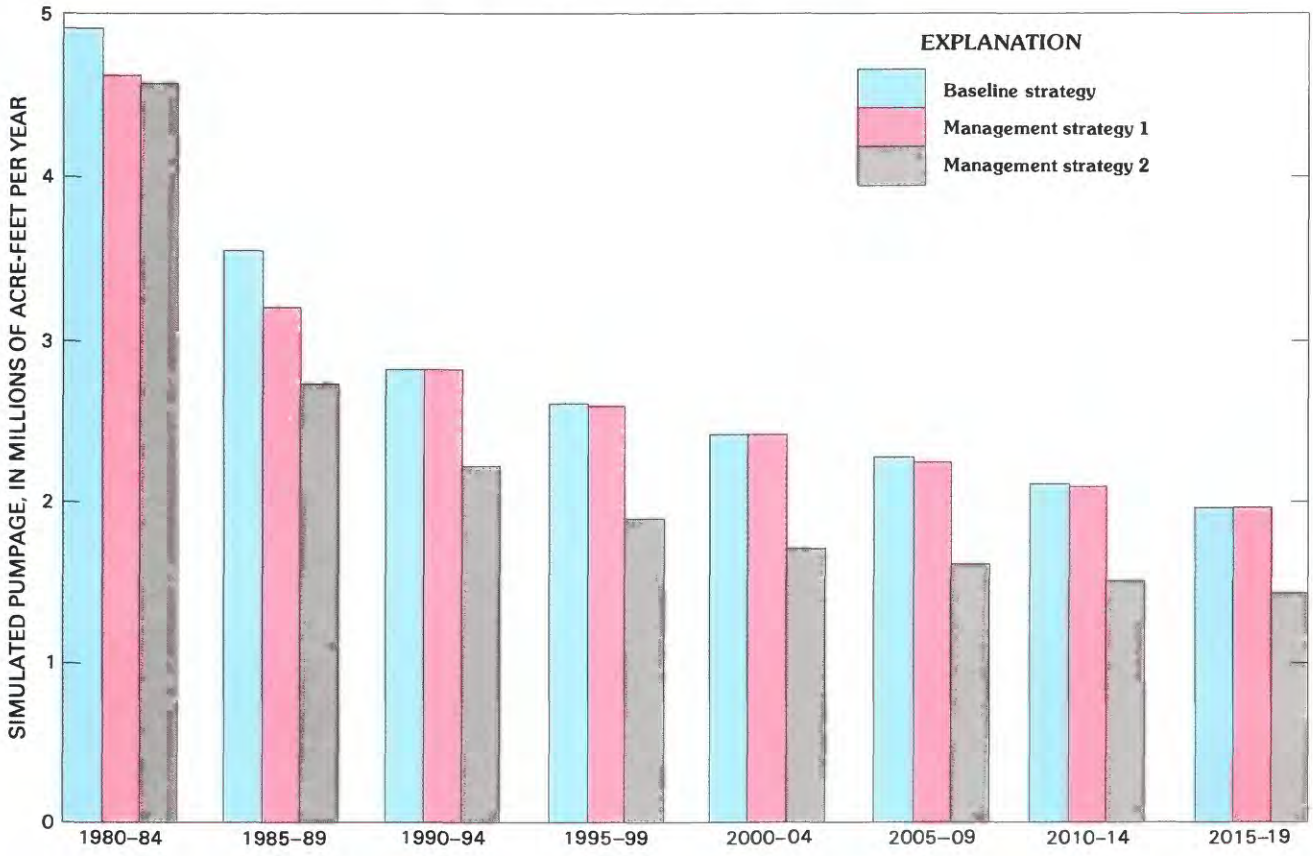
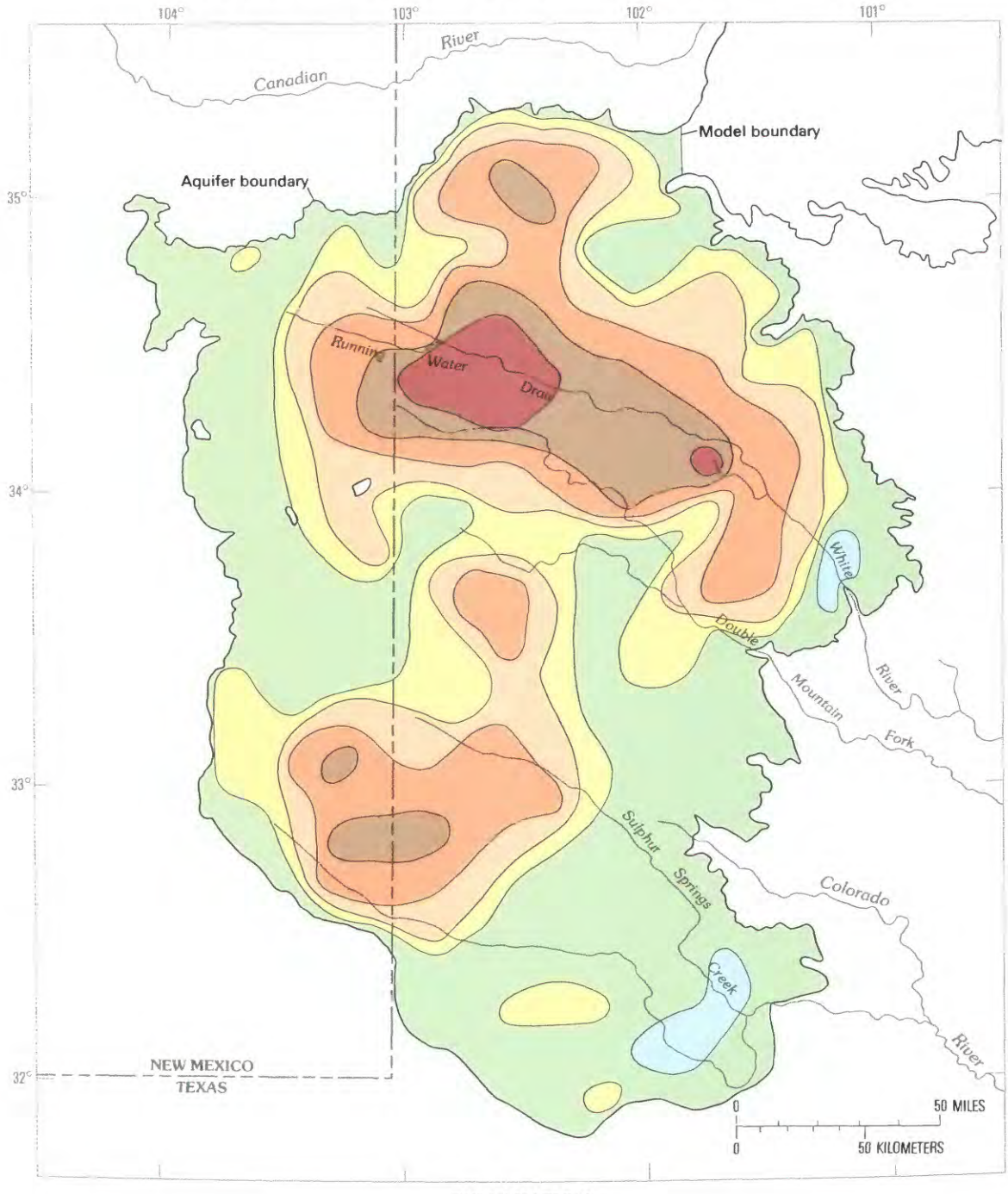


FIGURE 5.—Simulated pumpage for the southern High Plains by management strategy.

saturated thickness would exceed 100 ft in several areas that total 1,500 mi². The area in the east-central part of the southern High Plains represents 600 mi² 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 mi². The extent of the larger area would be 400 mi². By 2020, simulated 1980 to 2020 water-level declines would exceed 100 ft under 2,300 mi². 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



EXPLANATION

Water-level change, in feet

- Rise more than 10
- +10 to −10
- −10 to −25
- −25 to −50
- −50 to −100
- −100 to −150
- Decline more than 150

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

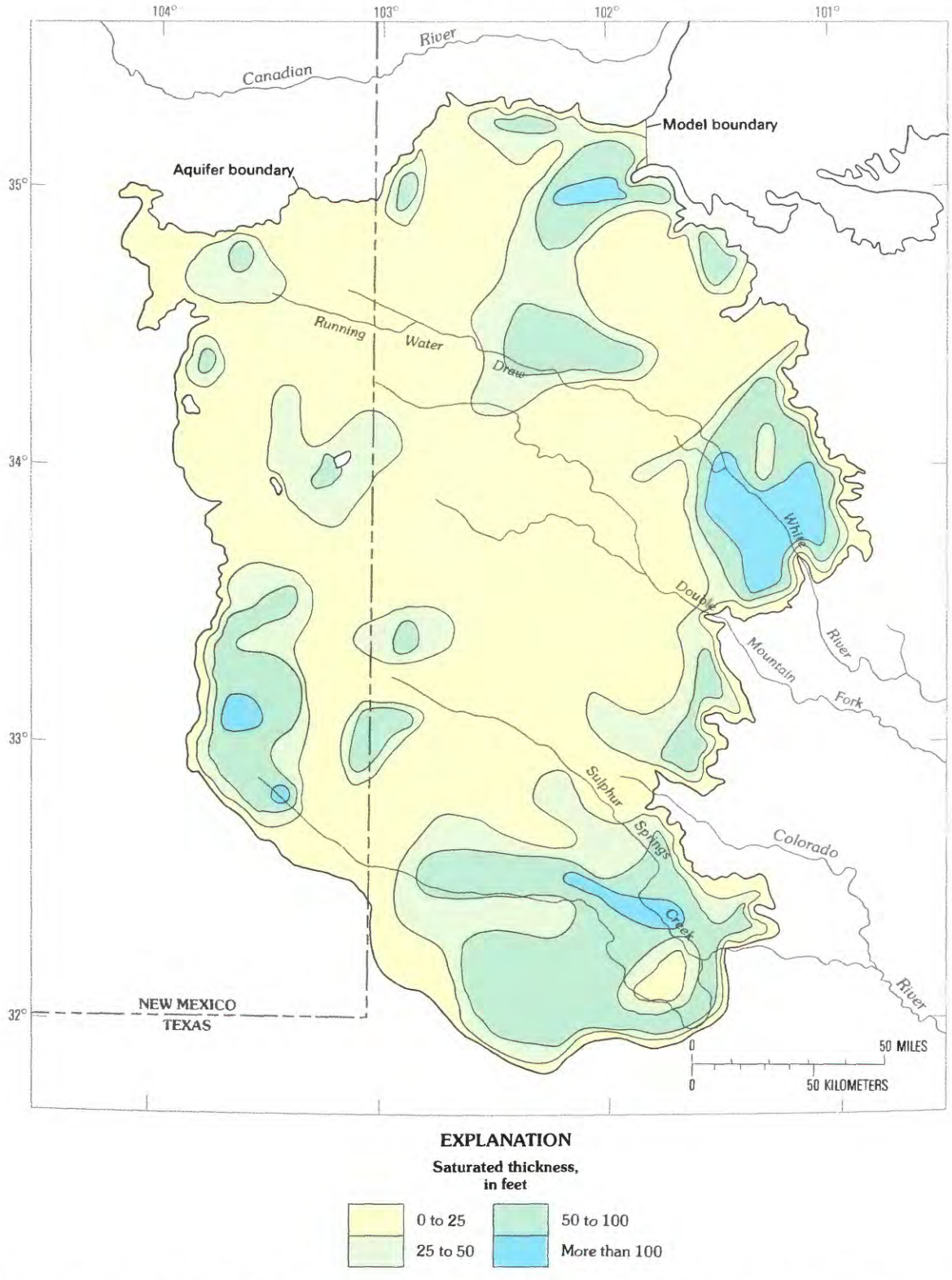


FIGURE 7.—Projected saturated thickness by 2020 in the southern High Plains resulting from pumpage for the baseline strategy.

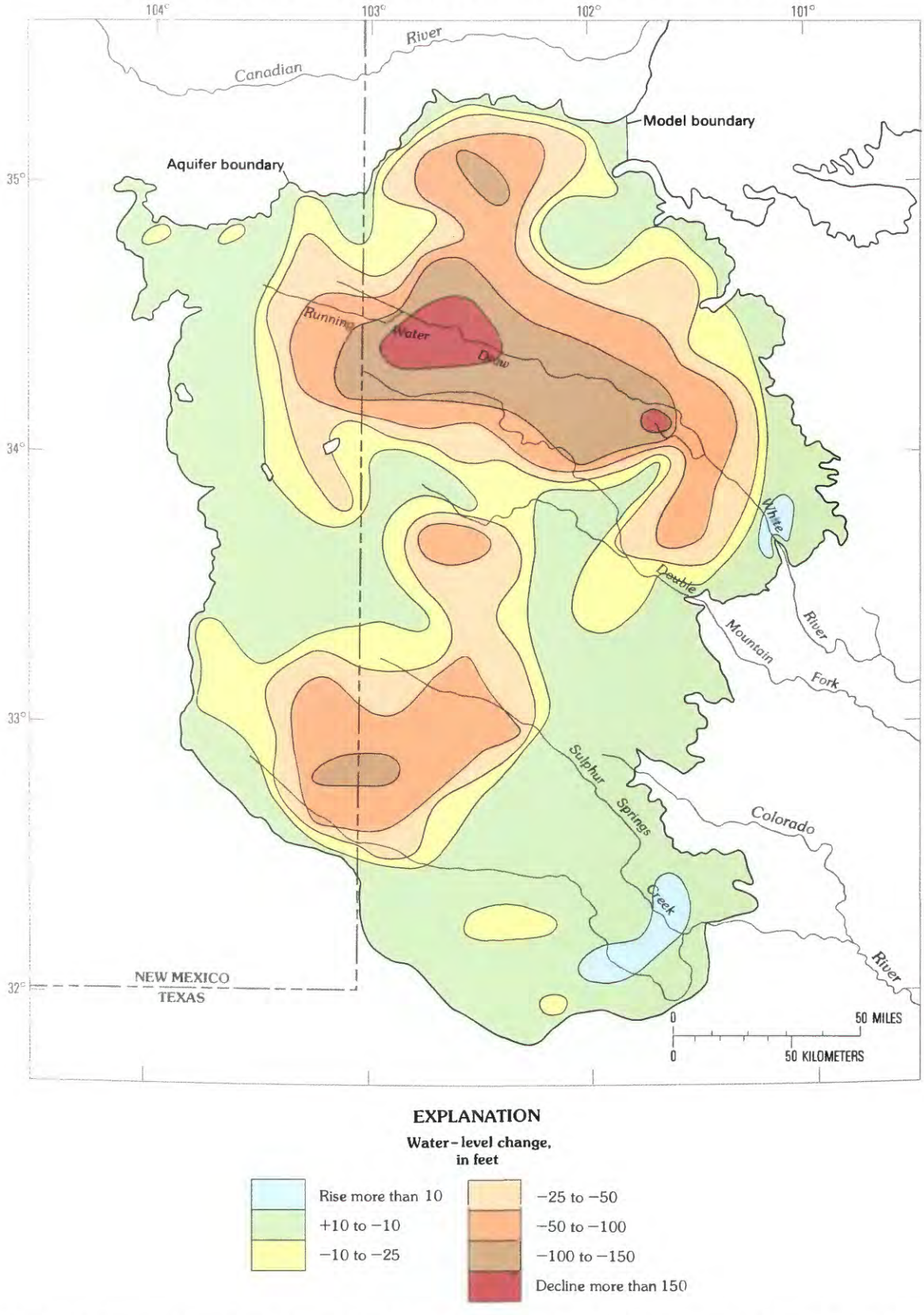


FIGURE 8.—Projected water-level changes, 1980 to 2020, for the southern High Plains resulting from pumpage for management strategy 1.

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

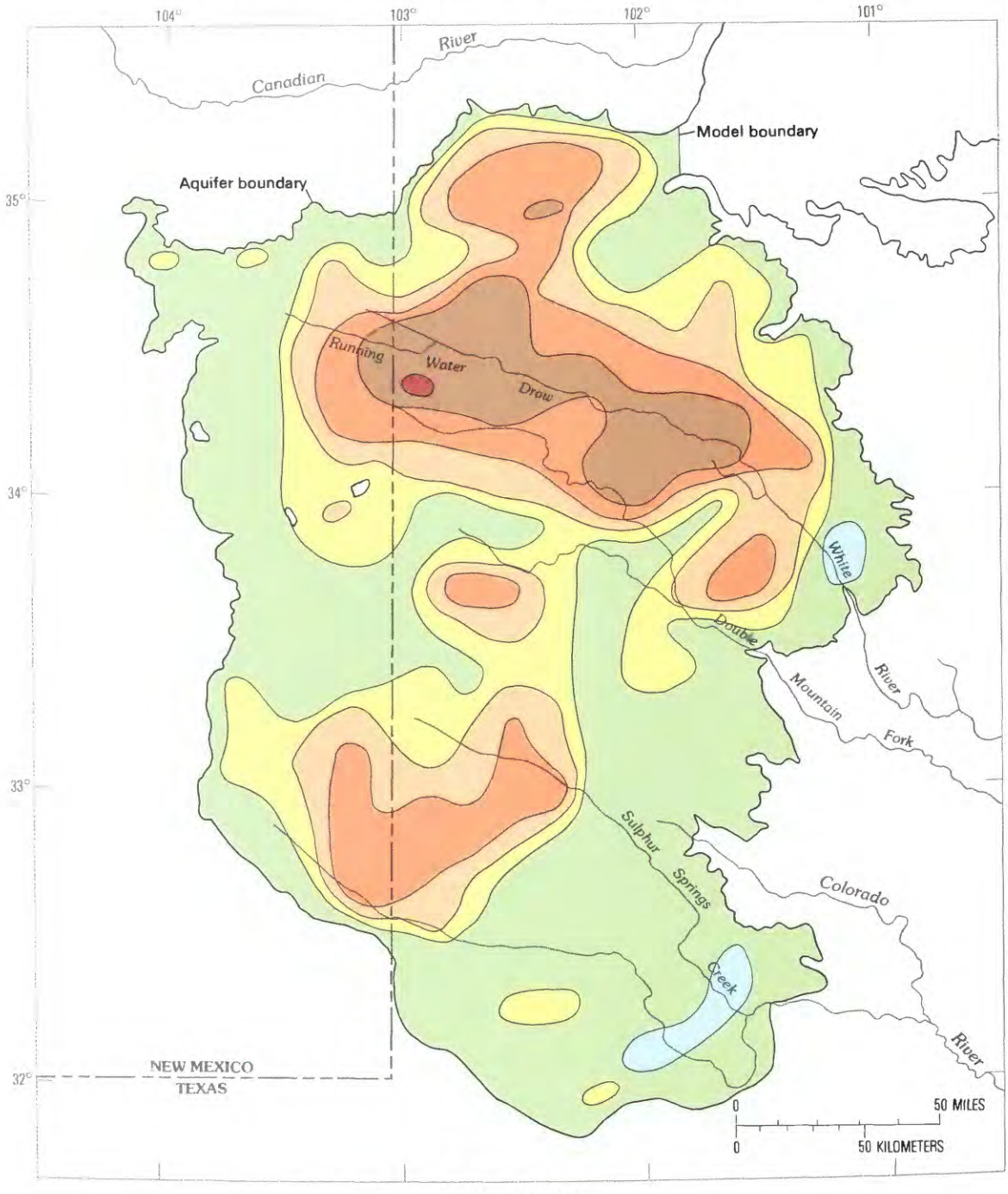
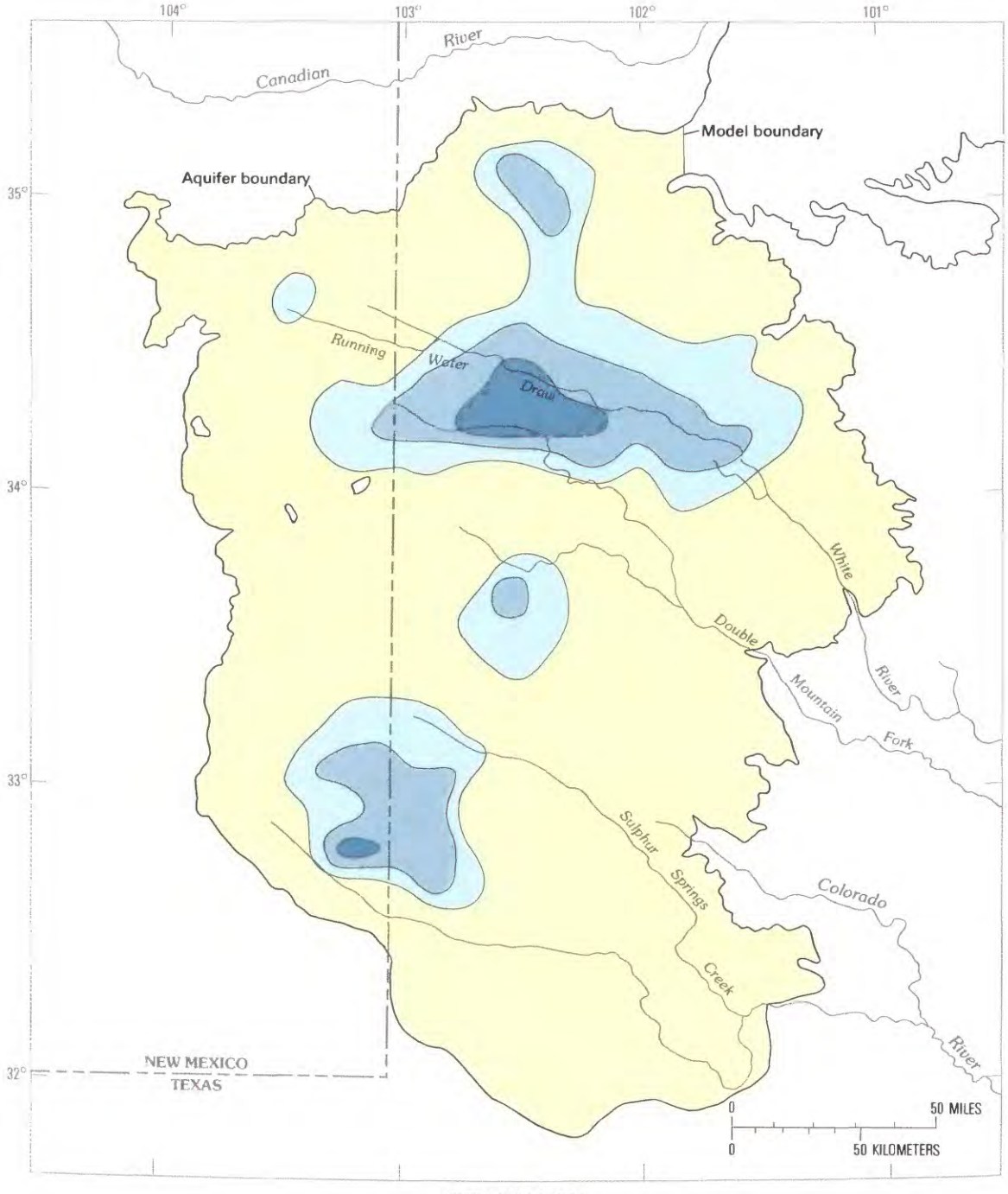


FIGURE 9.—Projected water-level changes, 1980 to 2020, for the southern High Plains resulting from pumpage for management strategy 2.



EXPLANATION

Saturated–thickness difference, in feet
(Management strategy two minus baseline)

0 to 10	25 to 50
10 to 25	More than 50

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

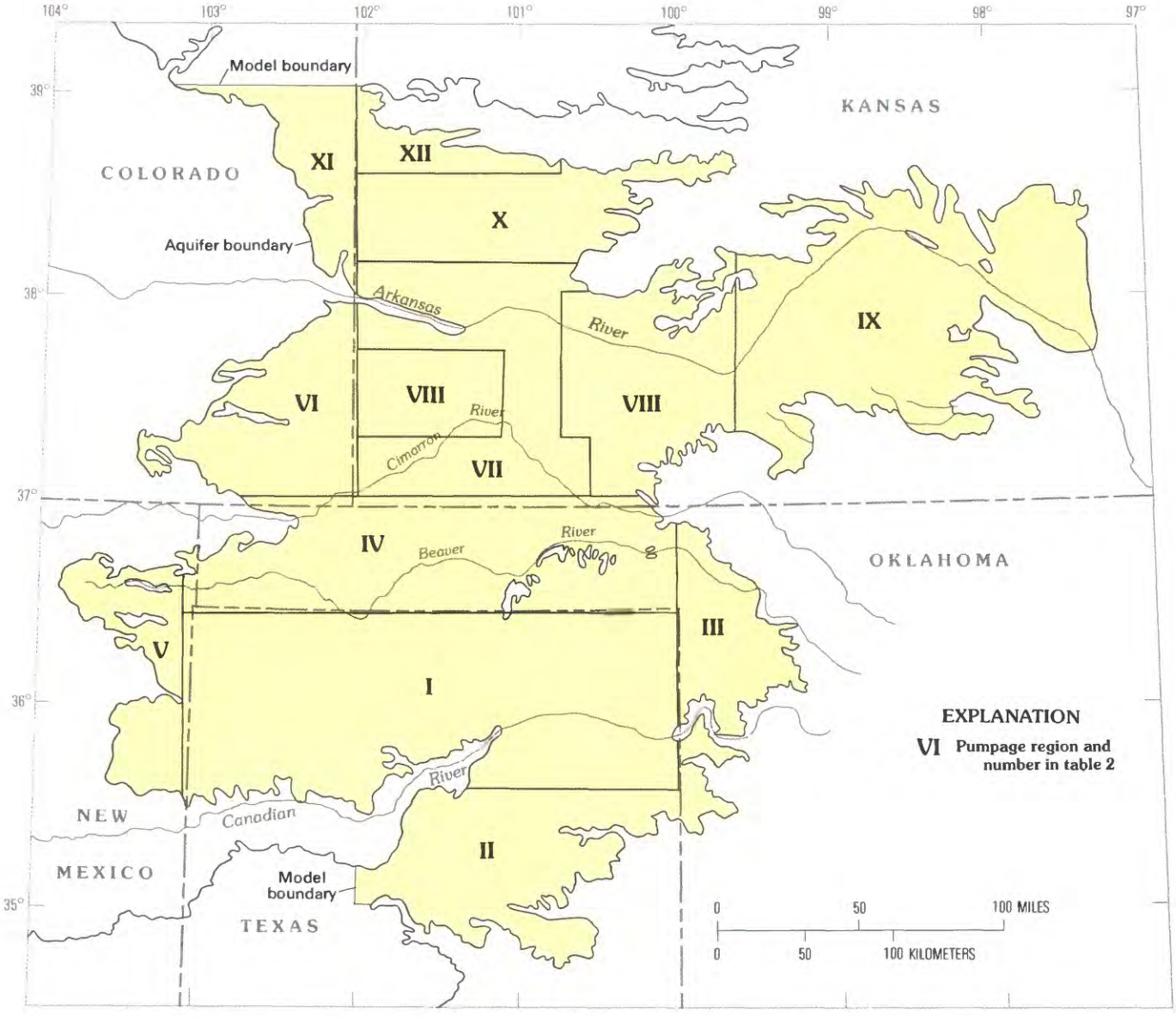


FIGURE 11.—Regions for which pumpage projections were available for the central High Plains.

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

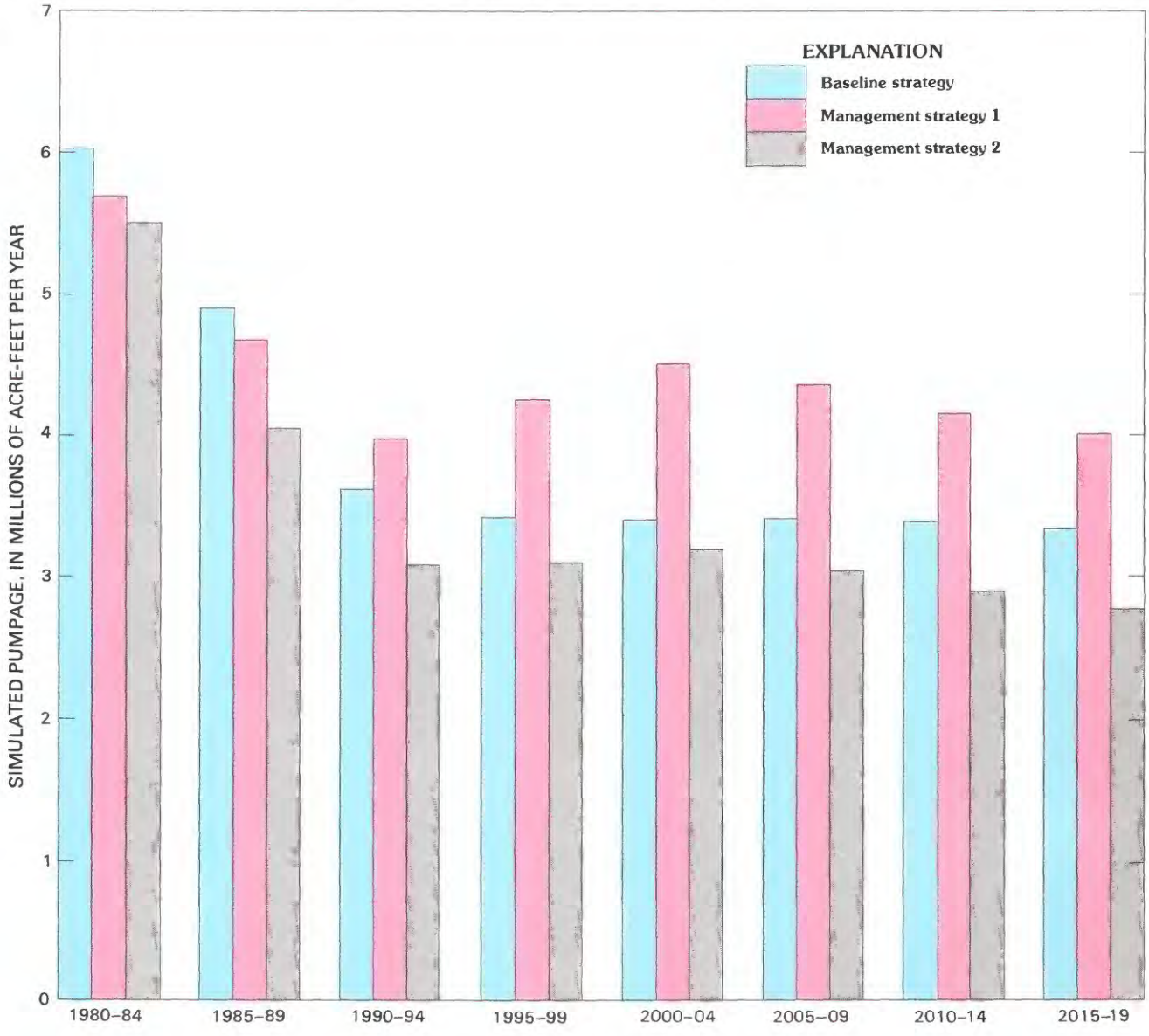


FIGURE 12.—Simulated pumpage for the central High Plains by management strategy.

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

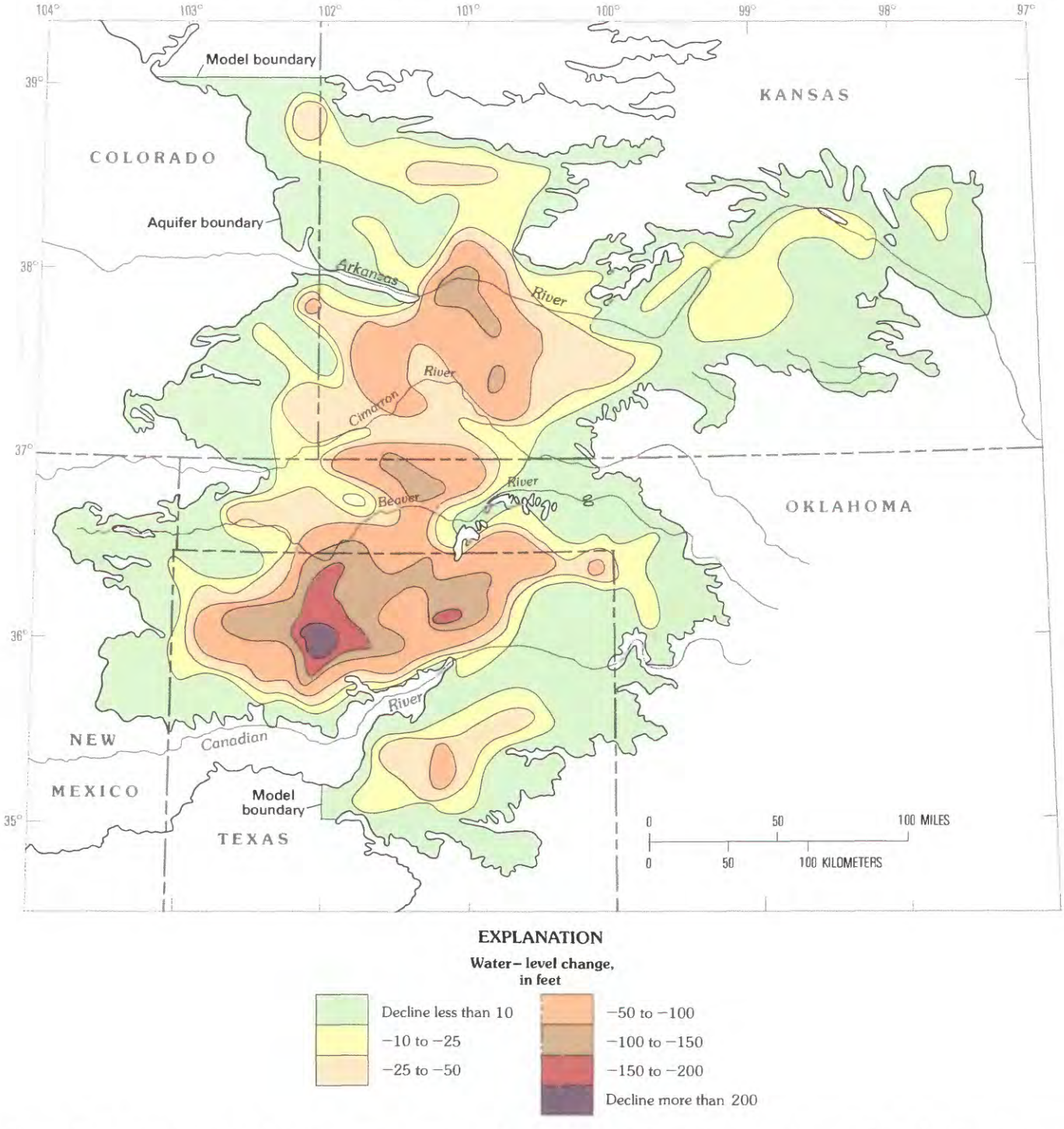


FIGURE 13.—Projected water-level declines, 1980 to 2020, for the central High Plains resulting from pumpage for the baseline strategy.

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.

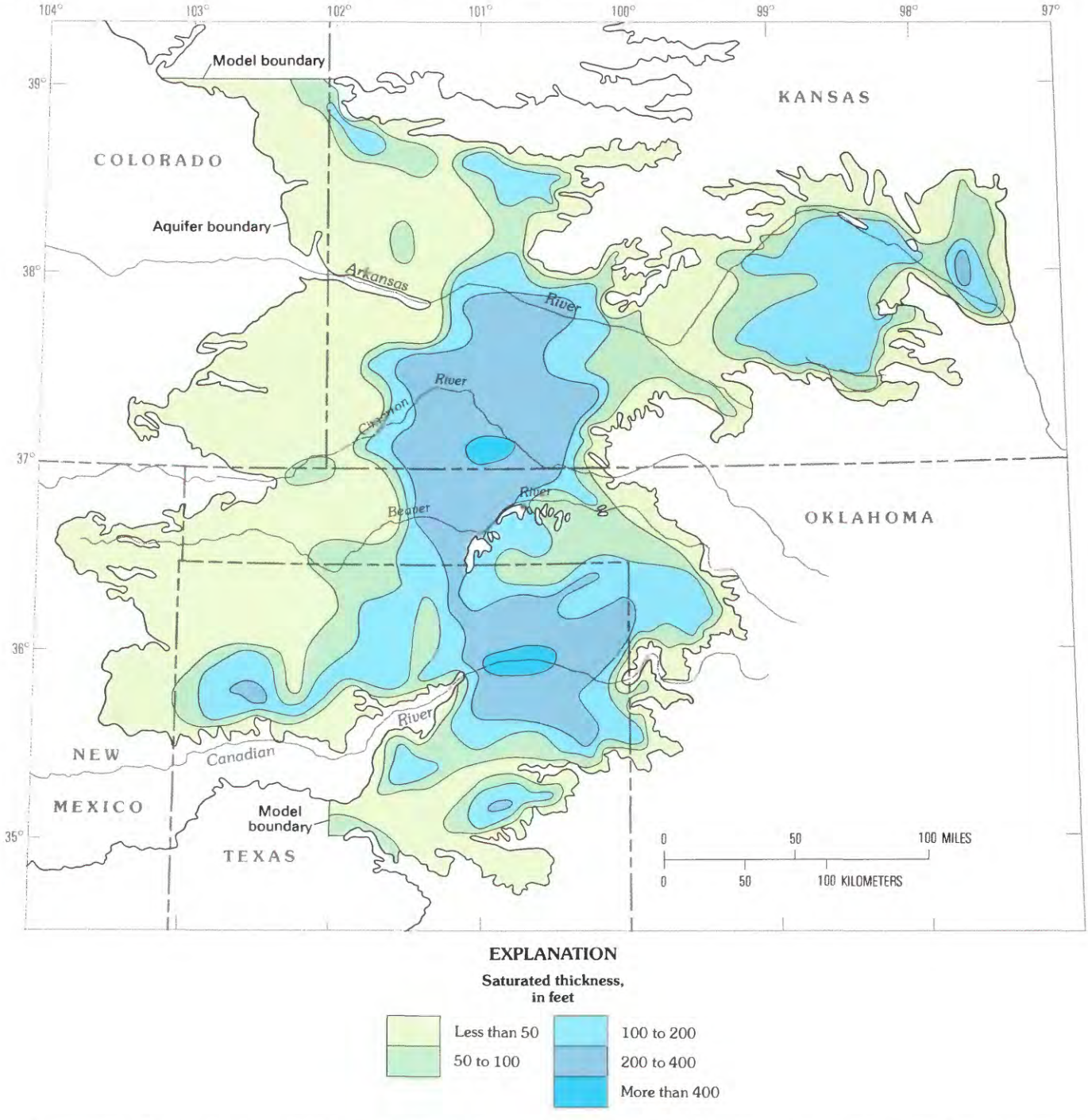


FIGURE 14.—Projected saturated thickness by 2020 in the central High Plains resulting from pumpage for the baseline strategy.

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.

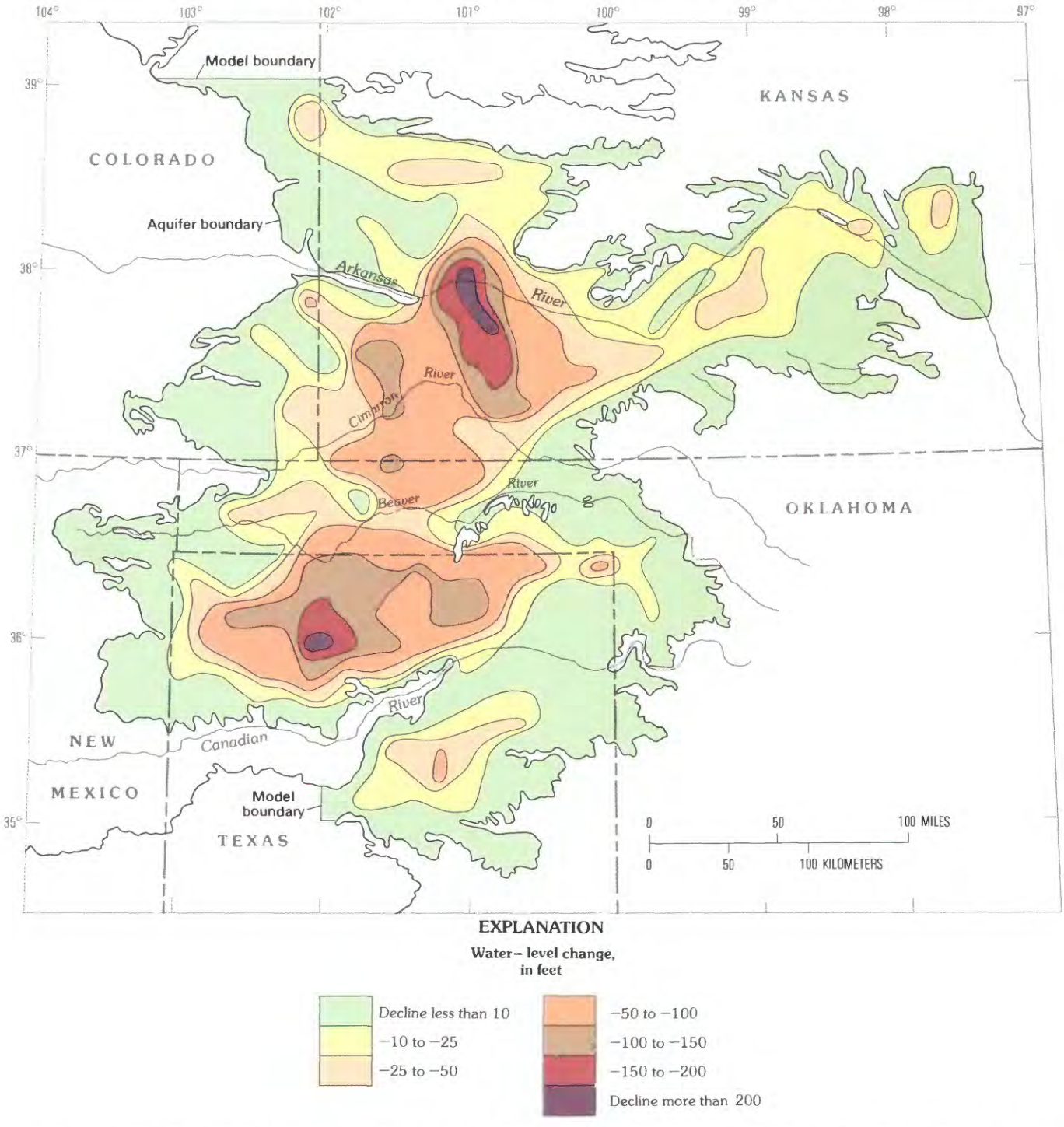


FIGURE 15.—Projected water-level declines, 1980 to 2020, for the central High Plains resulting from pumpage for management strategy 1.

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

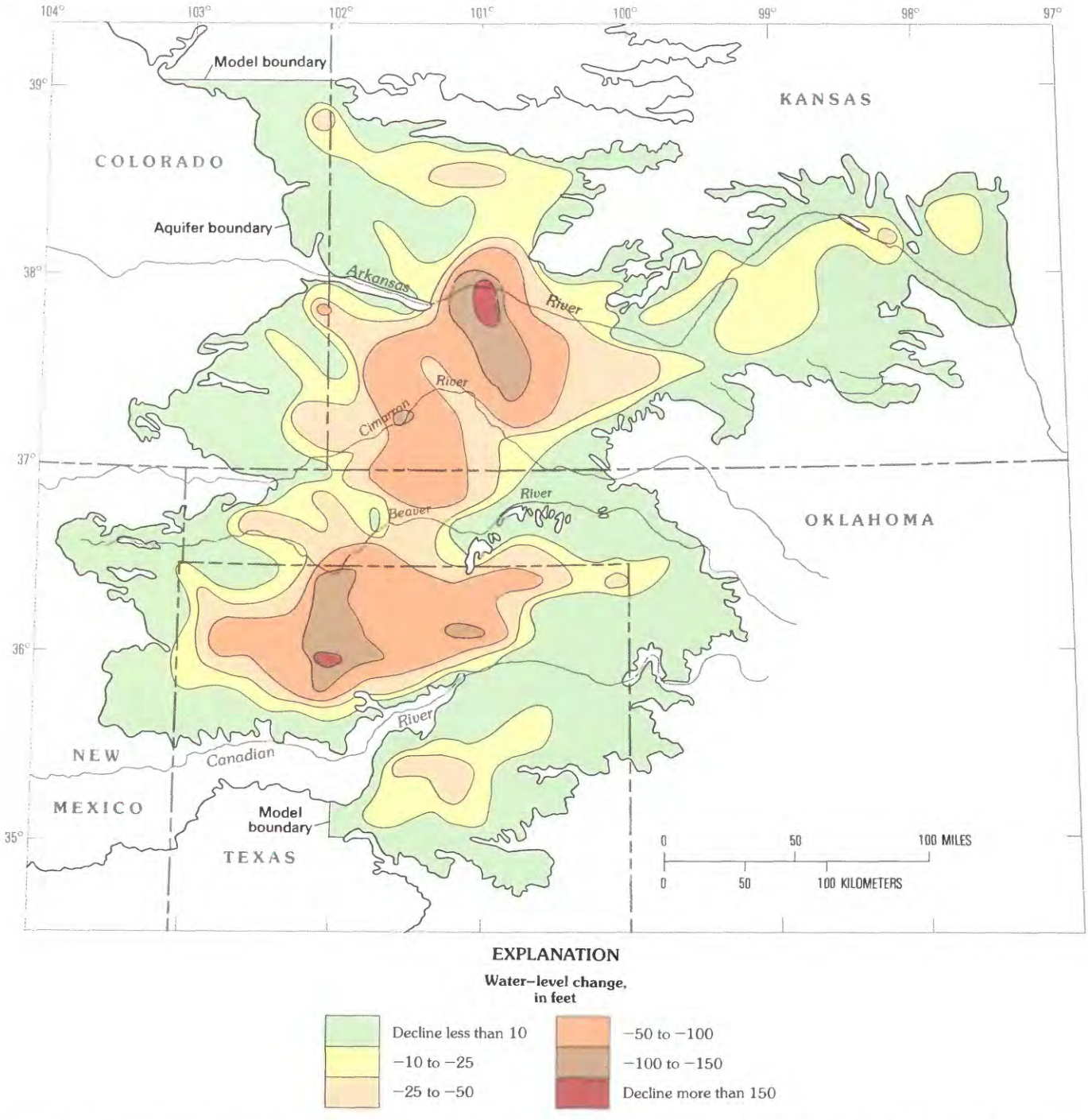


FIGURE 16.—Projected water-level declines, 1980 to 2020, for the central High Plains resulting from pumpage for management strategy 2.

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.

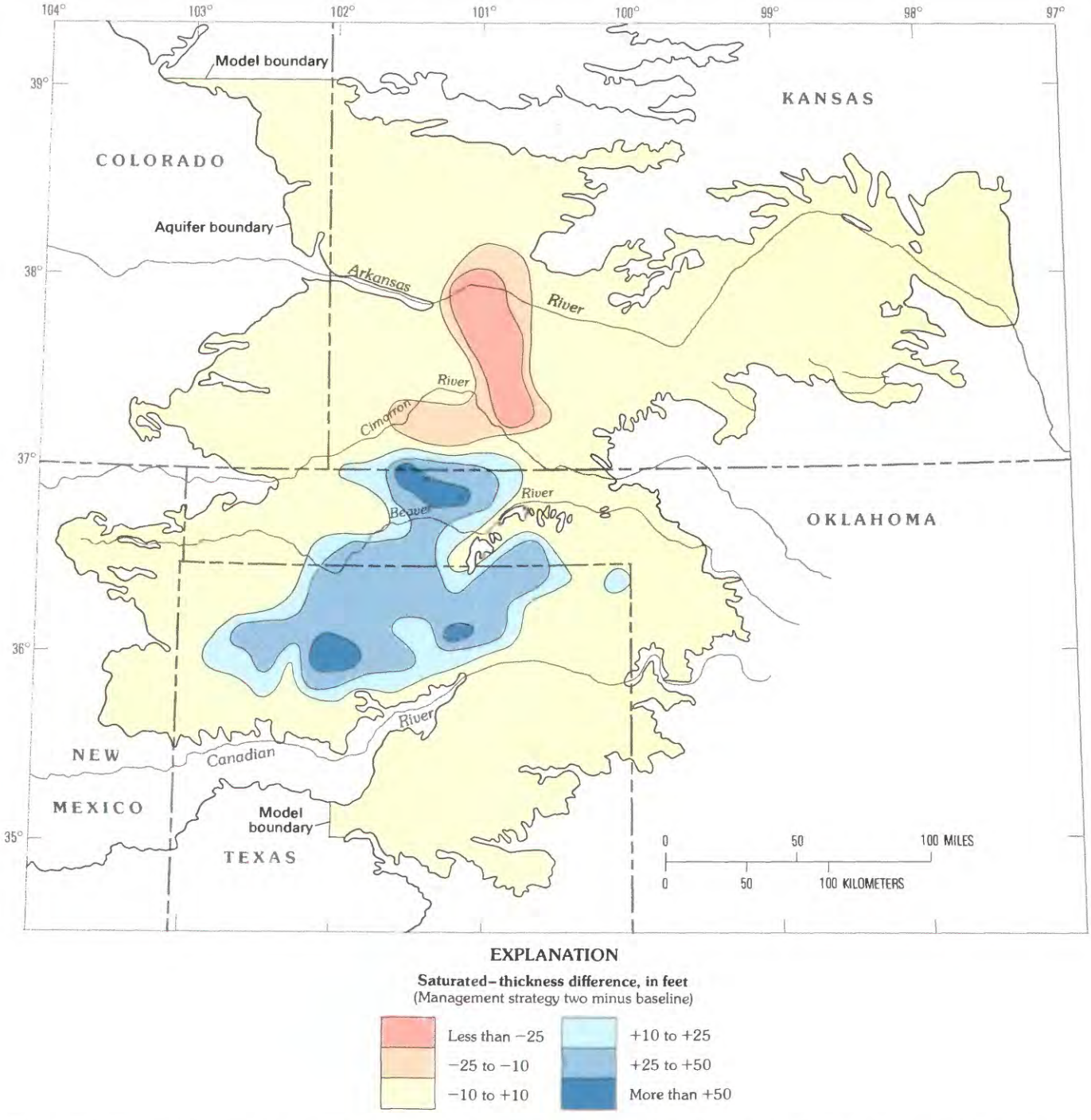


FIGURE 17.—Difference in projected saturated thickness by 2020 between management strategy 2 and the baseline strategy for the central High Plains. Decrease in difference indicates that management strategy 2 results in less saturated thickness than does baseline strategy; increase in difference indicates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

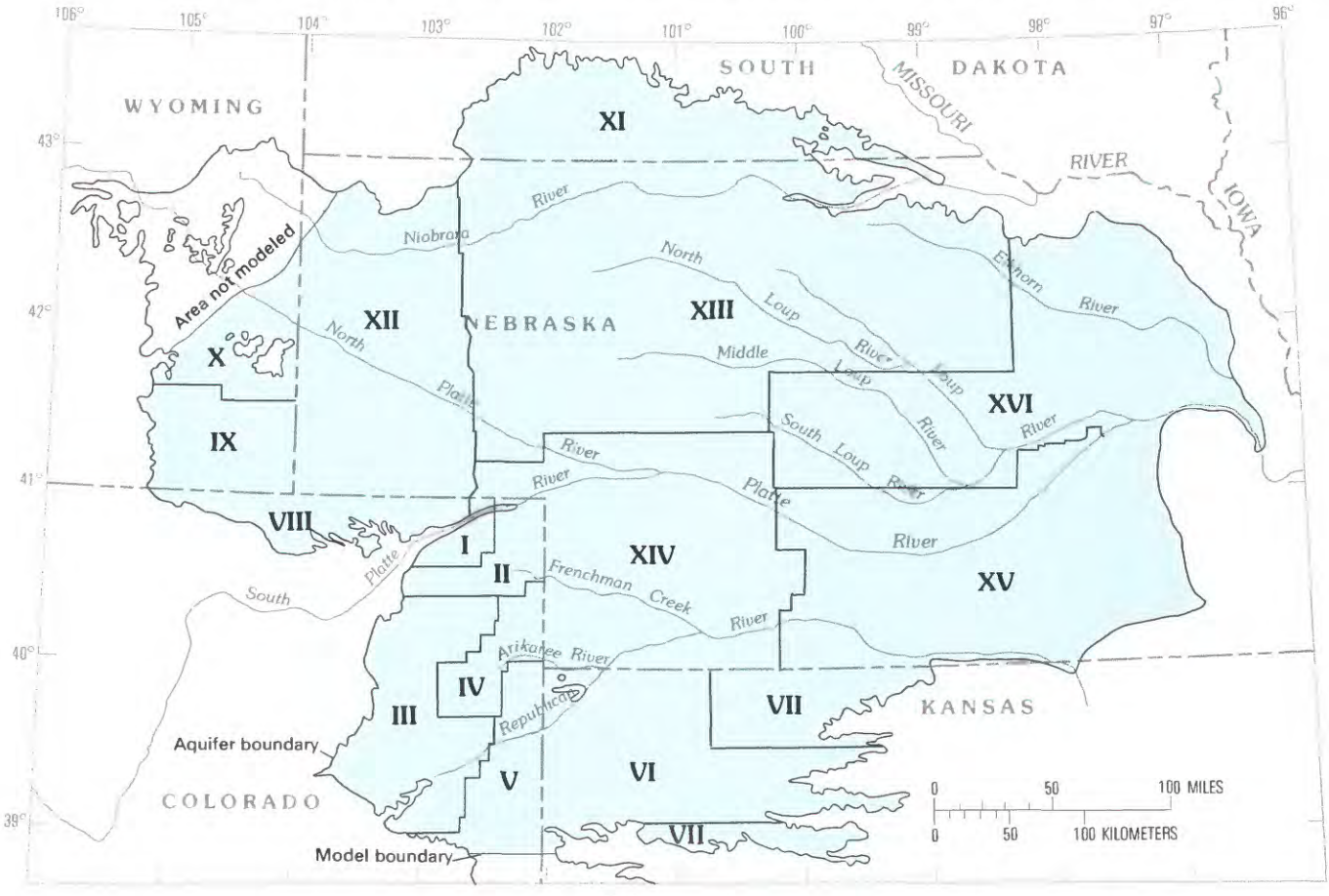


FIGURE 18.—Regions for which pumpage projections were available for the northern High Plains.

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.

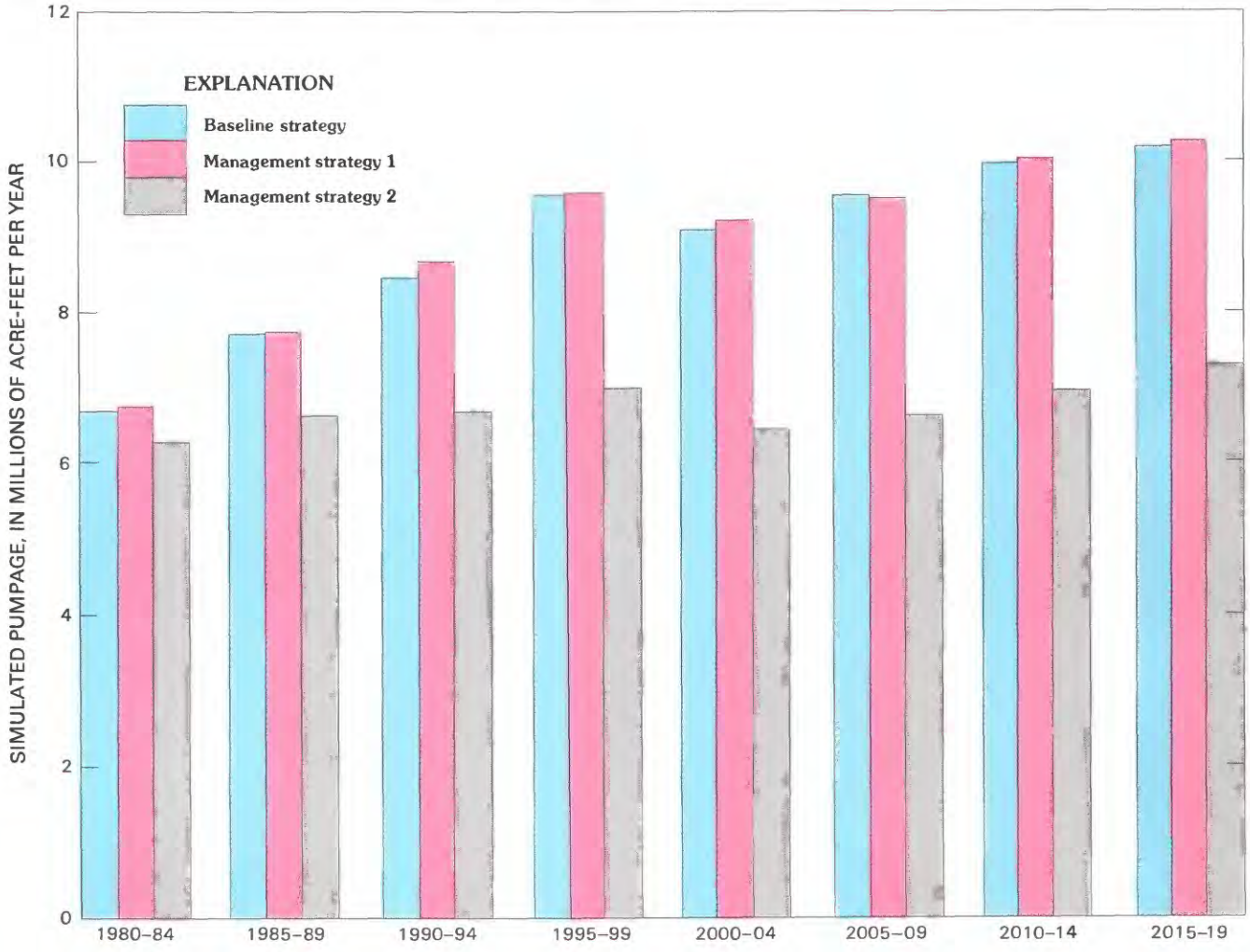


FIGURE 19.—Simulated pumpage for the northern High Plains by management strategy.

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

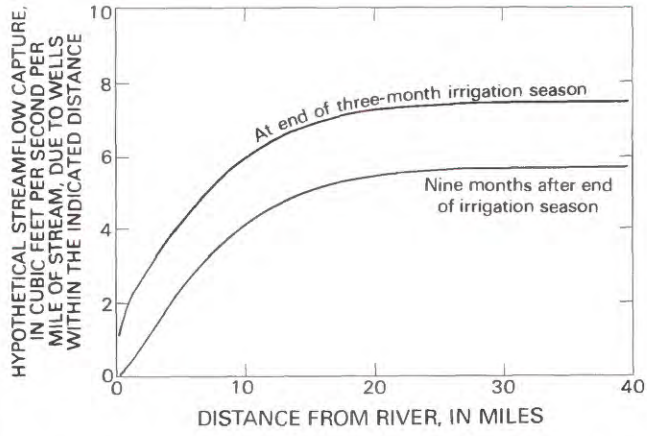


FIGURE 20.—Hypothetical streamflow capture for the northern High Plains computed based on estimated average aquifer parameters and two irrigation wells per square mile withdrawing 130 acre-ft of water per year.

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

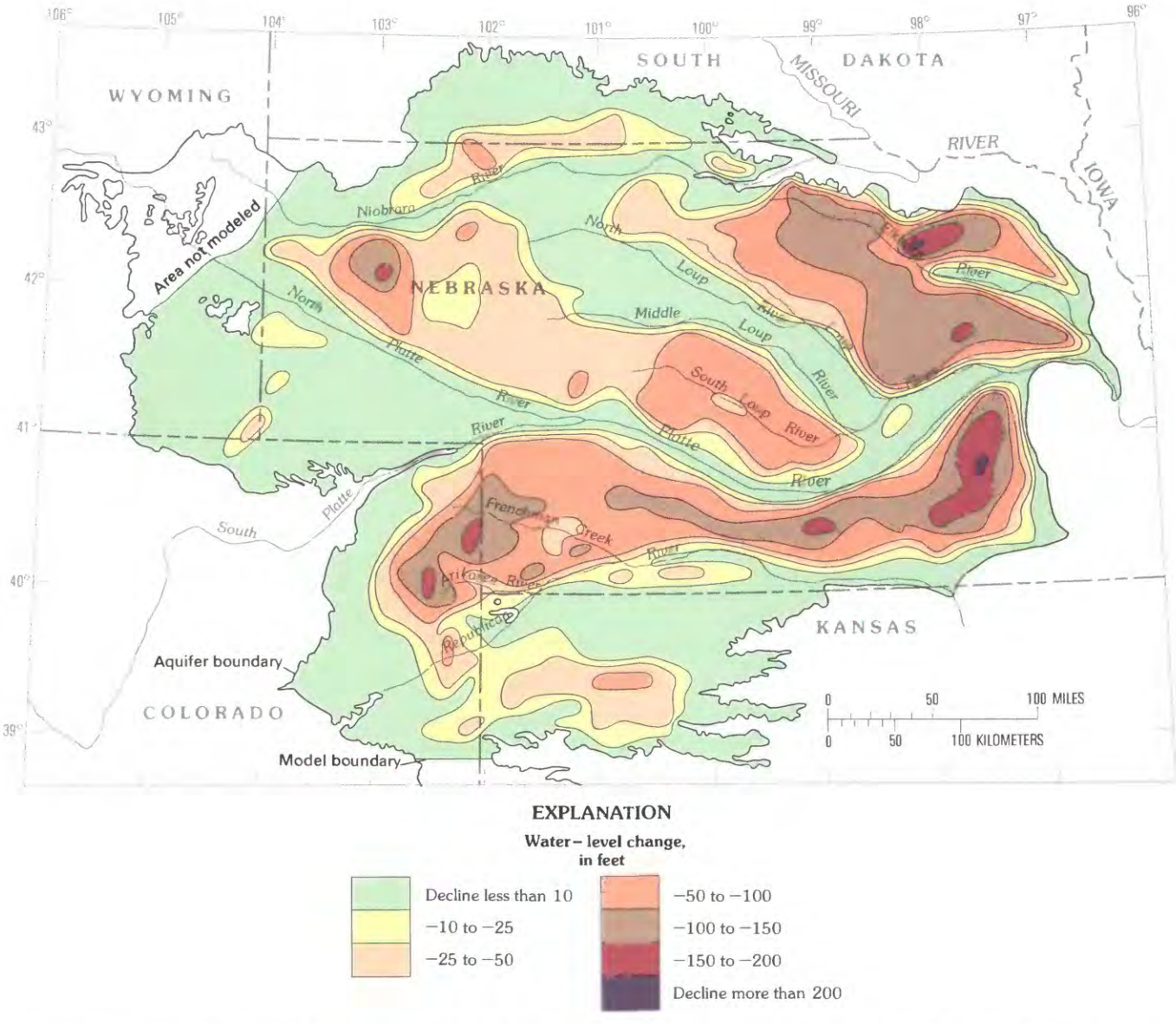


FIGURE 21.—Projected water-level declines, 1980 to 2020, for the northern High Plains resulting from pumpage for the baseline strategy.

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.

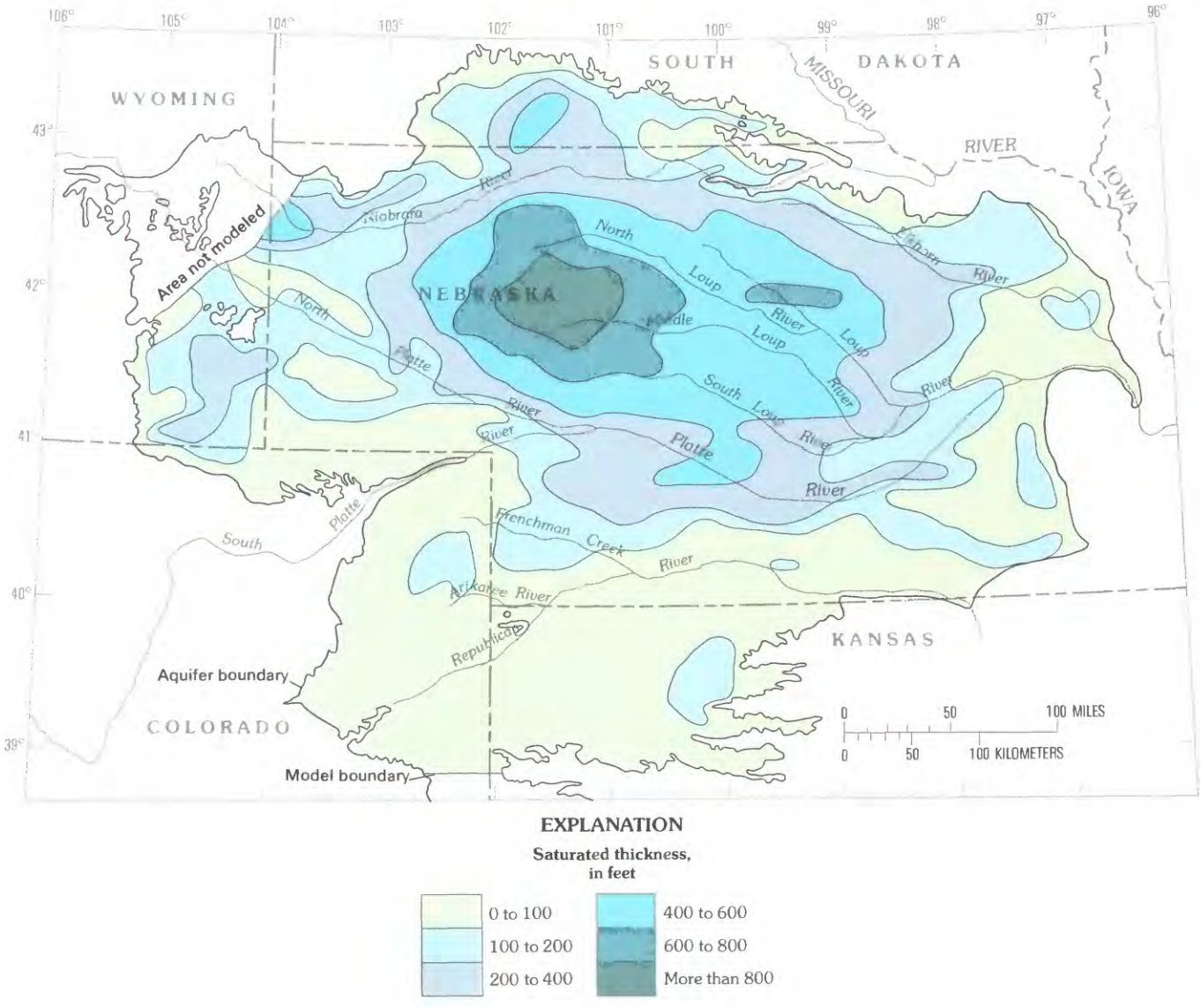


FIGURE 22.—Projected saturated thickness by 2020 in the northern High Plains resulting from pumpage for the baseline strategy.

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.

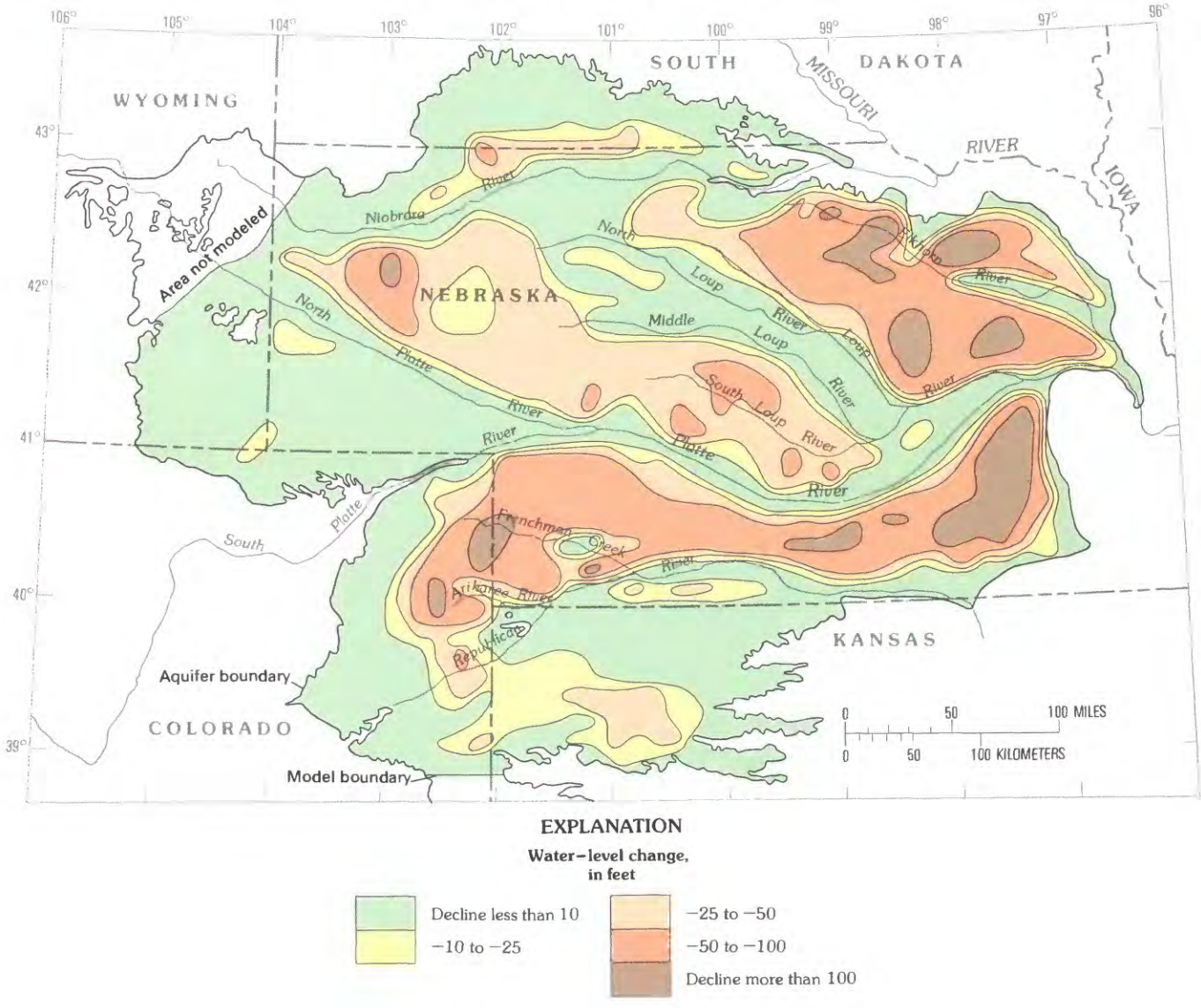


FIGURE 23.—Projected water-level declines, 1980 to 2020, for the northern High Plains resulting from pumpage for management strategy 2.

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

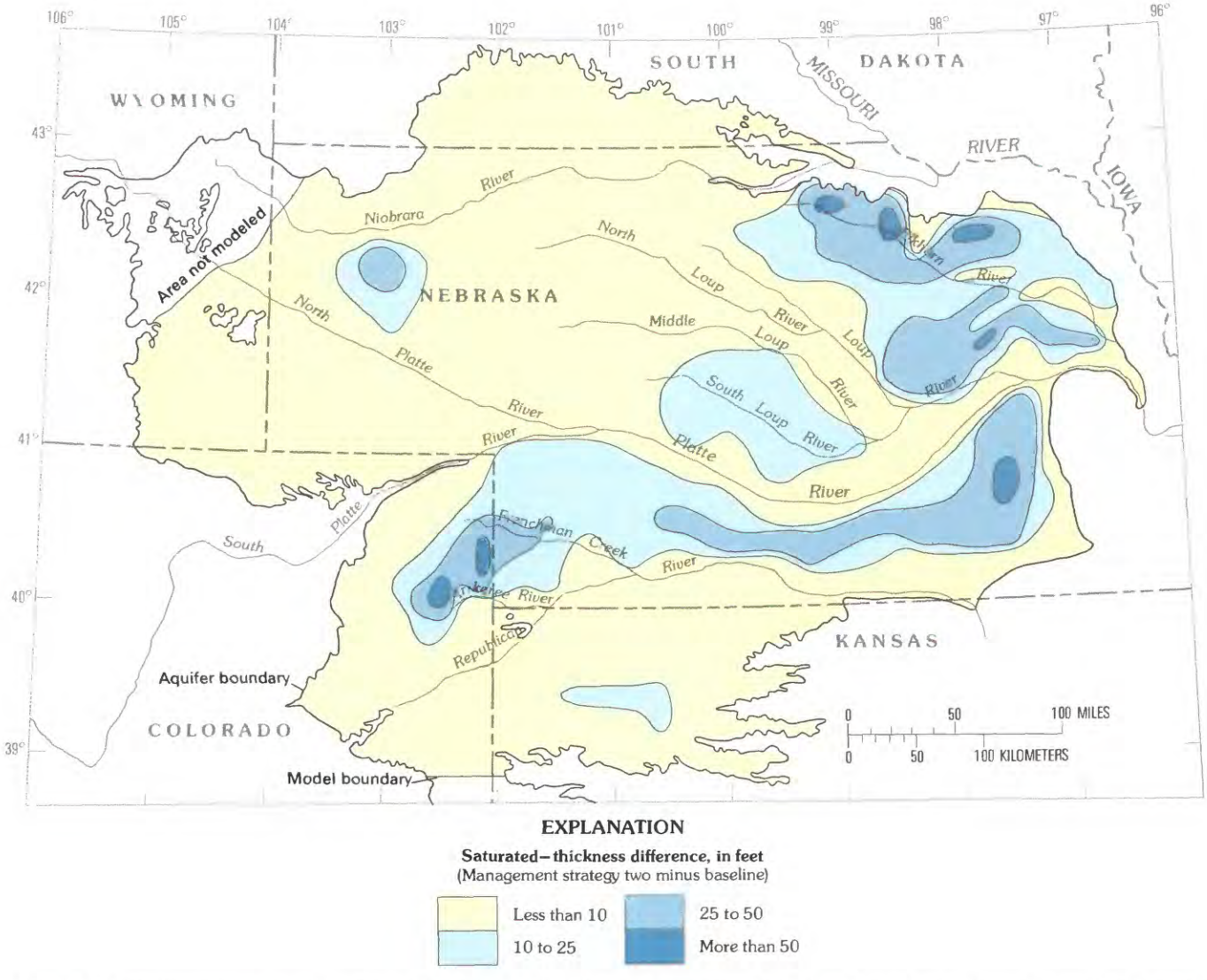


FIGURE 24.—Difference in projected saturated thickness by 2020 between management strategy 2 and the baseline strategy for the northern High Plains.

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

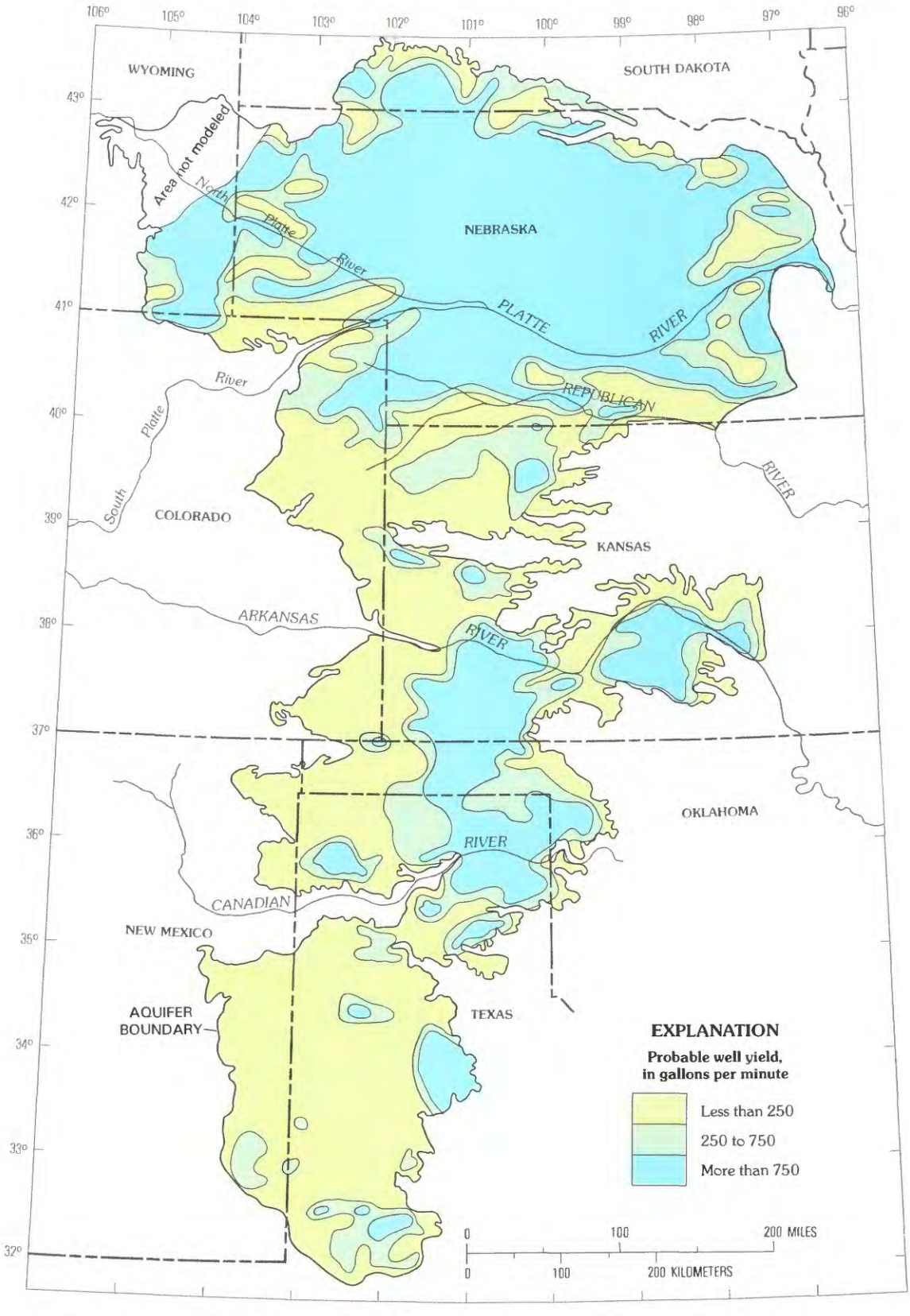


FIGURE 25.—Probable well yields by 2020 for the High Plains resulting from pumpage for the baseline strategy.

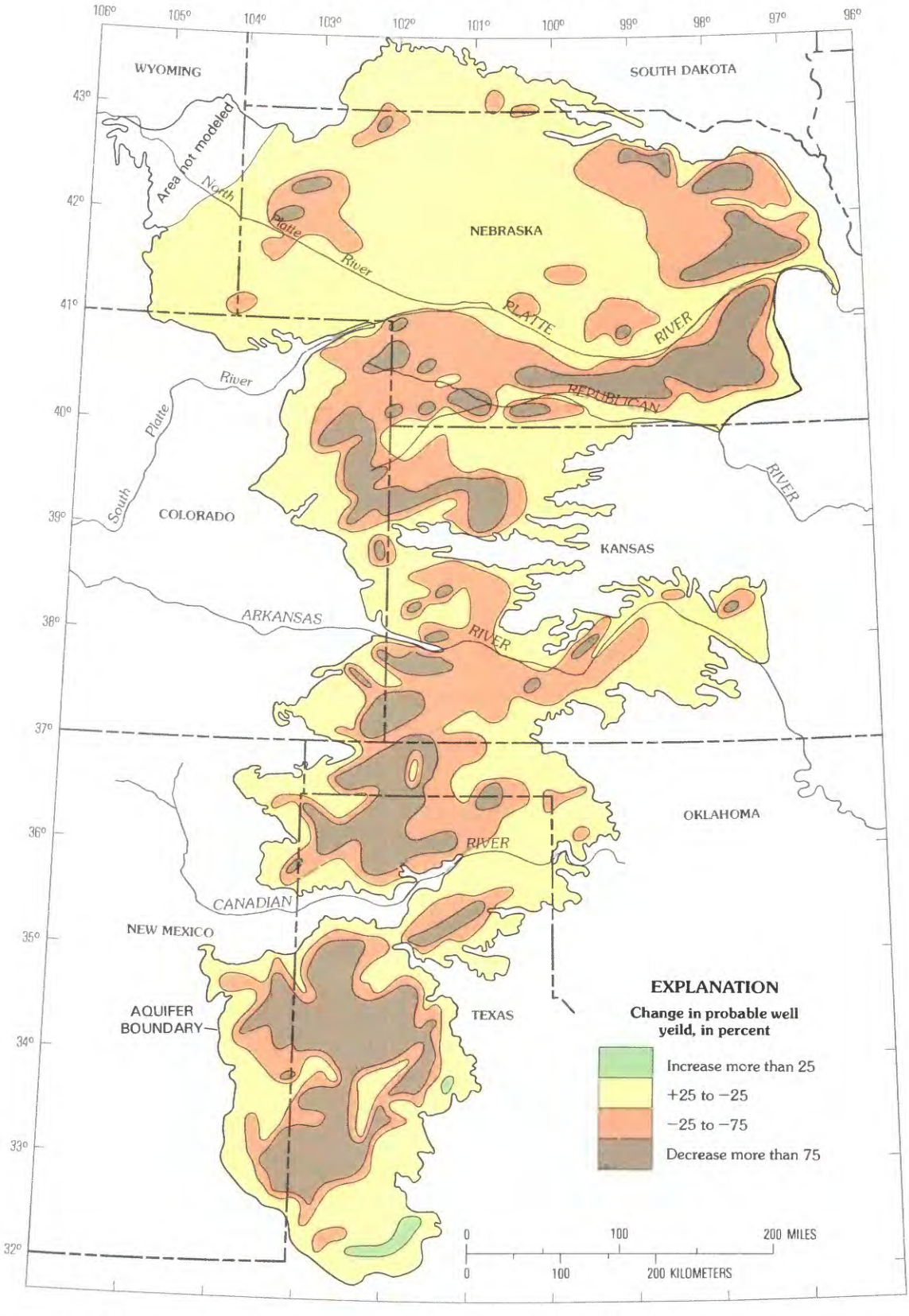


FIGURE 26.—Percentage changes in probable well yields, 1980 to 2020, for the High Plains resulting from pumpage for the baseline strategy.

25 percent by 2020. In two areas totaling 620 mi^2, 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 mi^2 and by more than 75 percent in 7,050 mi^2. 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-mi^2 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

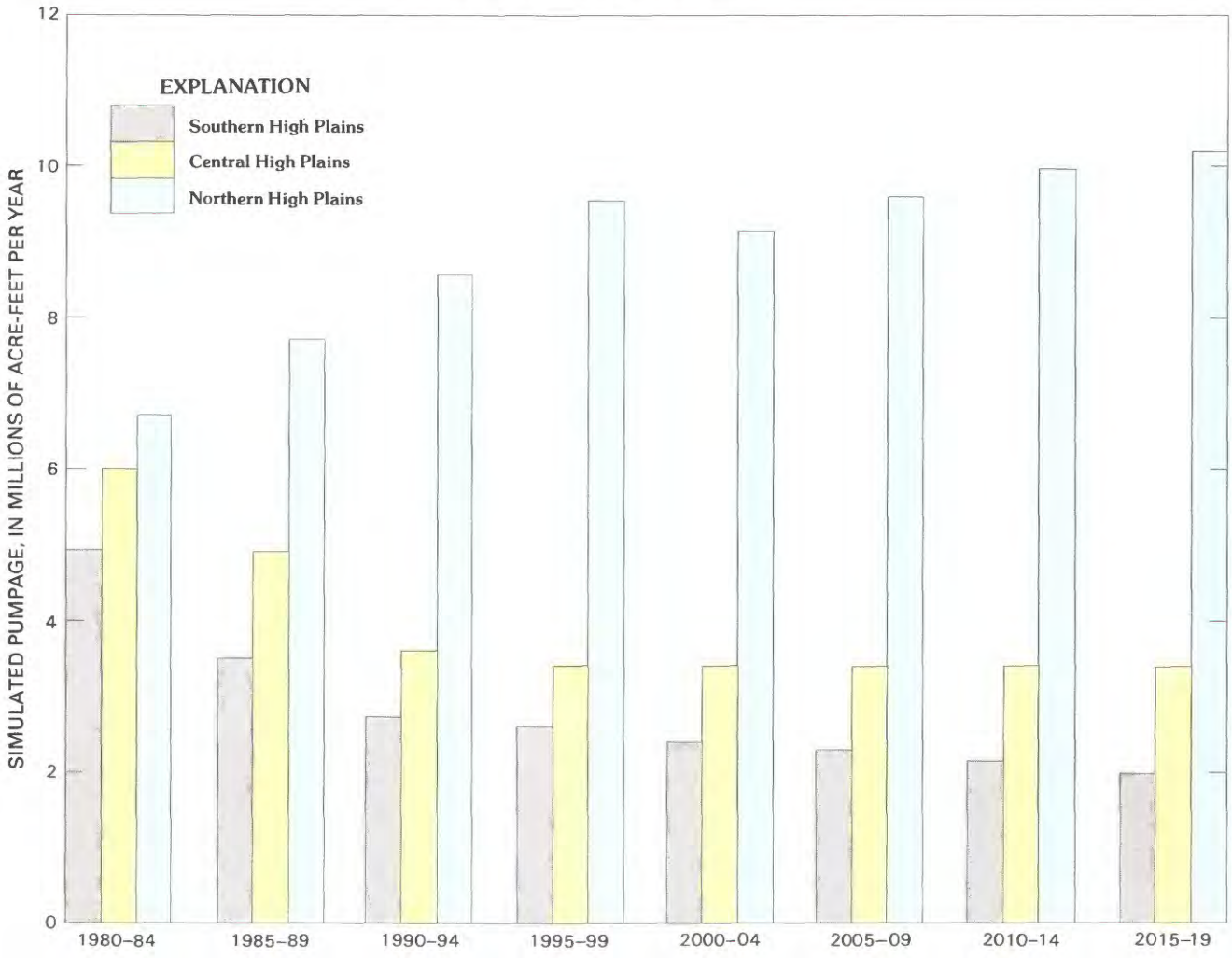


FIGURE 27.—Simulated pumpage for the baseline strategy by High Plains model region.

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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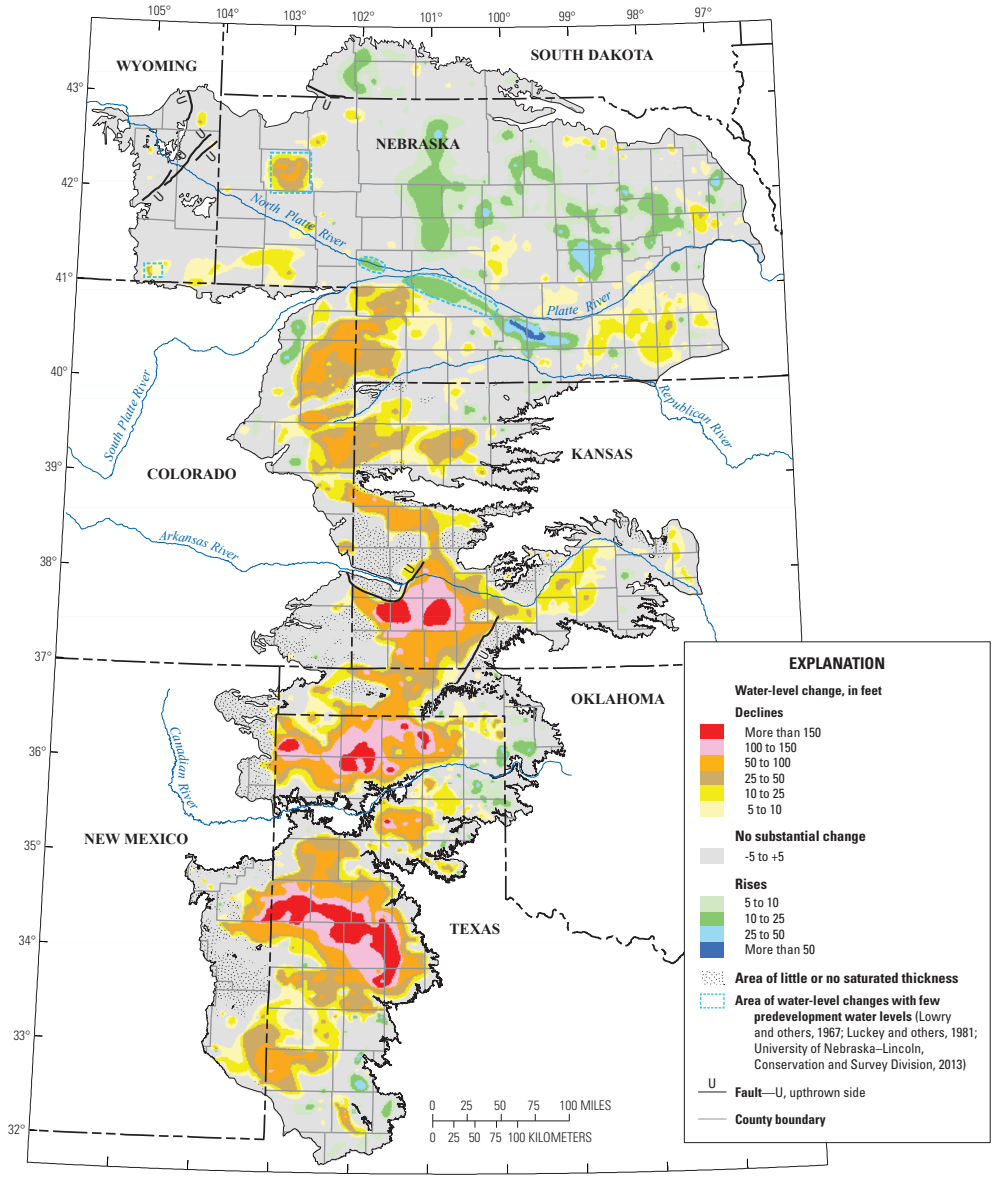
Appendix B

Water-Level Changes and Change in Water in Storage in the High Plains Aquifer, Predevelopment to 2013 and 2011-13 (U.S. Geological Survey Scientific Investigations Report 2014-5218).

Groundwater Resources Program

Water-Level Changes and Change in Water in Storage in the High Plains Aquifer, Predevelopment to 2013 and 2011–13



Scientific Investigations Report 2014–5218

U.S. Department of the Interior
U.S. Geological Survey

Cover illustration: Modified version of figure 1 from this report.

Water-Level Changes and Change in Water in Storage in the High Plains Aquifer, Predevelopment to 2013 and 2011–13

By Virginia L. McGuire

Groundwater Resources Program

Scientific Investigations Report 2014–5218

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)*	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)**	1,233	cubic meter (m^3)
million acre-foot (Macre-ft)	4,047,000,000	square meter-foot (m^2-ft)
million acre-foot (Macre-ft)	1.233	cubic kilometer (m^3)

*There are 640 acres in a square mile (mi^2).

**One acre-foot of water is equivalent to the volume of water that would cover 1 acre (43,560 ft^2) to a depth of 1 foot (325,851 gallons or 43,560 ft^3).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Water year is the 12-month period, October 1 through September 30, and is designated by the calendar year in which it ends.

Acknowledgments

Most of the water-level data used in this report were provided by the following State, local, and Federal entities: Colorado–Division of Water Resources (also known as the Office of the State Engineer); Kansas–Department of Agriculture, Division of Water Resources and the Kansas Geological Survey; Nebraska–Central Nebraska Public Power and Irrigation District, Natural Resources Districts, and University of Nebraska–Lincoln, Conservation and Survey Division; New Mexico–Office of the State Engineer; Oklahoma–Water Resources Board; South Dakota–Department of Environment and Natural Resources; Texas–Groundwater Conservation Districts and the Water Development Board; Wyoming–State Engineer's Office; and Federal–Bureau of Reclamation and U.S. Fish and Wildlife Service. The author thanks the above entities for providing the water-level data and for their responsiveness regarding questions about the data.

Water-Level Changes and Change in Water in Storage in the High Plains Aquifer, Predevelopment to 2013 and 2011–13

By Virginia L. McGuire

Abstract

The High Plains aquifer underlies 111.8 million acres (about 175,000 square miles) in parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. Water-level declines began in parts of the High Plains aquifer soon after the beginning of substantial irrigation with groundwater in the aquifer area (about 1950). This report presents water-level changes in the High Plains aquifer from predevelopment (generally before 1950) to 2013 and from 2011 to 2013. The report also presents change in water in storage in the High Plains aquifer from predevelopment to 2013 and from 2011 to 2013.

The methods to calculate area-weighted, average water-level changes; change in water in storage; and total water in storage for this report used geospatial data layers organized as rasters with a cell size of 500 meters by 500 meters, which is an area of about 62 acres. These methods were used to provide a raster dataset of water-level changes for other uses.

Water-level changes from predevelopment to 2013, by well, ranged from a rise of 85 feet to a decline of 256 feet. Water-level changes from 2011 to 2013, by well, ranged from a rise of 19 feet to a decline of 44 feet. The area-weighted, average water-level changes in the aquifer were an overall decline of 15.4 feet from predevelopment to 2013, and a decline of 2.1 feet from 2011 to 2013. Total water in storage in the aquifer in 2013 was about 2.92 billion acre-feet, which was a decline of about 266.7 million acre-feet since predevelopment and a decline of 36.0 million acre-feet from 2011 to 2013.

Introduction

The High Plains aquifer underlies 111.8 million acres (about 175,000 square miles [mi^2]) in parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 1; Qi, 2010). In the High Plains aquifer, groundwater generally is under unconfined conditions, and the water body, from a regional perspective, has a water table at which the water pressure is atmospheric (Weeks and Gutentag, 1981). The saturated thickness of the aquifer, which is the distance from the water table to the base of the aquifer, ranges from less than 50 feet (ft) to about 1,200 ft (McGuire and others, 2012). Gutentag and others (1984) reported that, in a few parts of the aquifer area, the water table is discontinuous; these areas total about 6.0 million acres (10,780 mi^2) and are labeled in this report's figures as "area of little or no saturated thickness." Wells drilled in areas of little or no saturated thickness (fig. 1) likely will not yield water unless the wells penetrated saturated sediment in buried channels or depressions in the bedrock surface (Gutentag and others, 1984).

The area overlying the High Plains aquifer is one of the primary agricultural regions in the Nation; in parts of the area, farmers and ranchers began extensive use of groundwater for irrigation in the 1930s and 1940s. Estimated irrigated acreage was 2.1 million acres in 1949, 13.7 million acres in 1980, 13.9 million acres in 1997, 12.7 million acres in 2002, and 15.5 million acres in 2005 (Heimes and Luckey, 1982; Thelin and Heimes, 1987; U.S. Department of Agriculture, 1999 and 2004; Kenny and others, 2009). In 2005, about 14 percent of the aquifer area was irrigated, not including the areas with little or no saturated thickness (Kenny and others, 2009).

About every 5 years, groundwater withdrawals for irrigation and other uses are compiled from water-use data and reported by the U.S. Geological Survey (USGS) and State agencies. Groundwater withdrawals from the High Plains aquifer for irrigation increased from 4 to 19 million acre-feet (Macre-ft) from 1949 to 1974; groundwater withdrawals for irrigation in 1980, 1985, 1990, and 1995 were 4 to 18 percent less than withdrawals for irrigation in 1974 (Heimes and Luckey, 1982; U.S. Geological Survey, 2008). Groundwater withdrawals from the aquifer for irrigation were 21 Macre-ft in 2000 (Maupin and Barber, 2005) and estimated as 19 Macre-ft in 2005 (U.S. Geological Survey, 2008; Kenny and others, 2009; McGuire, 2009).

Water-level declines began in parts of the High Plains aquifer soon after the onset of substantial irrigation using

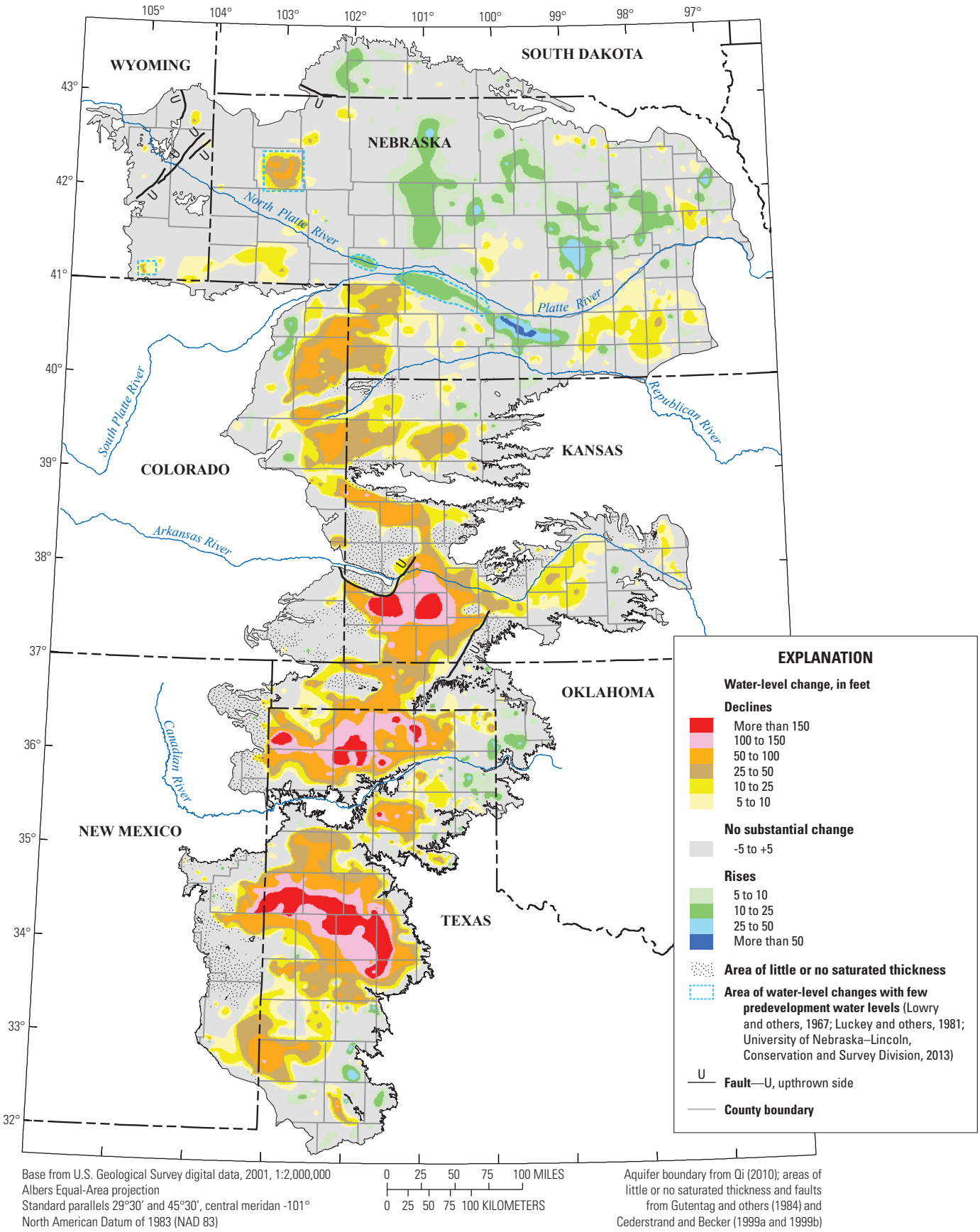

Figure 1. Water-level changes in the High Plains aquifer, predevelopment (about 1950) to 2013.

groundwater in the area—about 1950 (Gutentag and others, 1984). By 1980, water levels in the High Plains aquifer in parts of Texas, Oklahoma, and southwestern Kansas had declined more than 100 ft (Luckey and others, 1981).

Changes in the static water-level of an aquifer result from an imbalance between discharge and recharge. The static water level in a well is the water level after recovery from pumping in the measured well or in nearby wells. Discharge from the High Plains aquifer primarily consists of groundwater withdrawals for irrigation; but also includes groundwater withdrawals for public water supply and other uses; evapotranspiration where the water table is near land surface; and seepage to streams, springs, and other surface-water bodies, where the water table intersects the land surface (Maupin and Barber, 2005). Recharge to the aquifer primarily is from precipitation, but other sources of recharge include irrigation return flows and seepage from streams, canals, and reservoirs (Luckey and Becker, 1999). Water-level declines may result in increased costs to pump groundwater because of increased pumping lift and decreased well yields (Taylor and Alley, 2001). Water-level declines also can affect groundwater availability, surface-water flow, and near-stream (riparian) habitat areas (Alley and others, 1999).

In response to water-level declines, Congress, under the authority of Title III to the Water Resources Research Act (U.S. Public Law 98-242, 99-662), directed the USGS to monitor water levels in the High Plains aquifer. Since 1987, the USGS, in collaboration with numerous State, local, and Federal water-resources entities, have compiled water levels from wells completed in the High Plains aquifer. Water levels were measured in 8,332 wells for 2011 and 8,910 wells for 2012; water levels for 2013 were based on measurements from 8,613 wells (table 1).

Purposes of this report are (1) to present water-level changes in the High Plains aquifer from the time before substantial development of groundwater for irrigation (referred to hereinafter as “predevelopment”) to 2013 and from 2011 to 2013 (referred to hereinafter as 2011–13), (2) to present changes in drainable water in storage, which will hereinafter be referred as “water in storage,” in the High Plains aquifer from predevelopment to 2013 and from 2011–13, and (3) to publish the raster dataset depicting water-level changes from predevelopment to 2013. Predevelopment generally is before about 1950, but in some areas (for example, in the north-central part of the Texas Panhandle), predevelopment is the late 1990s, and in other areas (for example, in north-central Nebraska), currently (2014), groundwater has not been substantially developed for irrigation. Water in storage is the fraction of water in the aquifer that will drain by gravity and can be withdrawn by wells. The remaining water in the aquifer is held to the aquifer material and generally cannot be withdrawn by wells (Meinzer, 1923). Water levels used in this report generally were measured in winter or early spring, when irrigation wells typically were not pumping, and after water levels generally had recovered from pumping during the previous irrigation season.

Table 1. Number of wells used in this report for 2011, 2012, and 2013 water levels, and for the water-level comparison periods, predevelopment to 2013 and 2011–13, by State and in total for the High Plains aquifer.

State	Number of wells measured			Number of wells used in water-level comparison for indicated period	
	2011	2012	2013	Predevelopment to 2013	2011–13
Colorado	511	450	445	325	411
Kansas	1,419	1,645	1,579	506	1,253
Nebraska	3,306	3,673	3,514	1,508	3,099
New Mexico	115	149	120	100*	30
Oklahoma	143	154	150	80	133
South Dakota	105	85	103	68	98
Texas	2,681	2,699	2,688	745	2,424
Wyoming	52	55	14	17**	12
High Plains aquifer	**8,332**	**8,910**	**8,613**	**3,349**	**7,460**

*For 67 wells in the predevelopment-to-2013 water-level comparison period, 2009, 2010, 2011, or 2012 water levels were used instead of 2013 water levels because many wells in New Mexico were measured only once every 5 years or because the 2013 water level was not a static water level.

**For 16 wells in the predevelopment-to-2013 water-level comparison period, 2012 water levels were used instead of 2013 water levels because many wells in Wyoming, which were measured in predevelopment, were not measured in 2013.

Data and Methods

Area-weighted, average water-level changes, predevelopment to 2013 and 2011–13; change in water in storage, predevelopment to 2013 and 2011–13; and total water in storage in 2013 were calculated for this report using geospatial data organized as rasters datasets (hereinafter, “rasters”). The rasters used included saturated thickness as of 2009 (McGuire and others, 2012); change in water in storage, 2009–11 (McGuire, 2013); change in water in storage, 2011–13 (this report); and specific yield (McGuire and others, 2012). The methods used for these calculations are generally the same as methods used in McGuire (2013); these methods provide a final, raster dataset of water-level changes, from predevelopment to 2013, for other uses.

Characteristics of Raster Datasets

In this report, rasters, presented as maps and summarized with statistics, were generated for water-level changes and percent changes in saturated thickness from predevelopment to 2013. The rasters were generated using Esri® ArcInfo™ Workstation, version 10.0, a geographic information system (Esri, 1992 and 2010), which will hereinafter be referred as “GIS.” The rasters are georeferenced to geographic coordinates on an

Albers equal-area conic projection using the North American Datum of 1983 (NAD 83). The cell size for all rasters was 500 meters (m) by 500 m or about 62 acres. Water-level-change values were stored in units of feet. Changes in water in storage values were stored in units of square meter-feet (m^2-ft). Water in storage was summarized in units of Macre-ft. The raster of water-level changes, predevelopment to 2013, is available in two formats at the website listed in the Appendix. An additional raster for water-level changes, 2011–13, was generated and summarized with statistics, but not shown in this report.

The interpolation process used to generate the rasters, which are referred to in this report, results in cell values, for cells collocated with a measured well, that are generally similar to, but commonly not exactly equal to, the corresponding values based on those water-level measurements. The cell values represent the value for an area 500-m by 500-m and the measured values are point values within the area represented by the cell.

Characteristics of Water-Level Data

Water-level data used in this report generally were from wells measured with an electric or steel tape using methods similar to those described by Cunningham and Schalk (2011). The wells were measured by numerous State, local, and Federal water-resources agencies, and the measurement results were loaded into the USGS National Water Information System (NWIS) (U.S. Geological Survey, 2014).

Most of the wells were measured manually one to two times per water year. The water year starts with October of the previous year and ends with September of the given year. Generally, if a well was measured one time per water year, the well was measured in the winter or early spring; if a well was measured two times per water year, the well was measured in winter or early spring and in the fall. Some wells were measured nearly continuously using instrumentation (data recorders with sensors or floats) installed in the well that recorded the water level periodically (generally every 15 to 60 minutes) (Cunningham and Schalk, 2011). Water-level data used to map water-level changes were compiled for the specified water years (U.S. Geological Survey, 2014). Available water-level data for each well were reviewed to select a water level that (1) best represents the static water level for each applicable water year and (2) is consistent with water levels in nearby wells. If a static water level was not available for a given well for the specified water year, the water-level data for that well for the specified water year were not used in this report, except as noted in table 1.

Most of the measured wells supply water for irrigation; water-level precision and accuracy in irrigation wells can be adversely affected by excess oil used to lubricate the well's pump. The thickness of the excess oil and the depth to the oil-water interface can be measured with specialized water-level tapes or can be estimated using a method described in Cunningham and Schalk (2011). The specialized tapes often cannot be used in irrigation wells because opening(s) in the well casing for the tape generally are too small for the specialized tape. In this report, it is assumed that, if there is not oil in the well, the precision of the water-level measurements is 0.01 ft; if there is oil on the surface of the water, the precision of the water-level measurement likely is greater than 0.01 ft. The accuracy of the water-level measurement can be affected by many factors (Cunningham and Schalk, 2011); if there is oil on the surface of the water, the error in the water-level measurement could be as much as 5 ft, depending on the depth of the oil and whether the methods described in Cunningham and Schalk (2011) are used to correct the water-level measurement.

In all eight States underlain by the High Plains aquifer, available water levels for predevelopment and 1980 were compiled by Weeks and Gutentag (1981) and McGuire and others (2003). The predevelopment water level generally was estimated by using the earliest water-level measurement available for more than 20,000 wells. The median measurement year in the predevelopment period was 1957 (McGuire and others, 2003). The 1980 water levels are static water levels generally measured after the irrigation season in 1979 and before the irrigation season in 1980 (that is, in water year 1980), but some were measured 1 or 2 years earlier.

In seven of the eight States that are underlain by the High Plains aquifer—Colorado, Kansas, Nebraska, Oklahoma, South Dakota, Texas, and Wyoming—most water-level data used in this report were from wells measured annually. In areas underlain by the High Plains aquifer in New Mexico, a substantial number of wells are measured only once every 5 or more years.

In Colorado, Kansas, Nebraska, Oklahoma, South Dakota, and Texas, the water levels used to map water-level changes, predevelopment to 2013, were from wells with a static water level for predevelopment and for 2013. In New Mexico and Wyoming, the water levels used to map water-level changes, predevelopment to 2013, were from wells with a static water level for predevelopment, and a measured or estimated static water level for 2013.

Water levels for 2013 were estimated for wells in New Mexico using the most recent static water levels from 2009 to 2012, for wells not measured or without a static water level for 2013. A total of 67 water levels were estimated for 2013 for wells in New Mexico; these estimates used water levels measured in 2009 for 5 wells, in 2010 for 1 well, in 2011 for 23 wells, and in 2012 for 38 wells. Water levels for 2013 were estimated for wells in Wyoming using the most recent static water levels from 2012 for 16 wells not measured or without a static water level for 2013.

In the eight States that are underlain by the High Plains aquifer, the water levels used to map 2011–13 water-level changes were from wells with a measured static water level for 2011 and 2013. Estimated water levels were not used to map 2011–13 water-level changes.

Characterizing Water-Level Changes, Predevelopment to 2013

The raster of water-level changes, predevelopment to 2013, was generated using the same methods used in McGuire (2013) for the raster of water-level changes, predevelopment to 2011. The raster was generated using the GIS command "topogrid" with the water-level-change data from wells measured in predevelopment and measured or estimated for 2013 as the primary source data and contours of water-level change, to control the interpolation. The contours of water-level change, which were used to control the interpolation, were generated using primary and supplemental water-level-change data from wells measured in predevelopment and measured or estimated for 2013 and from published water-level change values in areas in Nebraska and Wyoming with sparse primary or supplemental water-level-change data (Lowry and others, 1967; Luckey and others, 1981; University of Nebraska–Lincoln, Conservation and Survey Division, 2013). The supplemental water-level-change data for the predevelopment-to-2013 period were from the following sources:

1. Wells measured before June 15, 1978, but not during or before the predevelopment period for the area, and in 2013; and
2. Wells measured in 1980 and 2013.

The mapped areas between a decline of less than 5 ft and a rise of less than 5 ft were termed areas of no substantial change and were assigned a value of zero water-level change rather than using the GIS interpolation of water-level change values in these areas. McGuire (2013) discusses the effect of using zero in the areas of no substantial changes instead of the GIS interpolation of water-level change values in these areas.

Characterizing Water-Level Changes, 2011–13

The raster of water-level changes, 2011–13, was generated using the GIS command "topogrid," which is the same method used in McGuire (2013) for the raster of water-level changes, 2009–11. The mapped areas between a decline of less than 1 ft and a rise of less than 1 ft were termed areas of no substantial change and were assigned a value of zero water-level change rather than using the GIS interpolation of water-level change values in these areas. McGuire (2013) discusses the effect of using zero in the areas of no substantial changes instead of the GIS interpolation of water-level change values in these areas. The area of no substantial change for the 2011–13 time period was defined differently than the range used for the predevelopment to 2013 time period because there were many water-level change values in the 2011–13 time period that are between a decline of less than 1 ft and a rise of less than 1 ft.

Characterizing Specific Yield

Specific yield of the aquifer is needed to calculate water in storage. Specific yield of a rock or soil, with respect to water, is the ratio of the volume of water, which the saturated rock or soil will yield by gravity, to the rock or soil volume (Meinzer, 1923). Specific yield was mapped for the High Plains aquifer from point estimates of area-weighted, average specific yield derived from lithologic logs for selected wells or test holes generally drilled to the base of the aquifer. The area-weighted, average specific yield of the High Plains aquifer ranges from near 0 to 30 percent. The area-weighted, average specific yield, not including the areas of little or no saturated thickness, ranges by State, from 8.1 percent in Wyoming to 18.5 percent in Oklahoma and is 15.1 percent overall for the aquifer (Gutentag and others, 1984; McGuire and others, 2012).

A specific-yield raster was created from a digital map of specific-yield ranges in the High Plains aquifer (Gutentag and others, 1984; Cederstrand and Becker, 1998). The GIS command "polygrid" was used to convert the average of the assigned range for the specific-yield polygons to a raster of the area (McGuire and others, 2012). The specific-yield value of cells in this raster of specific yield is hereafter referred to as the "average-mapped" specific-yield value.

Calculation of Area-Weighted, Average Water-Level Changes, Predevelopment to 2013 and 2011–13

In this report, area-weighted, average water-level changes, predevelopment to 2013 and 2011–13, were calculated using the same methods used in McGuire (2013) to calculate area-weighted, average water-level changes, predevelopment to 2011 and 2009–11. This method for calculating area-weighted, average water-level changes was used because the final raster can be used to easily calculate statistics for additional subareas of the aquifer.

Calculation of Total Water in Storage and Change in Water in Storage

Total water in storage for 2013 was calculated, using the respective raster cell values, by summing the rasters of saturated thickness for 2009 (McGuire and others, 2012) and the rasters of water-level changes from 2009–11(McGuire, 2013) and 2011–13, then multiplying the result by the raster of average-mapped specific yield (McGuire and others, 2012) and by a conversion factor to convert units of square meter-feet to million acre-feet. Changes in water in storage in the High Plains aquifer for the predevelopment to 2013 and the 2011–13 time periods were calculated in this report by applying "map algebra" techniques (Tomlin and Berry, 1979) to coregistered rasters sharing a common cell size and

mesh orientation. The raster cell values of water-level changes for each period were multiplied by the raster cell values of average-mapped specific yield (McGuire and others, 2012) and by a conversion factor to convert units of square meter-feet to million acre-feet. Changes in water in storage from predevelopment to 2013 and 2011–13, by State and as an overall High Plains aquifer total, were calculated using the applicable resultant raster.

Characterizing Percentage Change in Saturated Thickness, Predevelopment to 2013

The raster of percentage change in saturated thickness, predevelopment to 2013, was generated using the GIS command "topogrid." Inputs to topogrid were percent change in saturated thickness at each well measured in predevelopment and measured or estimated for 2013 and contours of percent change in saturated thickness. Predevelopment saturated thickness was calculated for each well by subtracting the altitude of the base of aquifer from the predevelopment water-level altitude. The contours of percent change in saturated thickness were used to constrain the interpolation in areas of sparse data; the contours of percent change in saturated thickness were generated using the percent change in saturated thickness at each well measured in predevelopment and measured or estimated for 2013 and published areas of water-level level changes in Nebraska and Wyoming with few predevelopment water levels, (Lowry and others, 1967; Luckey and others, 1981; University of Nebraska–Lincoln, Conservation and Survey Division, 2013). The percent change in saturated-thickness contours were reviewed and manually modified using supplemental data to construct the final contours. The supplemental data for changes in saturated thickness, in percent, were from the following sources:

1. Wells measured before June 15, 1978, but not in the predevelopment period for the area, and in the 2013 period; and
2. Wells measured in 1980 and in the 2013 period.

Water-Level Data

Water-level data used in this report were provided by the following State, local, and Federal, entities through data files or downloads from Web sites, and loaded into the USGS NWIS (U.S. Geological Survey, 2014):

- Colorado—Division of Water Resources (also known as the Office of the State Engineer);
- Kansas—Department of Agriculture, Division of Water Resources and the Kansas Geological Survey (Kansas Geological Survey, 2014);
- Nebraska—Central Nebraska Public Power and Irrigation District, applicable Natural Resources Districts, and the University of Nebraska–Lincoln, Conservation and Survey Division;
- New Mexico—Office of the State Engineer;
- Oklahoma—Water Resources Board;
- South Dakota—Department of Environment and Natural Resources;
- Texas—Groundwater Conservation Districts and the Water Development Board (Texas Water Development Board, 2014);
- Wyoming—State Engineer's Office; and
- Federal—Bureau of Reclamation, U.S. Fish and Wildlife Service, and USGS offices in Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming.

The data used in this report were retrieved for each applicable State from USGS NWIS (U.S. Geological Survey, 2014).

Water-Level Changes

Water-level changes in the High Plains aquifer are presented for two periods: predevelopment to 2013 and 2011–13. In addition, water-level changes are presented as the percentage change in saturated thickness from predevelopment to 2013.

Water-Level Changes, Predevelopment to 2013

The map of water-level changes in the High Plains aquifer, predevelopment to 2013 (fig. 1), is based on water levels from 3,349 wells (table 1) and on other published data (Lowry and others, 1967; Luckey and others, 1981; University of Nebraska–Lincoln, Conservation and Survey Division, 2013). The other published data were used in areas in Nebraska and Wyoming with few predevelopment water levels (fig. 1). Water-level changes in wells, predevelopment to 2013, ranged from:

- A rise of 85 ft in Nebraska to a decline of 256 ft in Texas;
- A rise of 38 ft to a decline of 196 ft in 99 percent of the wells;
- A rise of 5 ft to a decline of 5 ft in 36 percent of the wells; and
- A rise of 1 ft to a decline of 1 ft in 10 percent of the wells.

The area-weighted, average water-level change from predevelopment to 2013 was a decline of 15.4 ft (table 2). When summarized by State, the area-weighted, average water-level

change from predevelopment to 2013 ranged from a decline of about 41 ft in Texas to a rise of 1.8 ft in South Dakota (table 2). From predevelopment to 2013, not including the areas of little or no saturated thickness, water levels declined 5 ft or more in 37 percent of the aquifer area, 10 ft or more in 28 percent of the aquifer area, 25 ft or more in 19 percent of the aquifer area, and 50 ft or more in 12 percent of the aquifer area. In approximately 52 percent of the aquifer area, water-level changes ranged from a 5-ft decline to a 5-ft rise, which is considered areas of no substantial change. From predevelopment to 2013, water levels rose 5 ft or more in 11 percent of the aquifer area and 10 ft or more in 5 percent of the aquifer area.

Table 2. Area-weighted, average water-level changes in the High Plains aquifer, not including areas of little or no saturated thickness, predevelopment to 2013 and 2011–13, by State and as an overall total.

[Positive values for water-level rises; negative values for water-level declines]

State	Area-weighted, average water-level change, in feet	
	Predevelopment to 2013	2011–13
Colorado	-14.3	-2.2
Kansas	-25.5	-3.0
Nebraska	-0.3	-1.5
New Mexico	-16.5	-0.6
Oklahoma	-12.3	-2.0
South Dakota	1.8	0
Texas	-41.2	-3.5
Wyoming	-0.8	0
High Plains aquifer	**-15.4**	**-2.1**

Water-Level Changes, 2011–13

Water levels were measured in 7,460 wells before the irrigation season in 2011 and 2013 (table 1). Water-level changes in the measured wells ranged from

- A rise of 19 ft in Texas to a decline of 44 ft in Texas;
- A rise of 8 ft to a decline of 23 ft in 99 percent of the wells;
- A rise of 5 ft to a decline of 5 ft in 75 percent of the wells; and
- A rise of 1 ft to a decline of 1 ft in 21 percent of the wells.

Water levels declined 3 ft or more in 43 percent of the measured wells and declined 6 ft or more in 17 percent of the measured wells. Water levels rose 3 ft or more in 2 percent of measured wells and rose 6 ft or more in 1 percent of measured wells. Area-weighted, average water-level changes, 2011–13, by State ranged from a 3.5-ft decline in Texas to no change in South Dakota and Wyoming (table 2). The area-weighted, average water-level change for the aquifer for the period 2011–13 was a decline of 2.1 ft (table 2).

Percentage Change in Saturated Thickness, Predevelopment to 2013

Figure 2 presents water-level changes, predevelopment to 2013, as a percentage of predevelopment saturated thickness. This map (fig. 2) is similar in some areas to the water-level-change map for the same period (fig. 1); however, a large water-level change would not correspond to a substantial percentage change in saturated thickness if the predevelopment saturated thickness was large relative to the water-level change. Conversely, an area with small water-level change may correspond to a large percentage change in saturated thickness if its predevelopment saturated thickness was small. By 2013, percentage change in saturated thickness as a percent of the aquifer area, not including the areas of little or no saturated thickness, was a decrease of 10 percent or more in 25 percent of the area, a decrease of 25 percent or more in 15 percent of the area, a decrease of 50 percent or more in 5 percent of the area, an increase of 10 percent or more in 1 percent of the area, and between a rise of 10 percent and a decline of 10 percent in 74 percent of the area.

Change in Water in Storage, Predevelopment to 2013 and 2011–13

The volume of water in storage in the High Plains aquifer has been estimated, using different methods, to have been about 3.20 billion acre-ft (Bacre-ft) at predevelopment (McGuire and others, 2012), 3.25 Bacre-ft in 1980 (Gutentag and others, 1984), 2.98 Bacre-ft in 2000 (McGuire and others, 2003), 2.90 Bacre-ft in 2009 (McGuire, 2011), and recalculated as about 2.96 Bacre-ft in 2009 (McGuire and others, 2012). Water in storage in the High Plains aquifer in 2013 is estimated in this report as 2.92 Bacre-ft. Water in storage for 2013 was calculated using the rasters of water-level changes for the period of 2009-11 (McGuire, 2013) and 2011–13, the raster of saturated thickness for 2009 (McGuire and others, 2012), and the raster of average-mapped specific yield (McGuire and others, 2012).

Water in storage, predevelopment to 2013, which was calculated using average-mapped specific yield, declined 266.7 Macre-ft for the aquifer overall (table 3) or about an 8-percent decline in storage since predevelopment (McGuire and others, 2012). Changes in storage, predevelopment to 2013, by State, ranged from a decline of about 158.2 Macre-ft

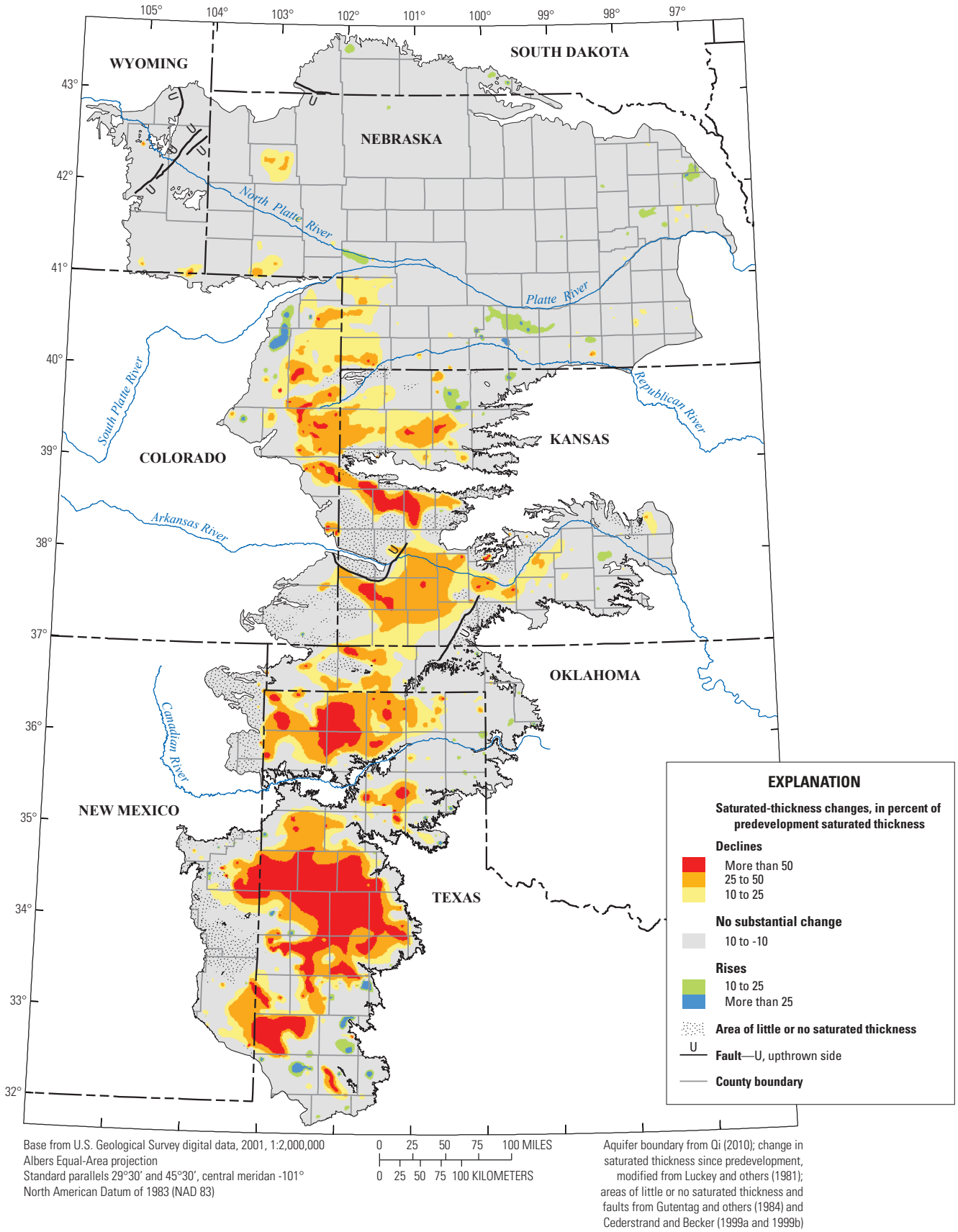

Figure 2. Change in saturated thickness of the High Plains aquifer, predevelopment (about 1950) to 2013.

in Texas to a rise of 0.4 Macre-ft in South Dakota (table 3). Water in storage, 2011–13, declined 36.0 Macre-ft overall; changes in water in storage, 2011–13, by State ranged from a decline of 13.2 Macre-ft in Texas to no change in South Dakota and Wyoming (table 3).

Table 3. Change in water in storage in the High Plains aquifer, predevelopment to 2013 and 2011–13, by State and as an overall total.

[Positive values for increases in water in storage; negative values for decreases in water in storage]

State	Change in water in storage, in million acre-feet	
	Final values calculated for this report, with average-mapped specific yield (range of 2.5 to 27.5 percent)	
	Predevelopment to 2013	2011–13
Colorado	-18.8	-3.0
Kansas	-67.5	-8.3
Nebraska	-2.0	-9.6
New Mexico	-9.7	-0.3
Oklahoma	-10.5	-1.6
South Dakota	0.4	0
Texas	-158.2	-13.2
Wyoming	-0.4	0
High Plains aquifer	**-266.7**	**-36.0**

Summary

The High Plains aquifer underlies 111.8 million acres (about 175,000 square miles) in parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. Water-level declines began in parts of the High Plains aquifer soon after the onset of substantial irrigation with groundwater (about 1950). In response to the water-level declines, Congress directed the U.S. Geological Survey to monitor water levels in the High Plains aquifer. Since 1987, the USGS, in collaboration with numerous State, local, and Federal water-resources entities, have compiled water levels from wells completed in the High Plains aquifer. Water levels were measured in 8,332 wells for 2011 and measured or estimated in 8,613 wells for 2013.

This report presents water-level changes in the High Plains aquifer from predevelopment (generally before 1950) to 2013 and from 2011 to 2013. The water levels used in this report generally were measured in winter or early spring, when irrigation wells typically were not pumping, and after water levels generally had recovered from pumping during the previous irrigation season. The report also presents total water in storage in 2013 and changes in water in storage and in saturated thickness from predevelopment to 2013. The methods to calculate area-weighted, average water-level changes; changes in water in storage; and total water in storage for this report used geospatial data layers organized as rasters with a cell size of 500 meters by 500 meters, which is an area of about 62 acres. These methods provide a raster dataset of water-level changes, predevelopment to 2013, for other uses.

The map of water-level changes in the High Plains aquifer from predevelopment to 2013 is based on water levels from 3,349 wells and other published data. Water-level changes from predevelopment to 2013, in individual wells, ranged from a rise of 85 feet (ft) in Nebraska to a decline of 256 ft in Texas. The area-weighted, average water-level change from predevelopment to 2013 was an overall decline of 15.4 ft.

Water levels were measured in 7,460 wells before the irrigation season in 2011 and 2013; water-level changes in the measured wells ranged from a 44-ft decline in Texas to a 19-ft rise in Texas. The area-weighted, average water-level change in the High Plains aquifer from 2011 to 2013 was a decline of 2.1 ft.

Total water in storage in 2013 was about 2.92 billion acre-feet overall, which was a decline of about 266.7 million acre-feet (or about 8 percent) since predevelopment. Water in storage, 2011–13, declined 36.0 Macre-ft overall; changes in water in storage, 2011–13, by State ranged from a decline of 13.2 Macre-ft in Texas to no change in South Dakota and Wyoming . By 2013, 15 percent of the aquifer area had a decrease in saturated thickness of more than 25 percent from its predevelopment saturated thickness, 5 percent of the aquifer area had more than a 50-percent decrease, and about 1 percent of the aquifer area had more than a 10-percent increase.

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Appendix

Appendix. Raster Datasets

Raster datasets are presented for figure 1, which is a map depicting water-level changes, predevelopment to 2013. The raster dataset is presented in both Esri® ArcInfo™ Workstation, version 10.0 (Esri, 1992 and 2010) grid and ASCII format at the following URLs:

- Esri® grid format: *http://water.usgs.gov/GIS/dsdl/sir2014-5218_hp_wlcpd13g.zip*
- ASCII format: *http://water.usgs.gov/GIS/dsdl/sir2014-5218_hp_wlcpd13a.zip*

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Appendix C

Analysis of High Plains Resource Risk and Economic Impacts (U.S. Department of Homeland Security Office of Cyber and Infrastructure Analysis, 2015)

ANALYSIS OF HIGH PLAINS RESOURCE RISK AND ECONOMIC IMPACTS

August 2015

NATIONAL PROTECTION AND PROGRAMS DIRECTORATE

OFFICE OF CYBER AND INFRASTRUCTURE ANALYSIS

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EXECUTIVE SUMMARY

The Department of Homeland Security (DHS) Office of Cyber and Infrastructure Analysis (OCIA) produced this report on High Plains Aquifer risk and associated economic impacts. The area overlying the High Plains Aquifer is one of the most prolific agricultural regions in the Nation, covering 111.8 million acres (175,000 square miles) in parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming.[1] Following World War II, improved pumps and center pivot irrigation technology made High Plains groundwater available for large-scale irrigated agriculture. The High Plains has since become one of the most intensively irrigated areas in the United States, accounting for about 30 percent of all groundwater withdrawn for irrigation. As of 2007, the High Plains supported 50 million acres of cropland, 15.4 million acres of which were irrigated. The High Plains supplies approximately one-fourth of the Nation's agricultural production. Associated crops provide significant amounts of feed to the Midwest cattle operations that account for 40 percent of U.S. feedlot beef output. The aquifer also provides drinking water to 82 percent of the people who live within its boundaries.[2] Increasing reliance on the High Plains aquifer has exceeded groundwater recharge rates. Water-level declines began in parts of the High Plains Aquifer soon after the onset of substantial irrigation, around 1950; by 1980, water levels had declined by more than 100 feet in parts of Texas, Oklahoma, and southwestern Kansas.[3]

This study explores how continued depletions of the High Plains Aquifer might impact both critical infrastructure and the economy at the local, regional, and national levels. County-level analysis examined 140 counties that overlie the High Plains Aquifer in the States of Kansas and Nebraska to estimate time to depletion of the groundwater resource at current pumping rates. The analysis uses climate projections to estimate future crop production. Current water use and management practices are projected to explore their related impact on the High Plains Aquifer, specifically in the region defined by Kansas and Nebraska together. Finally, the impacts of declining water levels and changes in crop production, including exhaustion of groundwater resources, are projected for specific economic industries and critical infrastructure.

The results of the crop modeling analyses represent a range of possible outcomes that could arise from future variations in groundwater availability, climate, and agricultural innovation. In the absence of any other changes, future climate projections were found to impose a small downward trend in dryland yields for corn, sorghum, soy, and winter wheat across Kansas and Nebraska. Irrigation use, historically, has offset the impacts of variations in temperature and precipitation on crop yields; however, declining water levels are likely to limit offsets in the future. Improvements to farm operations (for example, changing crops to more drought-resist strains) and technology could overcome the impacts of climate variability, if future trends are consistent with recent developments such as improved tilling practices, advanced fertilizers and genetically modified crops.

Despite efforts to reduce groundwater depletions, groundwater pumping in some areas within the High Plains region still exceeds sustainable groundwater recharge rates. To calculate when the aquifer is unlikely to be able to sustain continued pumping, the study projected current pumping rates into the future. Eighteen counties in Kansas were projected to have 25 or less years of available groundwater, while another 12 had an estimated aquifer life of less than 50 years. Thirty counties in Kansas and seven in Nebraska have a projected aquifer life of less than 100 years. Vulnerable counties are largely associated with extensive irrigated acreage or zones at the margin of the High Plains Aquifer where the formation thins.

The associated economic analysis relies on information from numerous sources including previous National Infrastructure and Analysis Center (NISAC) and agricultural economic reports, and input from key stakeholders to derive its assumptions and to limit the parameters and variables necessary to translate the scenario text into a quantitative economic model. To estimate the economic consequences of resource risk in the High Plains, the economic analysis employed a two-pronged approach: (1) starting at the national level and drilling down to identify

[1] The High Plains aquifer is composed of several water bearing units with the Ogallala formation as its principal member.
[2] Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2014, Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405, 56 p., http: //dx.doi.org/10.3133/cir1405,
[3] Luckey, R.R., Gutentag, E.D., and Weeks, J.B., 1981, Water-level and saturated-thickness changes, predevelopment to 1980, in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–652, 2 sheets, scale 1: 2,500,000. (Also available at http: //pubs.er.usgs.gov/publication/ ha652.)

major industries at the State and county levels while also categorizing industries as water intensive and therefore vulnerable to resource risk, and (2) translating microeconomic impacts to the macroeconomic level.

Industries deemed both economically dominant and characterized by high water intensity and use were selected for microeconomic impacts because of their likely sensitivity to higher prices for pumping groundwater. Qualitative analysis confirmed that of all those studied, the agriculture industry by output (volume and dollars), wages, employment, and water use is the most susceptible to increasing resource risk in the High Plains region. OCIA-NISAC completed a combined microeconomic and macroeconomic consequence analysis that focused on the agriculture industry to capture both the regional and national impacts associated with resource risk in the High Plains. Follow-on effects on other industries and critical infrastructure are the result of the physical-based relationships between industries represented through dollar relationships in the economic modeling.

KEY FINDINGS

- **Climate projections impose a small downward trend on dryland crop yields. While climate-related impacts on agriculture have been overcome by improvements to farm operations (including irrigation) in the past, declining water levels highlight the need to continue technological innovations.**
- **If current water use practices are continued into the future, sixty counties in Kansas and seven in Nebraska are projected to face exhaustion of groundwater supplies in 100 years or less.**
- **Declining water levels mean increased farm operations costs. Every $1,000 increase in utility expenditures corresponds to a 2.62 percent increase in the probability of a farm operation exiting the industry.**
  - **A 25 percent increase in utility costs over 50 years results in approximately a 0.1 percent decrease in Kansas State GDP.**
  - **A 25 percent increase in utility costs over 50 years results in approximately a 0.4 percent decrease in Nebraska State GDP.**
- **Exhaustion of groundwater supplies could also cause some farmers to switch to dryland farming. A modest shift from irrigated to dryland farming slightly impacts projected state GDP growth:**
  - **In Kansas, where 30 counties face groundwater depletion within the next 50 years, a 25 percent decrease in irrigated acres over 50 years results in approximately a 0.19 percent decrease in Kansas State GDP.**
  - **Reductions in irrigated acreages will affect follow-on industries such as agriculture support activities and consumer demand categories for disposable income.**
- **The critical infrastructure Sectors most affected by resource risk and economic impacts are Food and Agriculture, Water and Wastewater Systems, Chemical (ethanol production), and Energy (ethanol as a transportation fuel).**

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INTRODUCTION

The Department of Homeland Security's Office of Cyber and Infrastructure and Analysis (DHS/OCIA) manages the advanced modeling, simulation, and analysis capabilities of the National Infrastructure Simulation and Analysis Center (NISAC) in support of the DHS critical infrastructure protection mission. The National Infrastructure Simulation and Analysis Center (NISAC) analyzed the potential effects of aquifer depletion and increased pumping costs on the High Plains region of the United States, specifically the States of Kansas and Nebraska. NISAC collaborated with local DHS Protective Security Advisors (PSAs), state and local officials, and other DHS personnel to define the scope of this analysis.

The area overlying the High Plains Aquifer is one of the most prolific agricultural regions in the Nation.[4] This is in large part due to the extent, quality and accessibility of this groundwater resource. In terms of size, the High Plains Aquifer is one of the world's largest underground freshwater sources, underlying 111.8 million acres (175,000 square miles) in parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (Figure 1). The water-saturated thickness ranges from a few feet to more than 1,000 feet, generally greatest in the northern plains. In terms of quality, the High Plains Aquifer is characterized by high water yields owing to its origin as ancient runoff from the Rocky Mountains that deposited high permeability sands, gravel, clay, and silt. Groundwater of the High Plains Aquifer is also accessible with water depth ranging from 400 feet in parts of the north to between 100 and 200 feet throughout much of the south.

The High Plains Aquifer was first discovered by the United States Geological Survey in the 1890s, but was considered of limited agricultural importance.[5,6] Windmill pumps could only provide small quantities of water, approximately enough to irrigate 5 acres or provide for 30 cattle.[7] In a 1928 bulletin, the Nebraska Agricultural Extension Service highlighted the need for improved irrigation methods to supplement scarce rainfall and streams; while the underground water supply is abundant, "there are insufficient means of lifting it to the surface and applying it to the land."[8] Groundwater irrigation was thought to be of great potential value, particularly in raising corn yields, but pumps were small and expensive.[9,10,11]

Following World War II, improved pumps and center pivot irrigation technology made High Plains groundwater available for large-scale irrigated agriculture. The High Plains has become one of the nation's most intensively irrigated areas, accounting for about 30 percent of all groundwater withdrawn for irrigation in the United States.[12] More than 90 percent of the water pumped from the High Plains irrigates at least one fifth of all U.S. cropland. As of 2007, there were 50 million acres of cropland nationwide, of which 15.4 million acres were irrigated in the High Plains.[13] Crops that benefit from irrigation provided by the aquifer include cotton, corn, alfalfa, sorghum, soybeans, and wheat. Expansion of irrigated agriculture over the past 60 years has helped make the High Plains one of the most productive agricultural regions in the Nation. The High Plains region supplies approximately one-fourth of

[4] The High Plains aquifer is composed of several water-bearing units with the Ogallala formation as its principal member.
[5] Webb, W.P. 1931. The Great Plains, New York, NY: Grosset & Dunlap.
[6] U.S. Department of Commerce. 1937. The Future of the Great Plains: Report of the Great Plains Committee to the House of Representatives, 75th Cong., 1st session, doc. 144.
[7] Cunfer, G., 2005. On the Great Plains: Agriculture and Environment. Texas A&M University Press, College Station.
[8] Weakly, H. E. and L.L. Zook. 1928. "Pump Irrigation Results." Agricultural Experiment Station, University of Nebraska College of Agriculture, Lincoln, Bulletin 227 (June).
[9] Weakly, H.E. 1932. "Pump Irrigation and Water Table Studies." Agricultural Experiment Station, University of Nebraska College of Agriculture, Lincoln, Bulletin 271 (May).
[10] Weakly, H.E. 1936. "Pump Irrigation at the North Platte Experimental Substation." Agricultural Experiment Station, University of Nebraska College of Agriculture, Lincoln, Bulletin 301 (June).
[11] Brackett, E.E. and E.B. Lewis. 1933. "Pump Irrigation Investigations in Nebraska." Agricultural Experiment Station, University of Nebraska College of Agriculture, Lincoln, Bulletin 282 (July).
[12] Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2014, Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405, 56 p., http: //dx.doi.org/10.3133/cir1405.
[13] U.S. Department of Agriculture, Census of Agriculture for 2007: Washington, D.C., National Agricultural Statistics Service, at http: //www.agcensus.usda.gov/. At the time of reporting, the 2012 data was yet to be released.

the Nation's agricultural production.[14] Associated crops provide the Midwest cattle operations with enormous amounts of feed that account for 40 percent of the feedlot beef output in the United States.[15]

FIGURE 1—EXTENT OF HIGH PLAINS AQUIFER

The High Plains Aquifer originally filled with groundwater thousands of years ago during the last ice age. As the aquifer now receives less than an inch of annual recharge due to minimal rainfall, high evaporation, and low infiltration of surface water, this "fossil" groundwater resource is essentially nonrenewable.[16,17,18] Water-level declines began in parts of the High Plains Aquifer soon after the onset of substantial irrigation—around 1950.[19] By 1980, water levels in the High Plains Aquifer in parts of Texas, Oklahoma, and southwestern Kansas had declined by more than 100 feet.[20] In response to water-level declines, Congress, under the authority of Title III to the 1984 Water Resources Research Act (U.S. Public Law 98-242, 99-662), directed the U. S. Geological Survey (USGS), in collaboration with numerous Federal, State, and local water-resources entities, to access and track water-level changes in the aquifer. Using thousands of groundwater wells in this assessment the following results were noted:

[14] McMahon PB, Dennehey KF, Bruce BW, Gurdak JJ, Qi SL (2007) Water-Quality Assessment of the High Plains Aquifer, 1999–2004 (US Geological Survey, Reston, VA), Professional Paper 1749.
[15] Aquifer Close Up. Published by Center for Biological Computing, Indiana State University, Department of Life Sciences. http: //mama.indstate.edu/users/johannes/aquifer/htm
[16] Zwingle, E. 1993. "Wellspring of the High Plains," National Geographic, March, 80-109.
[17] Opie, J. 1993. Ogallala: Water for a Dry Land. Lincoln: University of Nebraska Press.
[18] McGuire, V.L., Johnson, M.R., Schieffer, R.L., Stanton, J.S., Sebree, S.K., and Verstraeten, I.M., 2003, Water in storage and approaches to ground-water management, High Plains aquifer, 2000: U.S. Geological Survey Circular 1243.
[19] Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984, Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–B, 63 p. (Also available at http: //pubs.usgs.gov/pp/1400b/report.pdf.)
[20] Luckey, R.R., Gutentag, E.D., and Weeks, J.B., 1981, Water level and saturated-thickness changes, predevelopment to 1980, in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–652, 2 sheets, scale 1: 2,500,000. (Also available at http: //pubs.er.usgs.gov/publication/ ha652.)

- Area-weighted, average water-level changes in the aquifer were an overall decline of 14.2 feet from predevelopment to 2011; and a decline of 0.1 foot from 2009–11;
- Total water in storage in the aquifer in 2011 was about 2.96 billion acre-feet;
- Changes in water in storage, predevelopment to 2011, involved an overall decline of about 246 million acre-feet (a depletion of approximately 8 percent); and
- Changes in water in storage, 2009-11, involved overall decline of 2.8 million acre-feet.[21]

However, these depletions are not evenly distributed over the aquifer area; rather, depletion varies by location due to differences in aquifer characteristics and the distribution of irrigation (Figure 2). Measured declines in groundwater of over 100 feet are not uncommon, with some of the most significant declines registered in Texas, Oklahoma, Kansas, and to a lesser extent in Nebraska.[22]

[21] McGuire, V.L., 2013, Water-level and storage changes in the High Plains aquifer, predevelopment to 2011 and 2009–11: U.S. Geological Survey Scientific Investigations Report 2012–5291, 15 p. (Also available at http: //pubs.usgs.gov/sir/2012/5291/.)

[22] McGuire, V.L., Lund, K.D., and Densmore, B.K., 2012, Saturated thickness and water in storage in the High Plains aquifer, 2009, and water-level changes and changes in water in storage in the High Plains aquifer, 1980 to 1995, 1995 to 2000, 2000 to 2005, and 2005 to 2009: U.S. Geological Survey Scientific Investigations Report 2012–5177, p. 28.

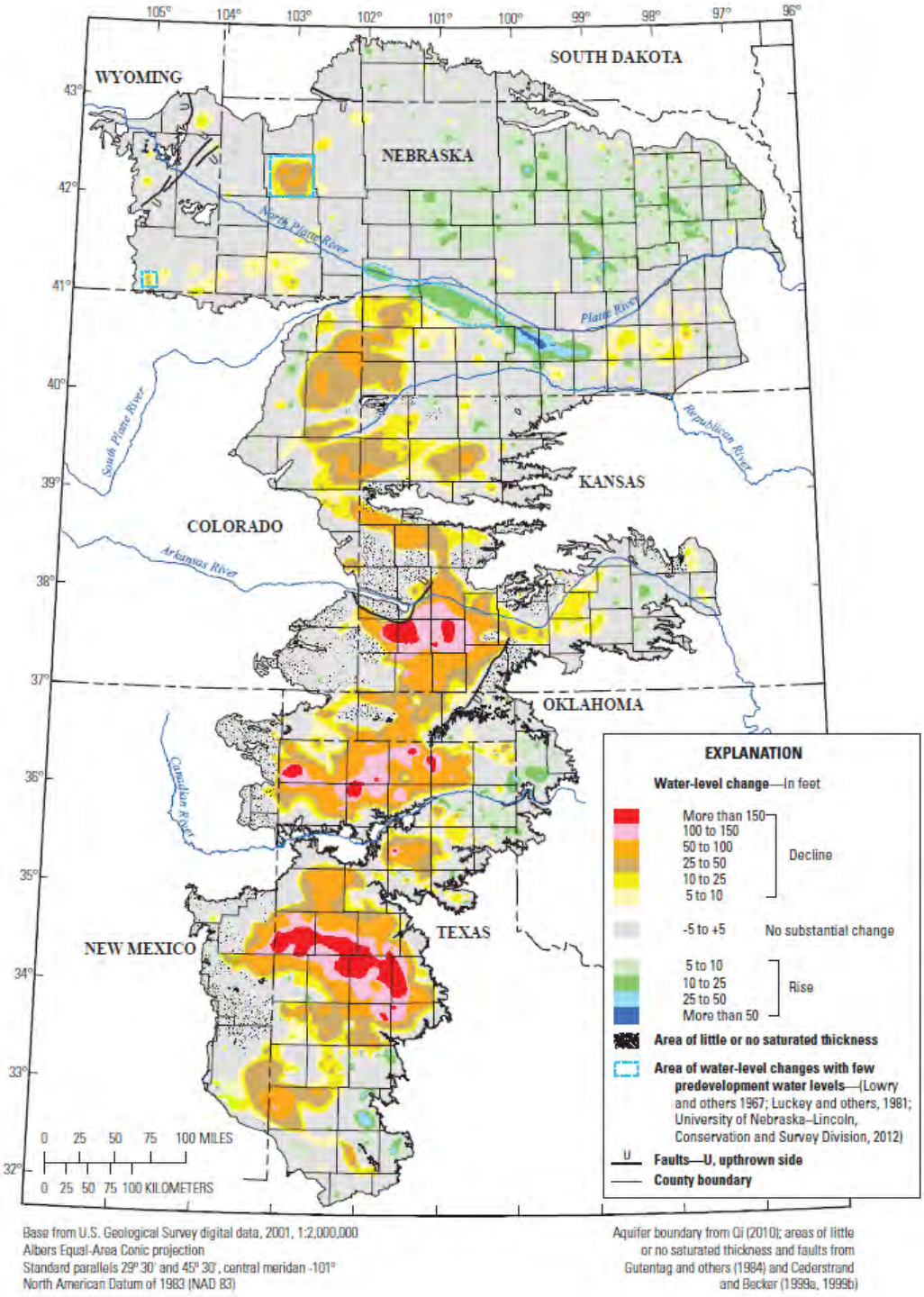

FIGURE 2—WATER LEVEL DECLINES FOR THE HIGH PLAINS AQUIFER FROM PRE-DEVELOPMENT TO 2011[23]

[23] McGuire, V.L., Lund, K.D., and Densmore, B.K., 2012, Saturated thickness and water in storage in the High Plains aquifer, 2009, and water-level changes and changes in water in storage in the High Plains aquifer, 1980 to 1995, 1995 to 2000, 2000 to 2005, and 2005 to 2009: U.S. Geological Survey Scientific Investigations Report 2012–5177, p. 28.

QUESTIONS

To explore how continued depletions of the High Plains Aquifer might impact both critical infrastructure and the economy at the local, regional and national scale, this OCIA NISAC study focused its research, modeling, and analysis on five overarching questions:

1. How might groundwater depletions evolve in the future?
2. How will variations in climate impact agricultural production in the future?
3. Which economic sectors are most vulnerable to groundwater depletion?
4. How might declining groundwater levels, aquifer depletion, and changes in agriculture production impact the economy and critical infrastructure?
5. How do impacts at the local level aggregate to affect the economy at a regional and national level?

ASSUMPTIONS

Given the complexity of aquifer depletion impacts, certain assumptions make the analysis tractable. This section reviews the most important research assumptions and their potential implications.

One key assumption of this work relates to the scale of analysis. Driven largely by the availability of data over the broad geographic region of Kansas and Nebraska, the county represents the finest scale of resolution for model simulation. This county-level view necessarily aggregates important variability occurring below the county scale. The analysis will not capture the detailed aquifer response at a particular location or simulate the behavior of a particular farmer or small co-op. Instead, this analysis will help identify system vulnerabilities and their potential implications.

Another important assumption is associated with the economic modeling. Although the agricultural industry in the High Plains region is capable of withstanding negative economic shocks, it is assumed that if individual farm operations face increasing input costs (energy for groundwater pumping) for a sustained period of time, then the continued successful operation of some of those irrigated farms may not be possible. This paper presents a predictive analytical approach for estimating whether farm operations will exit the market or reduce production. It is recognized that farm operations have other options. For example, an operator could sell the farm; an individual farm could be absorbed into a larger farm operation; a farmer could reduce irrigated acreage, adopt crop rotation or crop switching practices, or introduce genetically modified water-saving crops or new irrigation technologies; finally, a farmer could sell or rent water rights. The full set of options is extensive and complex and beyond the resources of this analysis. Limiting options to exiting the market or reducing production allows for a full set of responses in two representative categories and captures the impetus for a tipping point. Whether or not the farm operation continues in a different manner or does not continue and proceeds with available market options, either way represents a tipping point with the potential for regional and national macroeconomic impacts. The purpose of the study, therefore, is to inform resource management and planning exercises.

It is not the role of OCIA NISAC to endorse, promote, or enforce a particular set of policy options or regulations; therefore, this analysis does not address potentially offsetting policies or regulation.

DECISION SUPPORT

The intent of this study is to provide decision makers with an assessment of how continued depletions of the High Plains Aquifer as one variable used to inform the economic assessment, might impact both critical infrastructure and the economy at the local, regional, and national scale. The analysis provides insight into the extent to which future climate variability might impact crop production. Analyses also project how changing water demands will impact the rate of depletion of the High Plains Aquifer. From this context, the sectors of the economy and critical infrastructure that are most vulnerable to continued aquifer depletion are identified. The analysis also explores the relationship of these vulnerable infrastructure and economic sectors to the broader economy to estimate the full

effect of continued aquifer depletion. Insights gained from this study will help to inform future resource management and planning exercises. These analyses will also help identify and prioritize measures aimed at adapting to an uncertain and variable water resource future.

RESULTS

GROUNDWATER MODELING RESULTS

The importance of the High Plains Aquifer coupled with its declining groundwater levels has made this aquifer the subject of numerous studies. Over-pumping (pumping that exceeds groundwater recharge rates) is widely recognized as the cause of the depletions.[24] Given the existing body of work and the limited resources of this project, groundwater modeling efforts were focused solely on providing information tuned to the specific needs of the economic analysis. Thus, the groundwater results are not unique; rather, they are aimed at being consistent with other studies of the aquifer. Key to this analysis was groundwater data produced at a coarse spatial resolution (county level) distributed over a broad geographic region (Kansas and Nebraska).

Two sets of results are discussed that provide the necessary context for the economic analysis. The first set explores how groundwater is currently used by Kansas and Nebraska. The second set projects future changes in groundwater levels assuming that current groundwater pumping and management practices are sustained.

WATER USE AND INTENSITY BY INDUSTRY

Kansas freshwater withdrawals totaled 4,000 million gallons per day (MGD) in 2010 (Figure 3).[25]

- Irrigated agriculture accounted for 3,040 MGD (76 percent) of the freshwater withdrawals.
- Public supply accounted for 391 MGD (9.7 percent).
- Thermoelectric power generation used 377 MGD (9.4 percent).
- Livestock required 144 MGD (3.6 percent).

The ratio of groundwater to surface water withdrawals varied across these sectors. Ninety-four percent of all irrigated agriculture and 80 percent of livestock water demands were met with groundwater. In contrast, only 3 percent of thermoelectric water demand was met by groundwater. Total groundwater pumping in 2010 was 3,200 MGD.

Nebraska freshwater withdrawals in 2010 were 8,040 MGD (Figure 4).[26]

- Irrigated agriculture accounted for 5,660 MGD (70 percent) of the freshwater withdrawals.
- Thermoelectric generation was responsible for using 1,790 MGD (22 percent).
- Public supply accounted for 296 MGD (36 percent).
- Livestock required 114 MGD (1.4 percent).
- Aquaculture, the controlled cultivation of aquatic organisms, used 88.3 MGD (1.1 percent)
- All other sectors combined were responsible for only about 1 percent of the freshwater withdrawals.

[24] McGuire, V.L., 2013, Water-level and storage changes in the High Plains aquifer, predevelopment to 2011 and 2009–11: U.S. Geological Survey Scientific Investigations Report 2012–5291, 15 p. (Also available at *http://pubs.usgs.gov/sir/2012/5291/*.)
[25] Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2014, Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405, 56 p., http: //dx.doi.org/10.3133/cir1405.
[26] Ibid.

Irrigation relied heavily on groundwater at 76 percent, as did public supply, 99 percent; livestock, 82 percent; and industry, 93 percent. In contrast, thermoelectric generation withdrew only 0.3 percent from groundwater, and aquaculture, 7 percent. Total groundwater pumping in 2010 was 4,710 MGD.

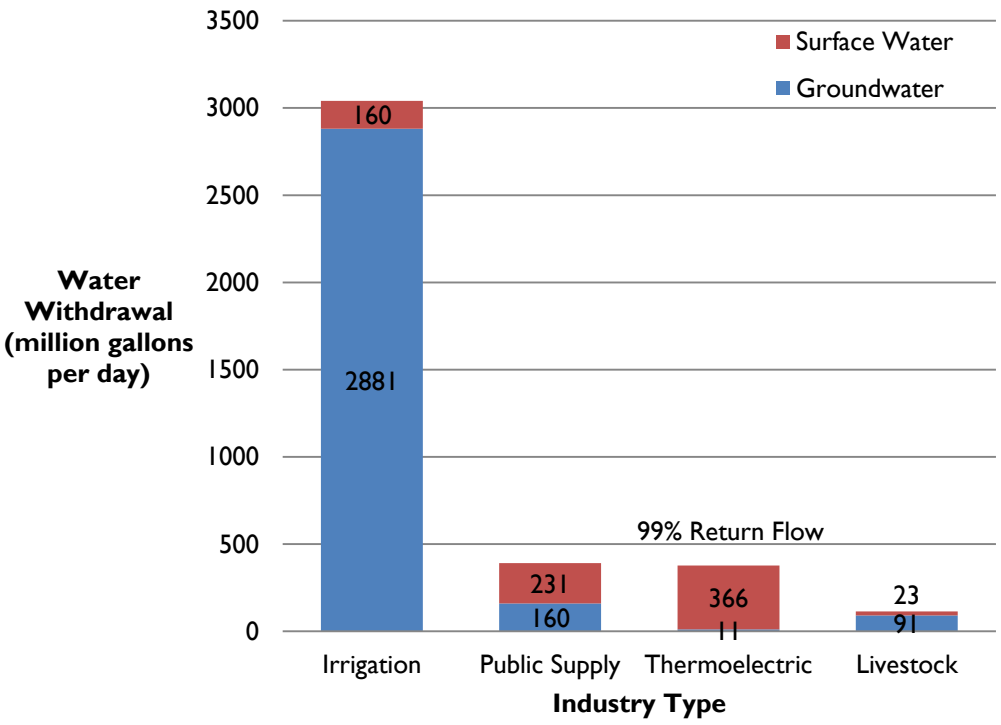

FIGURE 3—FRESHWATER WITHDRAWALS BY KANSAS IN 2010 BY SECTOR AND SOURCE

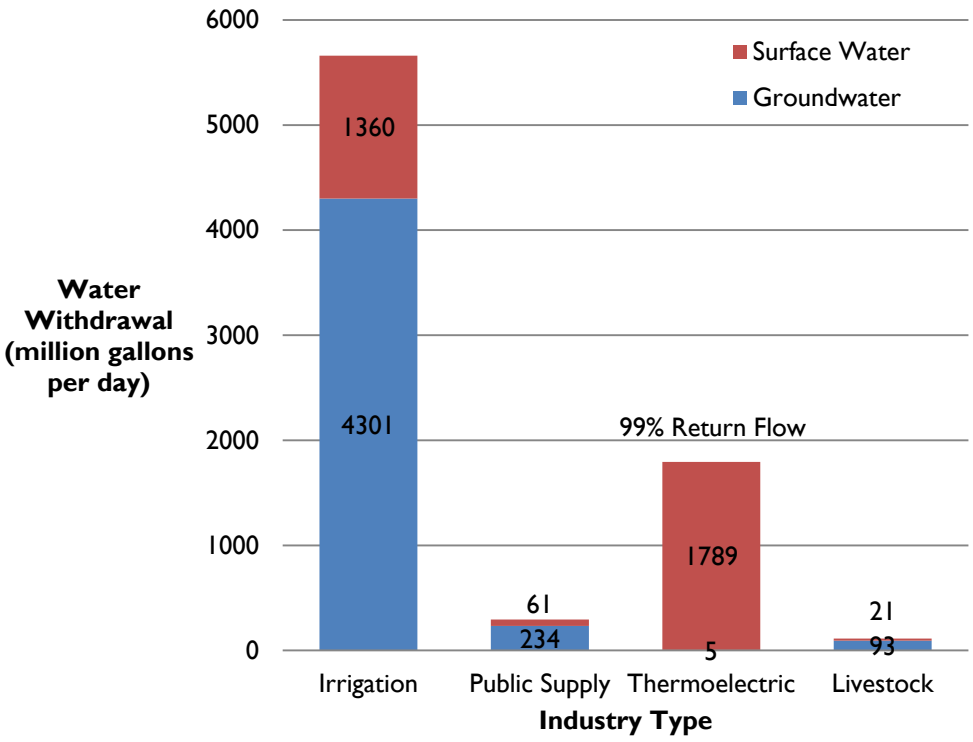

FIGURE 4—FRESHWATER WITHDRAWALS BY NEBRASKA IN 2010 BY SECTOR AND SOURCE

Beyond these state-level water withdrawal statistics, NISAC also considered water use by key industries. Irrigated agriculture is the largest user of water, most of which is sourced from groundwater. Nebraska accounts for 15.1 percent of the country's total irrigated acres, while Kansas accounts for 4.9 percent of total irrigated acres.[27] Nebraska has 187 percent more irrigated acres than Kansas, and corn makes up 64.3 percent of all Nebraska irrigated acres.[28] Corn requires between 20 and 25 inches of water for high-yield varieties, but may produce at lower yields with 15 to 16 inches of water. Other crops, such as wheat, are grown most commonly as dryland (non-irrigated) crops; when wheat is irrigated, it uses less water than corn because of its shorter growth time to maturity. It is also important to note that irrigation is not uniformly distributed over the two states. Figure 5 shows the relative distribution (percent by county) of irrigated acres for each county that overlies the High Plains Aquifer.

[27] U. S. Department of Agriculture, "Irrigated acres are concentrated in relatively few States," http: //www.ers.usda.gov/data-products/chart-gallery/detail.aspx?chartId=33213&ref=collection, July 20, 2015.
[28] U.S. Department of Agriculture, Census of Agriculture for 2007: Washington, D.C., National Agricultural Statistics Service, at http: //www.agcensus.usda.gov/.

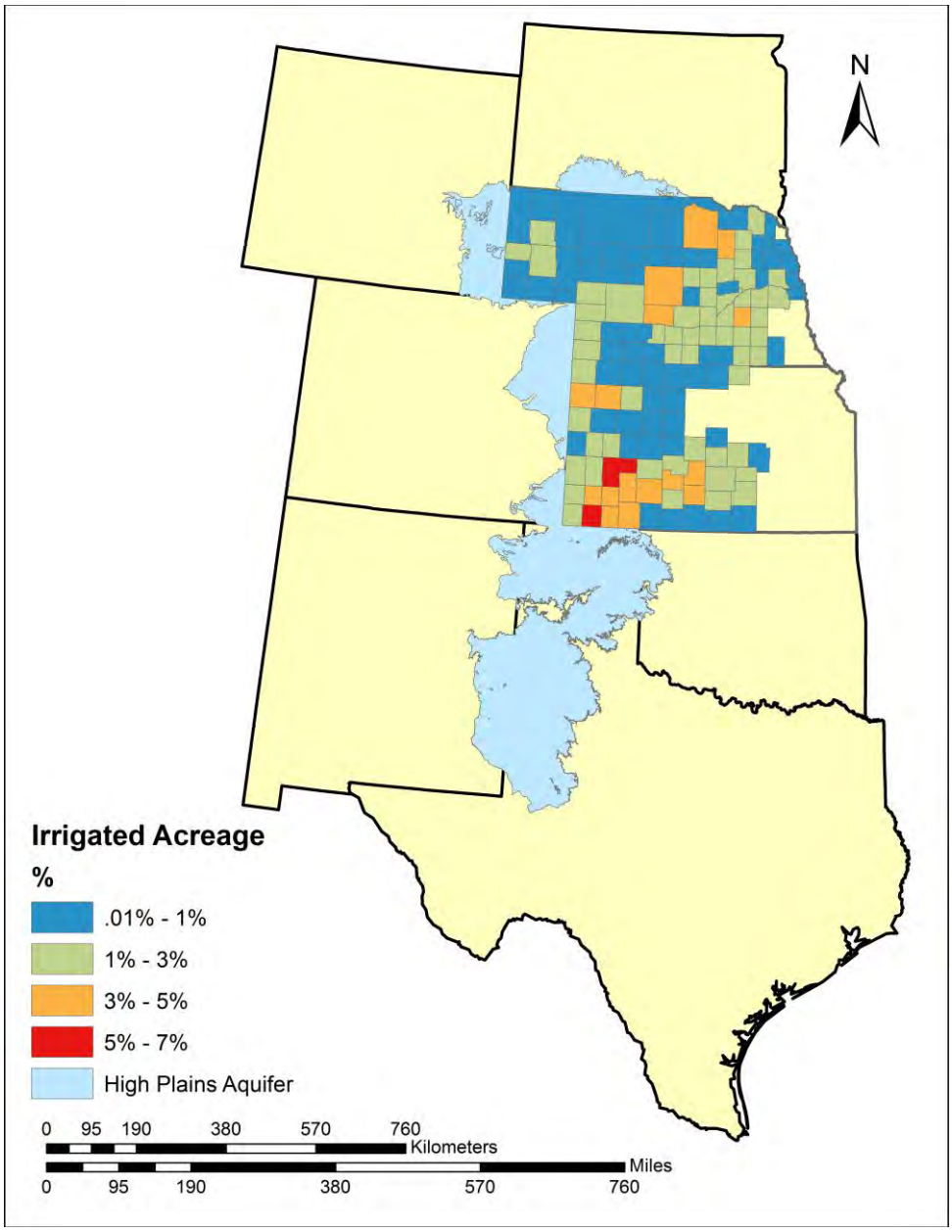

FIGURE 5—PERCENT OF IRRIGATED ACREAGE BY COUNTY (CALCULATED BY STATE)

Ethanol production is an increasingly important downstream user of corn and corn residual products (the stalks, leaves, and cobs that remain after harvest). According to the Agricultural Marketing Resource Center, ethanol producers became the second highest market for corn, behind only the domestic feed market. Strong demand for corn has helped maintain a strong demand for irrigation. In fact, Nebraska and Kansas rank first and second in irrigated acres for corn production. The processing of corn for ethanol production has its own set of water requirements. Corn ethanol uses water for five production processes: grinding, liquefaction, fermentation, separation, and drying. The U.S. Department of Agriculture estimates that a modern ethanol processing mill consumes three gallons of water for every gallon of ethanol produced; previous generations of processing mills can

use much more water.[29] Significantly, Nebraska ethanol mills can produce over 1.9 billion gallons of ethanol per year; Kansas ethanol facility capacity is over 500 million gallons per year.[30]

The livestock industry is an amalgamation of various producers and processors of animal products. Livestock farm operations primarily produce cattle and calves, hogs and pigs, poultry, and dairy cattle. Nebraska ranks behind only Texas in terms of the number of cattle and calves in inventory, with Kansas a close third. Water requirements for growing cattle can range from 5 to 20 gallons per day depending on such factors as cattle weight and ambient temperature. Other sectors of the livestock industry include value-added processing facilities such as slaughter, processing, packaging, and distribution operations for animal products. Water at a slaughtering facility is necessary for washing the carcass, cleaning the plant, and employee use. For cattle, water use is estimated at 0.09 gallons per pound of live weight.[31]

Thermoelectric power generation is important to both states.[32] Freshwater withdrawals are greater for Nebraska supplying 11 power plants totaling 4,918 megawatts (MW) of capacity fueled by coal, natural gas and nuclear. While withdrawals are relatively large, little of this water is consumed but rather is returned to its original source (albeit at a slightly higher temperature). Kansas has 16 thermoelectric power plants with 9,268 MW of capacity which are also powered by a mix of coal, natural gas, and nuclear. Water withdrawals associated with each plant depend on the capacity of the plant, its operation, the plant's fuel type and cooling type. Water use estimates for each of the thermoelectric power plants in the United States is available through the USGS.[33]

CHANGES IN GROUNDWATER LEVELS

Although efforts have been made to reduce groundwater depletions, groundwater pumping in many counties still exceeds sustainable groundwater recharge rates. Projecting current pumping rates forward in time, we have calculated the time to aquifer exhaustion.[34] Figure 6 shows when the aquifer is likely to no longer be able to sustain continued pumping at the current rate in counties of Kansas and Nebraska.

Counties of highest concern are those with 25 or less years of sustainable groundwater utilization. These vulnerable counties are largely associated with areas with extensive irrigated agriculture (Figure 5) and zones at the outer edges of the High Plains Aquifer where the geologic formation thins. In total 18 counties in Kansas are at the highest level of risk. In addition, there are 12 counties in Kansas with projected aquifer depletion years of 25 to 50 years. Thirty counties in Kansas and 7 in Nebraska are of concern with aquifer depletion years projected for between 50 and 100 years.

[29] Argonne National Laboratory, "Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline," http: //www.transportation.anl.gov/pdfs/AF/557.pdf, May 11, 2015.
[30] Nebraska Energy Office, "Fuel Ethanol Facilities Capacity by State and by Plant," http: //www.neo.ne.gov/statshtml/122.htm, May 8, 2015.
[31] Wulff, Scott M. et al., "Feasibility of Establishing Small Livestock Slaughter Plants in North Dakota," 1985, North Dakota State University Department of Agriculture and Applied Science, http: //ageconsearch.umn.edu/bitstream/23174/1/aer208.pdf, July 21, 2015.
[32] Thermoelectric generation uses water for cooling. Examples of thermoelectric generators include nuclear, natural gas, coal-fired and oil-fired plants.
[33] Diehl, T.H. and Harris, M.A., 2014. Withdrawal and Consumption of Water by Thermoelectric Plants in the United States, 2010. SIR2014-5184, U.S. Geological Survey. Available at: http://pubs.er.usgs.gov/publication/sir20145184
[34] Current pumping rates are based on the most recent county-level estimates available from the USGS (http://water.usgs.gov/watuse/data/2010) and do not reflect more recent changes in groundwater withdrawals.

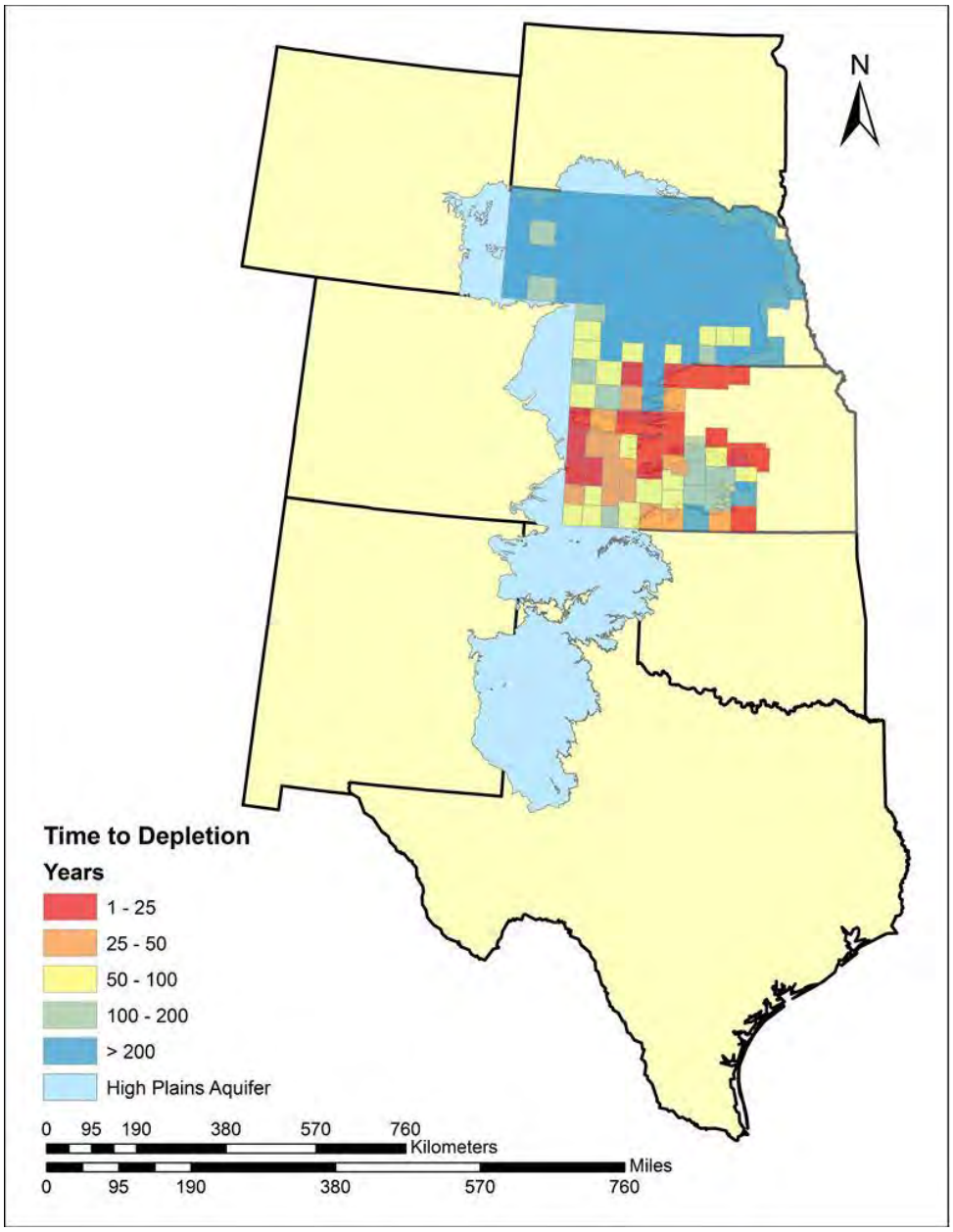

FIGURE 6—WHEN CONTINUED PUMPING OF THE HIGH PLAIN AQUIFER IS LIKELY TO BECOME UNSUSTAINABLE

As groundwater levels fall, obtaining water from the aquifer requires additional energy to pump the water from greater depths, increasing utility costs. To explore the effect of additional cost on farm operations, scenarios representing cost increases of 25 percent, 50 percent and 75 percent over current rates were analyzed. These analyses used current pumping and recharge rates to project groundwater level declines. The timing of projected groundwater decline (Figure 6) is consistent with the variability of irrigation (Figure 5). The time to 50 percent increase in pumping cost is shown (Figure 7).

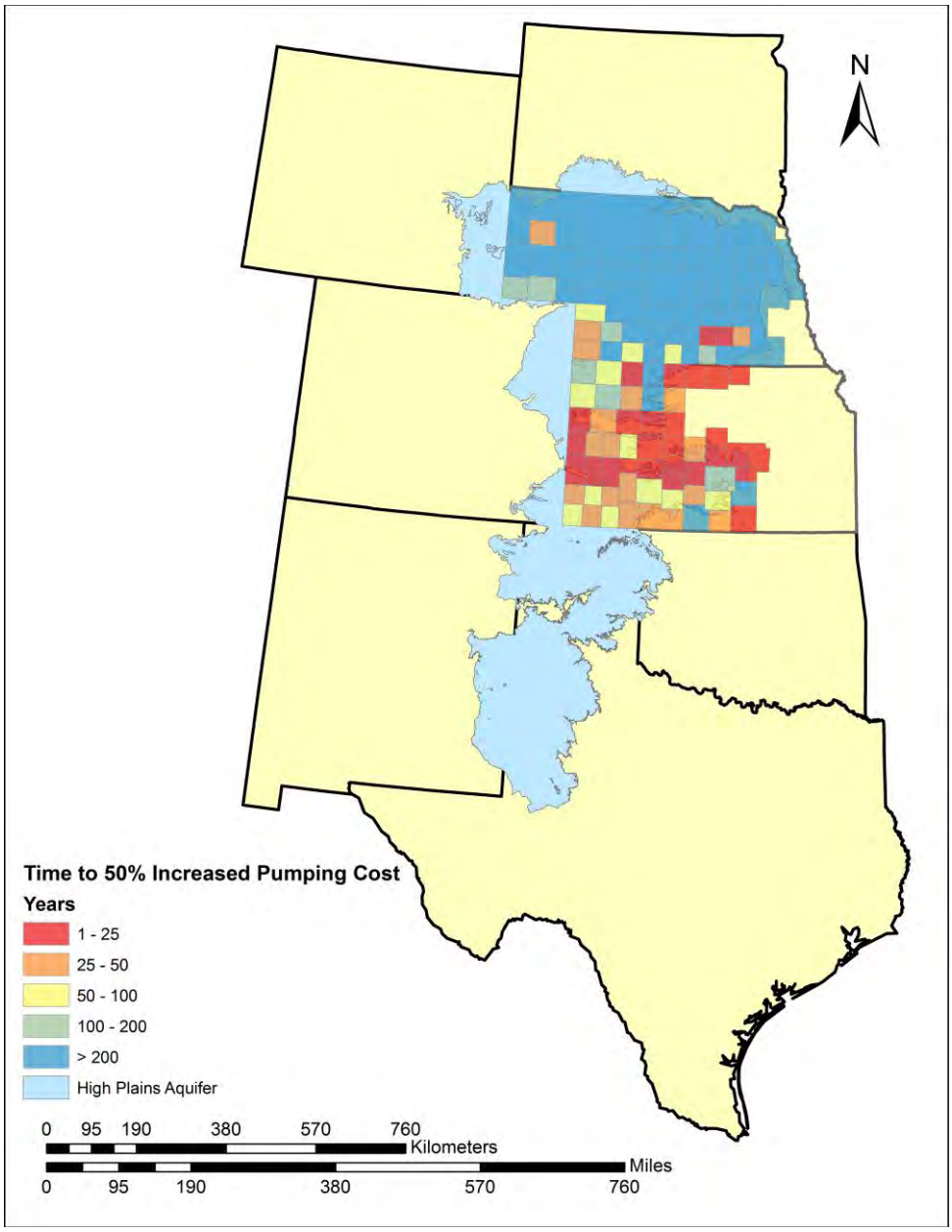

FIGURE 7—WHEN THE COST TO PUMP (LIFT) GROUNDWATER FOR IRRIGATION OR OTHER USES INCREASES BY 50 PERCENT OVER CURRENT RATES

CROP MODELING RESULTS

Projected changes in crop yields (2015-2060) for Dundy County, Nebraska, are shown in Figure 8 through Figure 11, relative to their respective 2015 yields for the Environmental Policy Integrated Climate (EPIC) model dryland simulation (orange line), statistical crop model dryland simulation (green line), and the statistical crop model irrigated simulation (blue line). Similar results were found throughout Kansas and Nebraska. Together, these results represent a range of possible outcomes that arise from future variations in climate, groundwater availability, and agricultural innovation. In absence of any other changes, the EPIC model results show that projected variations in temperature and precipitation impose small downward trends in dryland corn, sorghum, soy, and winter wheat yields. The results of the statistical crop model for dryland and irrigated yields show improvements to crop yields

that could arise in the future if improvements to farm operations and technology, including irrigation, are consistent with that of the recent past.

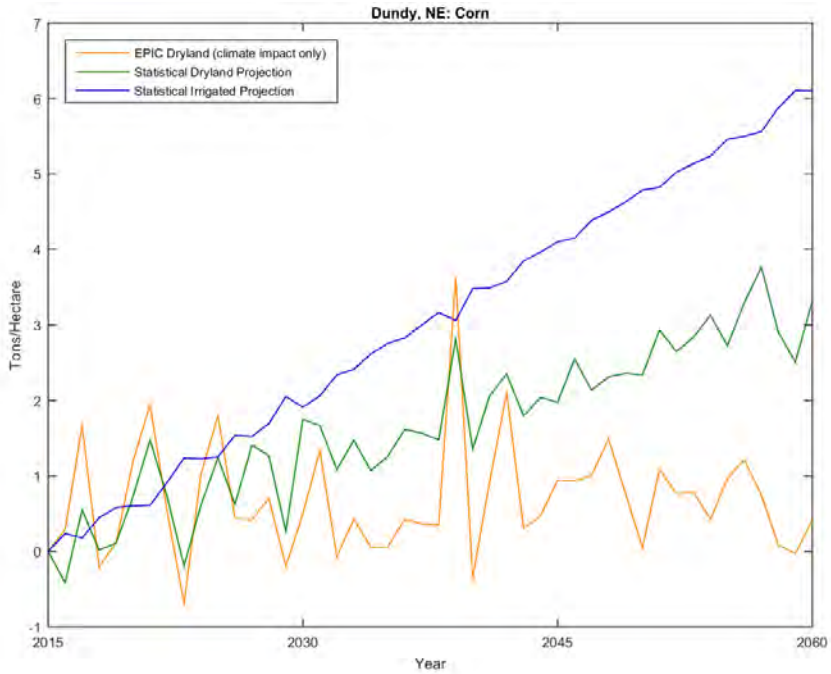

FIGURE 8—RESULTS FROM THE CROP MODELING SIMULATIONS FOR CORN IN DUNDY COUNTY, NEBRASKA

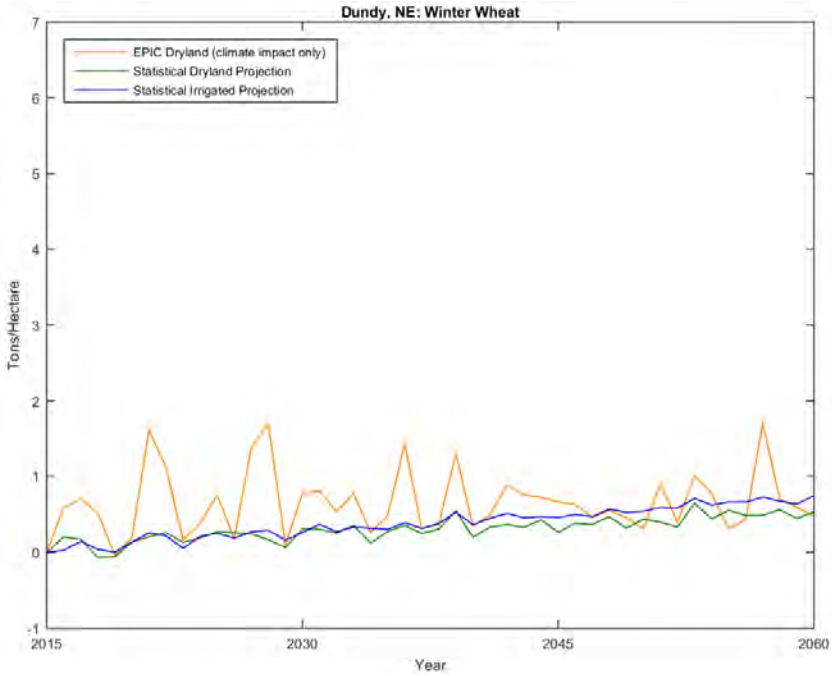

FIGURE 9—RESULTS FROM THE CROP MODELING SIMULATIONS FOR WINTER WHEAT IN DUNDY COUNTY, NEBRASKA

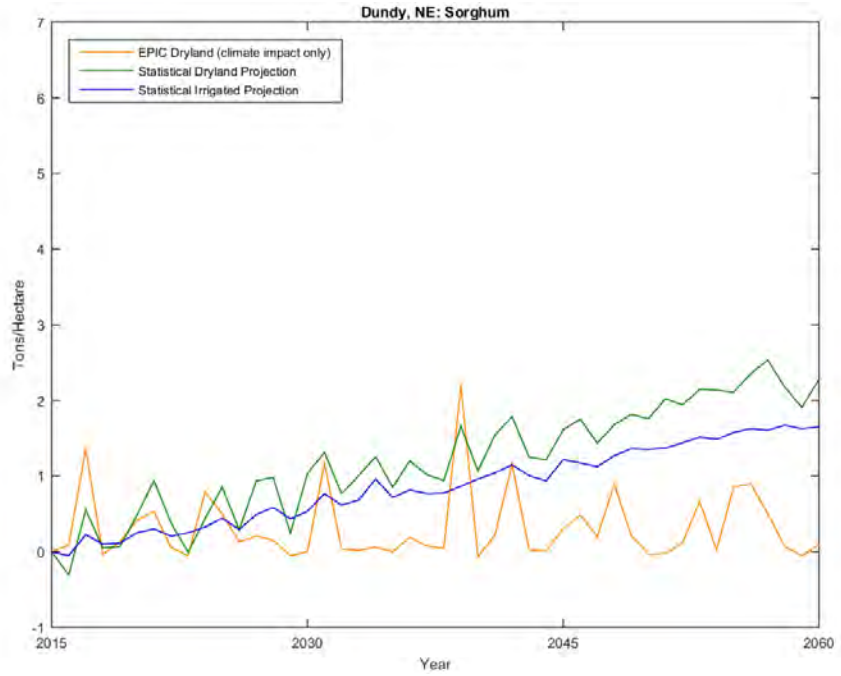

FIGURE 10—RESULTS FROM THE CROP MODELING SIMULATIONS FOR SORGHUM IN DUNDY COUNTY, NEBRASKA

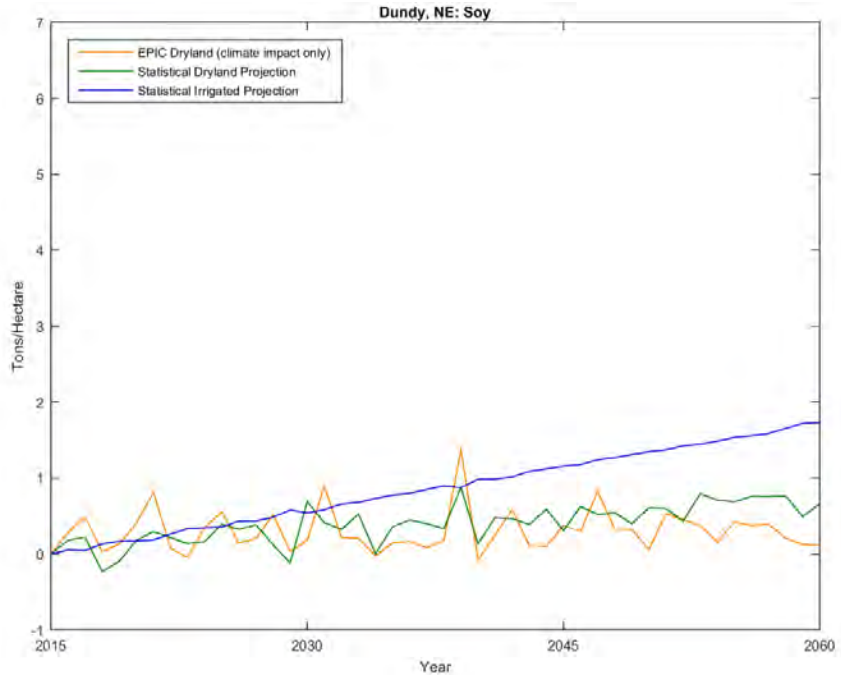

FIGURE 11—RESULTS FROM THE CROP MODELING SIMULATIONS FOR SOY IN DUNDY COUNTY, NEBRASKA

The path that actual yields follow in the future will depend on a number of factors, including the availability of water for irrigation. In the High Plains, farmers have used water supplied primarily by the High Plains Aquifer to maintain the production levels that have strengthened the agricultural sector throughout the High Plains. Whereas farmers have used irrigation to offset the impacts of climate variability on crop yields in the past, the depletion of the High Plains Aquifer could hinder their ability to do so in the future. As groundwater availability decreases over

time, it is possible that more agricultural land will be converted from irrigated to dryland farming, resulting in a reduction in agricultural production. Using the National Agricultural Statistics Service (NASS) historical yield data, the average percent difference between irrigated and dryland yield for Dundy County is calculated to be 70 percent for corn, 48 percent for sorghum, 43 percent for soy, and 29 percent for winter wheat. Additionally, transitioning from irrigated to dryland farming increases uncertainty in agricultural production from year to year because dryland crop yields are more dependent on prevailing weather conditions, which vary from year to year.

ECONOMIC ANALYSIS RESULTS

GENERAL ECONOMIC CONDITIONS: KANSAS

Kansas is home to nearly 2.9 million people, with a median household income around $51,332, which varies significantly between counties. Nonfarm employment in the state is around 1.4 million jobs, compared to around 1.0 million jobs in agriculture.

COMPOSITION OF KANSAS GDP

In 2013, Kansas GDP was $144.1 billion.[35] Overall, as shown in Figure 12, the economy appears to be improving from the downturn of 2007 to 2009. The five largest industries by output at the two-digit North American Industrial Classification System (NAICS) level are Wholesale trade, Healthcare and Social Assistance, Real Estate and Rental Leasing, Manufacturing, and Government (local and Federal).[36] Each of the five industries displays a positive growth trend (Figure 12).[37] Although the volume of agriculture products in Kansas is relatively high, the value of the products is relatively low, and representing less than 0.04 percent of output in the state. Largest crops by dollar value include wheat, corn, sorghum, and soybeans. Agricultural and farm output trends in Kansas are shown in Figure 13.

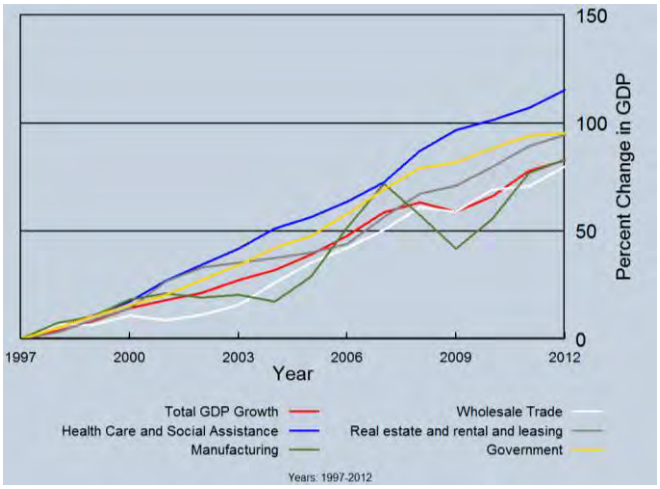

FIGURE 12—LEADING INDUSTRY OUTPUT TRENDS IN KANSAS

[35] Bureau of Labor Statistics, "Kansas Economy at a Glance," http: //www.bls.gov/eag/eag.ks.htm, October 1, 2014.
[36] http://www.census.gov/eos/www/naics/
[37] NAICS is the standard industry classification system formally established by the U.S. Census Bureau. Using the 2-digit NAICS references allows the reader to look up these industries specifically.

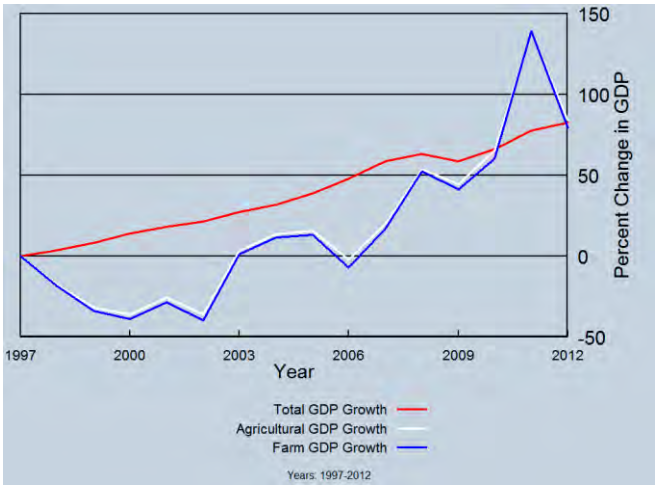

FIGURE 13—AGRICULTURAL AND FARM OUTPUT TRENDS IN KANSAS

EMPLOYMENT IN KANSAS

Manufacturing is the greatest contributor to Kansas GDP, and employment within manufacturing is also largely concentrated within counties that are dependent on the High Plains Aquifer (approximately 46 percent). Similarly, Farming is a substantial employer within Kansas, and is also concentrated within the area under study. This highlights two separate ways (employment and GDP) in which the economic well-being of Kansas is subject to the availability of the High Plains Aquifer.

The farm and non-farm employment by industry sector for Kansas are shown in Figure 14. Employment is presented at the two-digit NAICS level. The top five industries in Kansas include Manufacturing, Retail Trade, Farming, Healthcare and Social Assistance, and Government (local and Federal). Kansas has over 6,000 farm employees, whose ranks have seen tremendous growth since 2008, by as much as 20-25 percent in a year (refer to Figure 14 and Figure 15). In Kansas the healthcare sector continued to add jobs at a consistent rate, even during the financial downturn in 2008, performing better than the economy as a whole. The government sector (State and Federal combined) also added jobs since 2005, albeit more slowly. Government jobs include schools, universities, military installations, public services, and public administration.

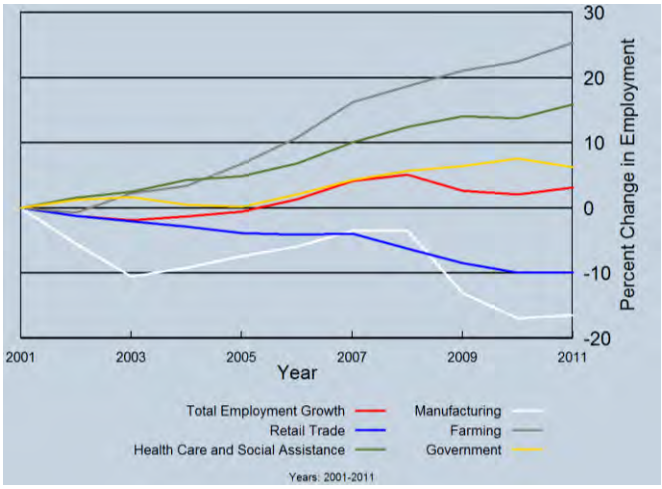

FIGURE 14—LEADING INDUSTRY EMPLOYMENT TRENDS IN KANSAS

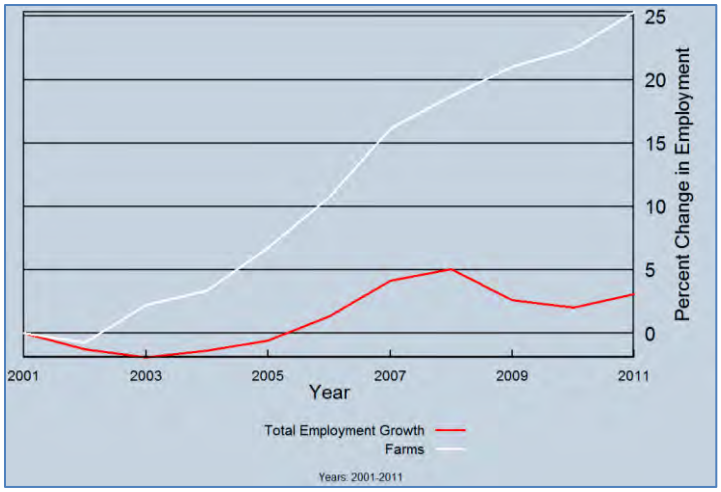

FIGURE 15—FARM EMPLOYMENT TRENDS IN KANSAS

GENERAL ECONOMIC CONDITIONS: NEBRASKA

There are approximately 1.88 million people in Nebraska with a median household income of $45,338 which also varies significantly between counties. In both Kansas and Nebraska, the unemployment rate varies considerably between counties.

COMPOSITION OF NEBRASKA GDP

In 2013, the GDP for Nebraska was $109.6 billion.[38] Output in Nebraska has been growing at a rate which exceeds the national average. During the most recent recession (December 2007 to September 2009, 18 months), Nebraska only experienced a minor bump in unemployment, reaching 4.9 percent in late 2009.[39] At the same time, the agricultural sector outperformed the broader State economy in terms of Industry output growth (see Figure 16). The five largest industries in Nebraska (in terms of output) are Government (Federal and Local), Manufacturing, Agriculture, Real Estate and Rental and Leasing, and Finance. The Agricultural industry has grown by 256 percent since 2004. In all, Nebraska's GDP grew 216 percent since 1997, averaging 5 percent growth per year.

Agriculture has proven to be a resilient industry during unstable economic times, providing consistent employment growth and accruing increasing share of GDP. Domestically, the promotion of ethanol targets adds an additional market for corn and, to a lesser extent, sorghum. Distillers' grains, a coproduct of ethanol manufacturing, are highly valued as fodder for commercial livestock production because they are high in protein and therefore act as a more efficient nutrient source.

[38] Bureau of Economic Analysis, "Industry Data," http: //www.bea.gov/iTable/iTable.cfm?ReqID=51&step=1#reqid=51&step=2&isuri=1, October 1, 2014.
[39] NBER, "Business Cycle Dating Committee of the National Bureau of Economic Research," http: //www.nber.org/cycles/sept2010.pdf, March 18, 2015.

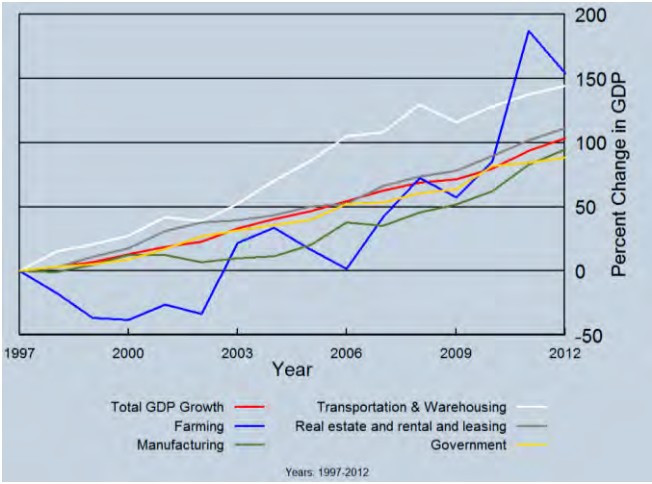

FIGURE 16—LEADING INDUSTRY OUTPUT TRENDS IN NEBRASKA

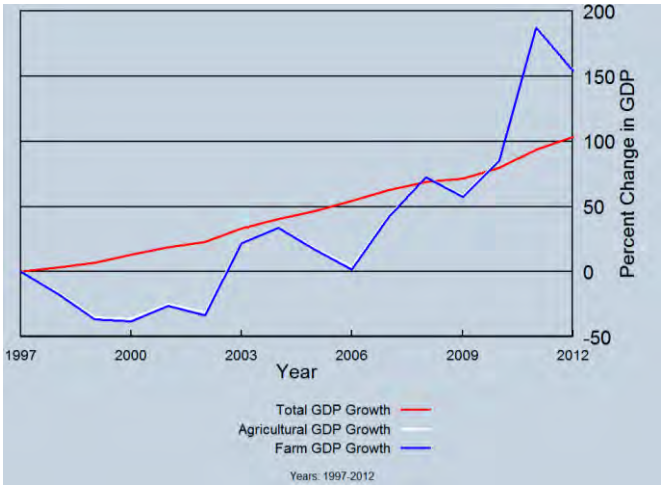

FIGURE 17—AGRICULTURAL AND FARM OUTPUT TRENDS IN NEBRASKA

EMPLOYMENT IN NEBRASKA

Nebraska Agriculture is robust, but accounts for only 1.8 percent of employment. The rest of Nebraska's economy is primarily service oriented, with 848,000 Service industry jobs (86 percent) compared to 138,000 manufacturing positions (14 percent). Despite historic employment growth in agriculture, the Nebraska Department of Labor expects crop and animal production employment to decrease by 11-15 percent by 2022, while services and manufacturing employment is expected to grow. Agricultural and farm output trends in Nebraska are shown in Figure 17.

According to the Quarterly Census of Employment and Wages program run by the U.S. Bureau of Labor Statistics, the industries that employ the greatest number of full-time equivalent workers include Federal and State Government (320,049), Healthcare and Social Assistance (132,432), Retail Trade (129,436), and Manufacturing (96,605). Overall, the largest employment growth of the major industries previously listed is expected to be in Healthcare and Social Assistance due to demographic trends. Manufacturing and Government currently contribute equally to Nebraska's GDP output, tying for first place. Manufacturing has seen a consistent decline in employment since 2008, despite the predominance of Nebraska's manufacturing sector in total economic output.

The non-farm employment by industry sector for Nebraska are shown in employment is presented at the two-digit NAICS level. The top five industries in Nebraska include: Retail Trade, Farming, Manufacturing, Healthcare and Social Assistance, and Government (local and Federal). In Nebraska, as shown in Figure 18, the number of jobs in manufacturing declined during 2009, losing approximately 11 percent of its workforce that year and approximately 4 percent in the following year. Healthcare employment continues to grow as the country's population ages. During the same years retail and manufacturing sectors in Nebraska have experienced increases in contribution to State GDP. The percent change in employment in Nebraska's employment for industries at the two-digit NAICS level is shown in Figure 18.

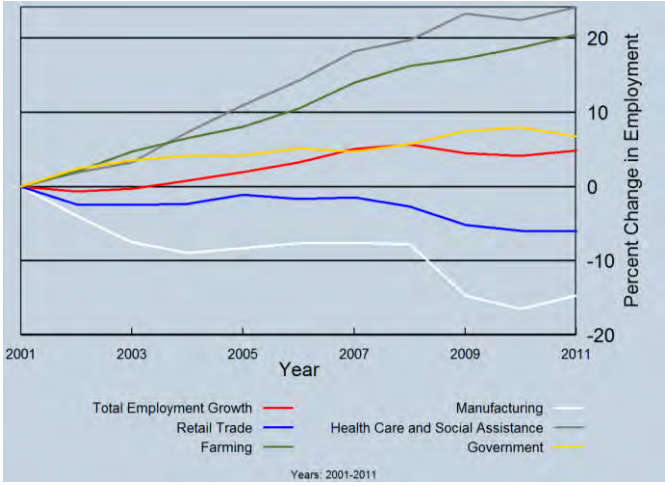

FIGURE 18—LEADING INDUSTRY EMPLOYMENT TRENDS IN NEBRASKA

Nebraska Agriculture GDP contribution has doubled since 1997, with a large portion of this growth attributable to Farming (see Figure 19). At the same time, farm employment has increased 25 percent. The agricultural sector and its related industries have experienced higher growth rates post-2008 than pre-2008, as value-added products like beef and ethanol retained strong demand.

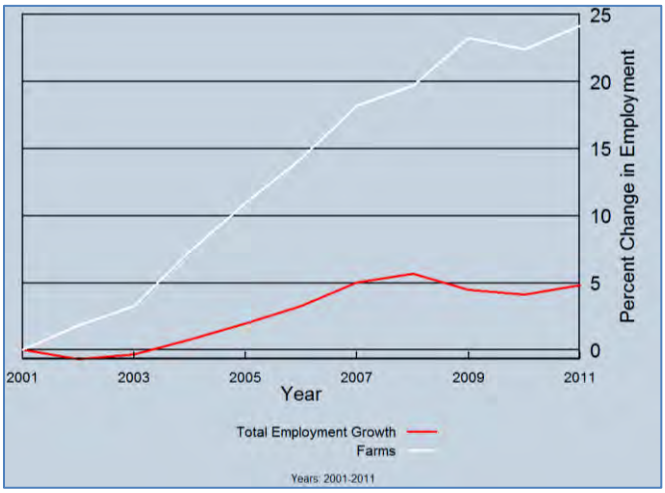

FIGURE 19—FARM EMPLOYMENT TRENDS IN NEBRASKA

ECONOMIC ANALYSIS RESULTS

SCENARIO SET A–FARM PROPRIETOR INCOME

Scenario Set A builds on data resulting from previous climate change effects to the aquifer and crop models projecting yields from the depletion of the aquifer and estimates changes in farm operation market participation decisions, induced by increased groundwater extraction costs and how those changes propagate through the regional economy. Change in market participation was based on an empirically-estimated relationship between extraction costs and farm operation exit decisions. The empirical model used for this study builds on previous work exploring the factors which determine farm operation exit (Hoppe and Korb, 2006). Using farm operation utility costs as a proxy for extraction costs, the empirical model yields an estimated response to exogenously imposed increases in the utility associated with water extraction.

Farm exit probability was estimated using data from all states located on the High Plains Aquifer (Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming, from here on referred to collectively as High Plains States). The data set was limited to farm operations which had responded to at least 3 censuses ($n = 234{,}142$).

Increasing extraction costs may marginally increase the likelihood that a farm operation exits the industry. The number of farm operations in Kansas and Nebraska has been trending downward in recent years. Table 1 presents the number of farm operations responding to the Census of Agriculture in Kansas and Nebraska for each Census-year from 1982 to 2012. Between 1982 and 2012 both states experienced declining numbers in farm operations. Annually, Kansas has lost approximately 0.5 percent of farm operators. Since 1982, cumulative decline in farm operations in Kansas are approximately 16 percent. Annual percent decline for farm operations in Nebraska is approximately 0.6 percent. Cumulatively, this amounts to approximately a 17 percent decline in Nebraska farm operations between 1982 and 2012.

TABLE 1—FARM OPERATION COUNT IN KANSAS AND NEBRASKA (1982-2012)

Years	Farms in Each State	
	Kansas	**Nebraska**
1982	73,315	60,243
1987	68,579	60,502
1992	63,278	52,923
1997	65,476	54,539
2002	64,414	49,365
2007	65,531	47,712
2012	61,773	49,969
Percent Change in Farms (1982-2012)	**-15.743%**	**-17.054%**
Annualized Percent Change in Farms (1982-2012)	**-0.525%**	**-0.568%**

The annualized percent change in farms between 1982 and 2012 for each state is assumed to be captured within the baseline REMI model.[40] Increases in farm exit over the historical average are calculated using the marginal effect of increased utility costs on exit probability estimated by the microeconometric empirical model, combined with hypothetical increases in utility expenditures. This impact is implemented within the REMI model as a decrease in Farm Proprietor's income. This is calculated by reducing farm proprietor income by the percentage difference in the number of farms estimated following historical trends and the number of farms estimated when utility costs are increased by 25, 50, or 75 percent. It should be noted that the increase in utility costs are not modelled as an instantaneous change. The increase is applied uniformly over the REMI entire simulation period (2015-2060), as the depletion of the High Plains Aquifer is not expected to be instantaneous, but rather a gradual decline.

[40] : Regional Economic Models, Inc. "REMI PI+v1.7 (changes from PI+ v1.6R)," Regional Economic Models, Inc.

Scenario Set A depicts farm exits as decreases to farm proprietor income as this represents the overall shrinking of the farm market. Scenario Set A conditions have different probabilities in Kansas and Nebraska as reflected in the differences in the time to increase pumping costs by 50 percent (see Figure 7). Figure 20 shows the change in projected GDP relative to a baseline (no expected increases in utility costs due to groundwater level decline) for Kansas under three scenarios of energy (utility) cost increases of 25 percent (lower than expected), 50 percent (expected), and 75 percent (higher than expected). Even in the 75-percent scenario, the expected change in projected GDP represents a slight lowering of the projected state GDP growth over the 49-year forecast period.

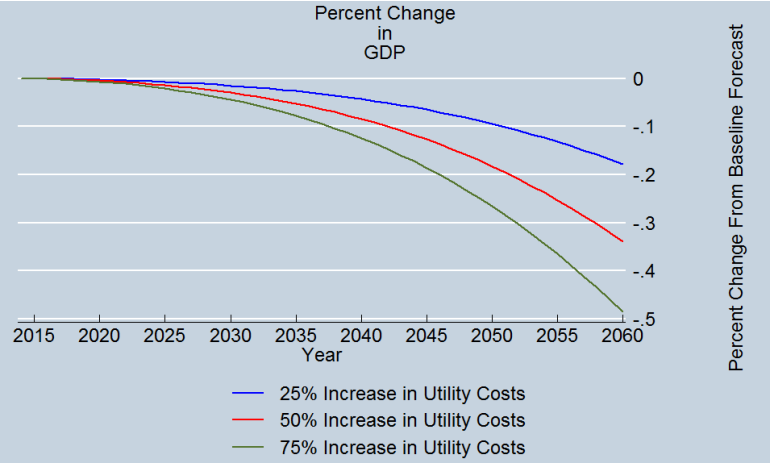

FIGURE 20—KANSAS: ANNUAL PERCENT CHANGE IN GDP, SCENARIO SET A

Figure 21 shows the result for Nebraska projected change in the state GDP due to the scenario assuming a 25 percent increase in utility costs which is higher than expected given the lower rates of groundwater drawdown in Nebraska. As in the case with Kansas, the higher than expected cost increase scenario result represents a slight reduction in the forecast state GDP growth.

In Kansas and Nebraska, utility cost increases can directly affect proprietor income of those involved with agriculture production. As farm operations exit, proprietor income falls, which propagates to all of the industries where proprietor income is spent. The largest dollar losses secondary to farm loss are for the Construction, Retail Trade, Health Care and Social Services, Real Estate and Rental Leasing, and Finance and Insurance. These industries correlate to personal disposable income spending or changes in population (Health Care and Social Services).

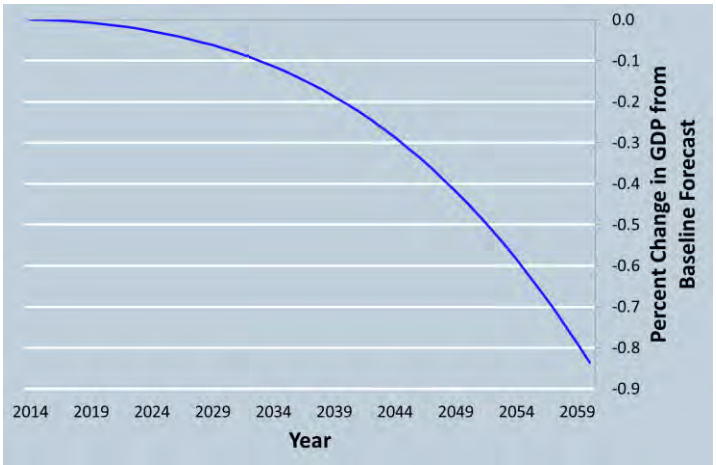

FIGURE 21—NEBRASKA: ANNUAL PERCENT CHANGE IN PROJECTED GDP UNDER SCENARIO SET A WITH 25 PERCENT INCREASE IN UTILITY COSTS

SCENARIO SET B–REDUCED IRRIGATED CROP ACREAGE RESULTS

Scenario Set B estimates the economic impacts of decreased irrigation due to depletion of groundwater resources in Kansas. As shown in the section on Crop Modeling, the historical yield of a given irrigated crop is higher than the yield for the same crop in the absence of irrigation. This impact is modelled as a decrease in farm output. The REMI model calculated the expected change in agricultural industry output associated with a reduction in the percentage of irrigated acreage for 4 crops: corn, soybeans, winter wheat, and sorghum. The per-acre difference in yield associated with switching from irrigation to dryland is calculated as the difference in the yield estimated by the statistical model and the yield estimated by the Environmental Policy Integrated Climate (EPIC) model for dryland. The change in total yield for each crop in each county associated with an exogenous decrease in irrigated acreage is evaluated using 3 scenarios. Scenario Set B assumes that the number of irrigated acres in Kansas decreases by 25, 50, or 75 percent and the number of non-irrigated acres increases by the same amounts. Of course, the impact to the entire agriculture industry within each county must be weighted by each crop's contribution to agriculture industry output.

The impact on annual State GDP for Kansas represents a greater percent change from baseline when compared to Scenario Set A (Figure 22). At the industry sector level, all results for Kansas are dominated by agriculture and forestry support activities.

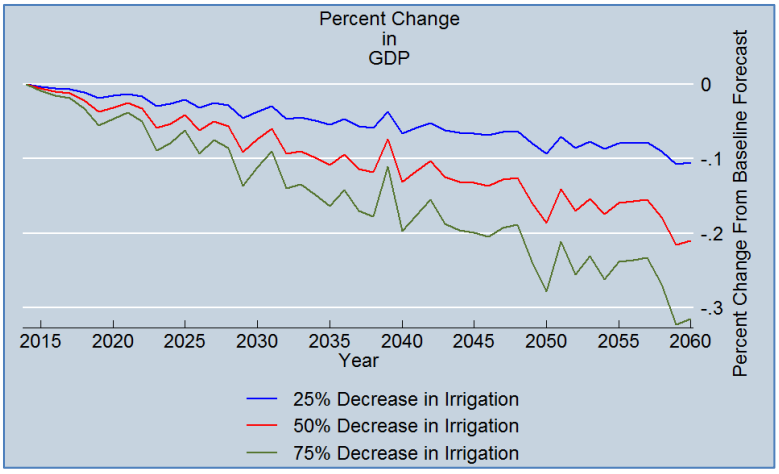

FIGURE 22—KANSAS: ANNUAL PERCENT CHANGE IN GDP, SCENARIO SET B REDUCED IRRIGATED ACERAGE

Although farm operations can adapt to increased resource risk with a variety of decisions such as changing crop rotations or crop types and utilizing new technologies, this analysis considered only two potential responses independently: increased probability of farm exit (translating to decrease in farm proprietor income) and decreased levels of irrigation (translating to decrease output in the agricultural industry). Furthermore, NISAC conducted this analysis without considering the costs of formulation, implementation, or enforcement of policy or regulatory action to combat or offset the effects of a chronic disruption (resource risk).

CRITICAL INFRASTRUCTURE

For Scenario Set A, reduction in farm proprietor's income (farm exits), the likely primary critical infrastructure affected is the Food and Agriculture Sector. The effect will not be severe, however, because the primary impact is to income and not overall agriculture output.

For Scenario Set B, decreases in agriculture production result from reductions in irrigated crop acreage. The Food and Agriculture, Energy, and Chemical critical infrastructure Sectors are the most likely to be affected due to follow-on effects to food and beverage manufacturing, animal processing, and chemical manufacturing. The likely impact would be market shortage passed on to consumers in the form of higher prices for some goods such as food and transportation fuels.

The Water and Wastewater Systems critical infrastructure Sector will be affected by both growing population demands and declining groundwater levels. Communities at highest risk are those in counties which have less than 50 years of projected aquifer depletion years. These communities face increasing expenses associated with falling groundwater levels (i.e., increased expense to lift water) and costs associated with extending or replacing failing groundwater wells.

The Transportation Systems critical infrastructure Sector is likely to be affected by potentially less market demand for transportation services as a result of less agriculture and chemical (ethanol) related production. While less production would result in an excess supply of transportation infrastructure, it is likely that the Transportation Systems Sector would find alternative customers.

METHODS

This section focuses on summarizing the data gathered from stakeholders and formulation of models to assess potential climate impacts on crop productivity, aquifer depletions, the economy, and infrastructure.

GROUNDWATER MODELING

To evaluate the economic implications of High Plains Aquifer depletions on Kansas and Nebraska, an estimation of future potential changes in groundwater levels and the associated cost to pump that water to the surface was necessary. Simulation of depth-to-groundwater also provided insight as to how soon the groundwater resource may become exhausted. To accomplish these analyses, a groundwater budget implemented at the county level was formulated. Specifically, groundwater storage, and the related depth to groundwater, was calculated by tracking the annual difference between groundwater inflow (e.g., recharge and river leakage) and groundwater outflow (pumping). Implementing the model required a variety of data, most of which was acquired from the USGS, with supporting information collected from the Kansas Geological Survey, and the Nebraska Department of Natural Resources. Model calibration was performed using measured data tracking changes in groundwater level, aggregated by county, available at 5-year intervals from 1985 to 2010.[41]

CROP MODELING

A range of impacts to agriculture in the High Plains region could arise from future variations in climate, groundwater availability, and agricultural innovation. Two crop models simulated corn, soy, sorghum, and winter wheat yields using downscaled weather inputs generated by the Geophysical Fluid Dynamics Laboratory Coupled Model 3. [42] They included the Environmental Policy Integrated Climate (EPIC) model and a statistical model of stochastic production functions.[43,44,45] The EPIC model is a physical process-based cropping system model which is used here to analyze the impact that future variations in temperature and precipitation have on crop yields, independently from other factors. The statistical crop model projects crop yield as a function of a linear trend in historic yield, precipitation, and temperature. Simulations for both the EPIC and statistical crop models were performed at the county level for one county per climate division overlying the High Plains Aquifer within Kansas and Nebraska (14 counties total), as shown in Figure 23.[46] Model calibration was performed using historical yield data from the National Agricultural Statistics Service (NASS).[47]

[41] USGS, "Water-level change, High Plains aquifer, 2000 to 2005," http: //water.usgs.gov/GIS/metadata/usgswrd/XML/sir12-5177_hp_wlc0005.xml, March 6, 2015.
[42] Donner et al., 2011, The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component am3 of the GFDL global coupled model CM3. Journal of Climate, 24, 3484–3519.
[43] Williams, 1995, The EPIC model. In: Singh, V. P. (Ed.), Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, CO, pp.909-1000.
[44] Isik and Devadoss, 2006, An analysis of the impact of climate change on crop yields and yield variability. Applied Economics, 835-844.
[45] Just, R. E., and Pope, R. D. (1978). Stochastic specification of production functions and economic implications. Journal of Econometrics, 67-86
[46] NOAA [will update footnote]
[47] NASS, "Quick Stats," http: //quickstats.nass.usda.gov/, accessed February 18, 2015.

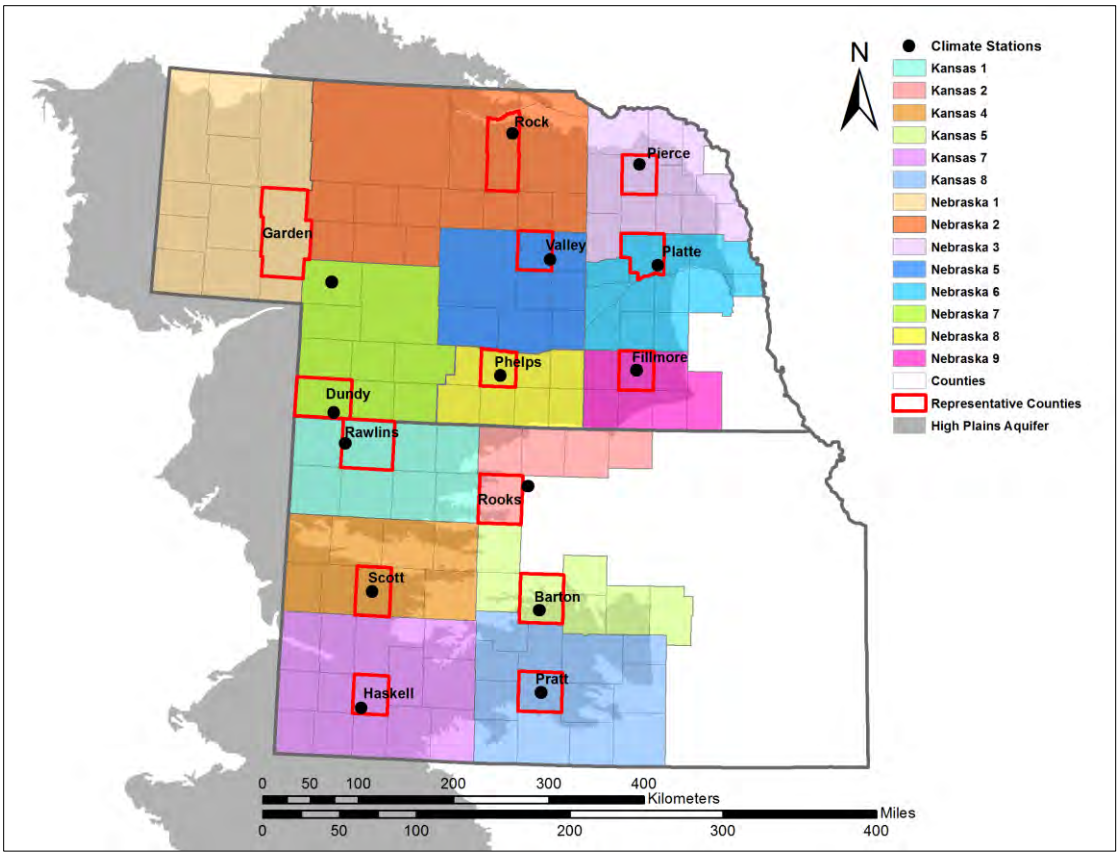

FIGURE 23—SPATIAL EXTENT OF THE CROP MODELING EXPERIMENTS

ECONOMIC MODELING

This study considers two separate market responses to increased resource risk in Kansas and Nebraska. Scenario Set A considers how increased pumping costs due to groundwater level decline impact the likelihood that a farm operation exits the industry. Scenario Set B considers how groundwater depletion reduces irrigation and translates to lower yields and reduced output in the Agriculture Industry. Although these are modelled as mutually-exclusive scenarios, aggregate response to a decrease in water resources would likely include both exit and decreased yield.

While the direct impacts of a water resource risk are primarily concentrated in the Agriculture Industry, the impact is not limited solely to farm operations and other firms in Agriculture. Farm operations use inputs provided by other local firms and provide employment to local residents. The personal income of farm operators is often spent in the community where they farm. The regional economic impacts are important to consider in addition to the impacts to the Agriculture Industry. The regional economic consequences of water resource risk for the two scenarios are estimated using the Regional Economic Models, Inc. (REMI) PI+ model, an empirically-validated model that combines aspects of input-output, computable general equilibrium, econometric, and economic geography modeling.[48]

The framework combines microeconometric empirical models with long-term macroeconomic simulation to capture firm, industry, regional, and national level consequences. Furthermore, a qualitative analysis of existing economic conditions in Kansas and Nebraska addresses potential economic consequences which cannot be

[48] A REMI analysis is carried out in two steps. First, a baseline forecast is computed, in which there is no change to the economy, and second, an alternative forecast is generated based on a specific scenario. The economic impact of the change in the economy is measured as the difference between the baseline and alternative forecasts. Sandia uses the state-level version of REMI PI+ with 67 industries.

estimated directly. Water use efficiency and profit maximization are at the center of the microeconomic analysis. It is assumed farmers will continue to drill deeper wells until it is no longer profit maximizing to do so. The results of the analysis should not be over-generalized, as they are limited to the specific scenarios. In reality, market response to resource risk is much broader than what is modelled in this study.

CONCLUSION

Expansion of irrigated agriculture over the past 60 years has helped make the High Plains one of the most productive agricultural regions in the Nation, accounting for one-fourth of U.S. agricultural production. This expansion in productivity has come at a cost. The High Plains Aquifer, vital to groundwater supply in the High Plains region, is being depleted at a rate far exceeding its recharge. If current water use and management practices are continued, 60 counties in Kansas and 7 in Nebraska could experience aquifer depletion issues in the next100 years.

Shrinking groundwater supplies and changing climatic conditions could pose risks to the High Plains' agricultural production. In the absence of any other changes, future climate projections were found to reduce dryland yields for corn, sorghum, soy, and winter wheat. Although farmers have used irrigation to offset the impacts of climate variability on crop yields in the past, the depletion of the High Plains Aquifer could hinder their ability to do so in the future. The conversion of acreage from irrigated to dryland farming may become increasingly necessary as groundwater levels decline. Such conversion would result in reduced agricultural production throughout the High Plains as well as increased uncertainty in crop yields from year to year.

Having modeled groundwater use and farm production in Kansas and Nebraska, this analysis identified several potential impacts to the economy and the critical infrastructure in these two States:

- Kansas and Nebraska provide significant amounts of commodities by dollar and volume to nearly all contiguous 48 states and Washington, DC.
- Economic impacts will scale with energy costs to extract groundwater. For this analysis, the economic impacts are primarily confined to Kansas and Nebraska.
- Farm exits, as modeled through reductions in farm proprietor income, will affect disposable income and reduce demand for consumer goods. This effect is confined to Kansas and Nebraska.
- Reductions in irrigated acreage will affect follow-on industries such as agricultural support activities and food and beverage manufacturing.
- Reductions in irrigated acreage have large implications for critical infrastructure in the High Plains region. Critical infrastructure affected through economic impacts includes both the Food and Agriculture Sector (farms, farm products) and Chemical Sector (ethanol production). Precise implications for the Energy Sector would depend on the centrality of ethanol to the overall transportation fuels portfolio.
- Variations in climate may lead to reductions in crop yields. Although farmers have previously mitigated climate-related losses through irrigation, the decreasing groundwater supply of the High Plains Aquifer could limit their ability to do so in the future.

Detailed effects beyond those captured in this analysis would require higher resolution analysis of detailed sub-sector data and existing modeling output.

ACRONYMS AND ABBREVIATIONS

EPIC	Environmental Policy Integrated Climate
GDP	gross domestic product
MGD	million gallons per day
MW	megawatt
NAICS	North American Industrial Classification System
NASS	National Agricultural Statistics Service
NISAC	National Infrastructure Simulation and Analysis Center
REMI	Regional Economic Models, Inc.
USGS	U.S. Geological Survey

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Homeland Security

National Protection and Programs Directorate

NPPD Customer Feedback Survey

Product Title:

1. Please select the partner type that best describes your organization. Select One

2. Overall, how satisfied are you with the usefulness of this product?

- ○ **Very Satisfied**
- ○ **Somewhat Satisfied**
- ○ **Neither Satisfied Nor Dissatisfied**
- ○ **Somewhat Dissatisfied**
- ○ **Very Dissatisfied**

3. How did you use this product in support of your mission?

- ☐ Integrated into one of my own organization's information or analytic products
- ☐ Used contents to improve my own organization's security or resiliency efforts or plans
  - If so, which efforts?
- ☐ Shared contents with government partners
  - If so, which partners?
- ☐ Shared contents with private sector partners
  - If so, which partners?
- ☐ Other (please specify)

4. Please rank this product's relevance to your mission. ***(Please portion mark comments.)***

- ○ Critical
- ○ Very important
- ○ Somewhat important
- ○ Not important
- ○ N/A

5. Please rate your satisfaction with each of the following:

	Very Satisfied	Somewhat Satisfied	Somewhat Dissatisfied	Very Dissatisfied	N/A
Timeliness of product or support	○	○	○	○	○
Relevance to your information needs	○	○	○	○	○

6. How could this product or service be improved to increase its value to your mission? ***(Please portion mark comments.)***

To help us understand more about your organization so we can better tailor future products, please provide (OPTIONAL):

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