NUMERICAL MODEL OF THE MIDDLE ARKANSAS RIVER SUBBASIN

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EXECUTIVE SUMMARY

Ground-water levels have been declining during the last few decades in most of the High Plains aquifer in the Middle Arkansas River subbasin, which extends from the Ford-Edwards county line to the confluence with Rattlesnake Creek in southwest Rice County. The water-level declines have decreased ground-water discharge to the Arkansas River, thereby causing declining streamflow. Smaller stream inflows to the subbasin, especially from the Arkansas River, have also decreased streamflow during this period. In response to these declines, the Division of Water Resources of the Kansas Department of Agriculture (DWR) and the Kansas Water Office (KWO) requested that the Kansas Geological Survey develop a calibrated ground-water flow model to provide additional information on the nature of stream-aquifer interactions and the effect of ground-water pumpage for use in planning and management of water resources in the Middle Arkansas subbasin. A numerical model was constructed for an area extending from northeast Ford County through much of Edwards and Pawnee counties to north-central Stafford and southern Barton counties. The DWR and KWO formed a Technical Advisory Committee to oversee the project.

The major focus of the project was the development of a calibrated transient model that simulated ground-water flow and stream-aquifer interactions during the period 1944-2004. The model included 6,209 active model cells, each a quarter-mile square, covering a total of 1,552 square miles, and incorporated six recharge zones and two hydraulic conductivity zones. Calibration was accomplished using observed ground-water levels across the model area for 1980, 1990, and 2000, hydrographs for 26 wells with long-term water-level records, and annual streamflows at the stream gaging stations on the Arkansas River near Kinsley, Larned, and at Great Bend. The parameter estimation program PEST was employed to optimize parameters during the calibration process.

The average net pumping (ground-water pumped minus recharge from irrigation water seepage) increased from 14,060 acre-ft/yr for the first 30 years of the model (1944-1973) to 177,080 acre-ft/yr for the last 15 years (1990-2004). Pumpage for 1990-2003 was from water-use records, and for other years was estimated from regression equations for total and irrigation pumpage based on annual reported water use, authorized quantity, and precipitation from 1990 to 2003. The percentage of irrigation return recharge was calculated for each year for three different zones in the active model area based on data for changes in irrigation type. Results from the calibrated model indicated that the average long-term recharge from areal precipitation for the model area during 1994-2004 was 1.81 in/yr. The model indicated that there was a substantial storage decline in the High Plains aquifer starting in the late 1970s that was accompanied by a decrease in streamflow and also a reduction in ground-water flow out of the subbasin. By 2004, the cumulative loss in aquifer storage reached about 1,500,000 acre-ft. The net streamflow gain (baseflow minus stream leakage) in the subbasin decreased from an annual average of 35,530 acre-ft/yr during 1944-1973 to 5,140 acre-ft/yr during 1990-2004, even though the average precipitation recharge for 1990-2004 (2.31 in/yr) was greater than for 1944-1973 (1.78 in/yr).

Five different scenarios were simulated with the calibrated transient model. One scenario involved running the model for 1944-2004 using increased stream inflows during 1980-2004.

Two cases were simulated for this scenario using inflow increases of 6.8% and 83% relative to the 1980-2004 inflows. The results of this scenario indicated that much of a small increase in stream inflow recharges the aquifer, but most of a large increase in stream inflow passes through the subbasin. For either case, the increased stream recharge reduced the storage decline in the aquifer by <10%.

The other four scenarios involved simulations of future conditions (50-year period 2005-2054) using different pumping strategies under the climatic conditions of 1980-2004 (repeated twice). A scenario with continued pumping at current levels indicated that ground-water levels continue to decline, causing further decreases in streamflow and lateral outflow of ground water. In this scenario, the cumulative loss in aquifer storage that began in the late 1970s sums to about an additional 1,500,000 acre-ft for 2005 to 2054. The decrease in lateral ground-water outflow decreases the ground-water inflow to the Rattlesnake Creek subbasin that borders the southeast side of the Middle Arkansas subbasin.

A scenario in which there was no pumping showed that the long-term water-level declines in the main aquifer that began in the late 1970s start to reverse within a few years after the wells are shut off. The change from streamflow loss to increase takes a few years longer to respond due to the need to raise water levels enough to create substantial baseflow and reduce stream loss. Most of the aquifer storage lost from the late 1970s to 2004 is regained after about 20 years.

Two reduced pumping scenarios were run, one with a 24% reduction of pumping in the proposed area for the Conservation Reserve Enhancement Program (CREP) in the subbasin (equivalent to an average annual decrease in net pumping of 25,287 acre-ft/yr or a 14.3% reduction over the model area compared to continued pumping), and the other with the retirement of water rights in the Circle K Ranch in southwest Edwards County (equivalent to an average decrease of 7,323 acre-ft/yr from continued pumping during 2005-2054). Although the losses in aquifer storage, streamflow, and lateral ground-water outflow were not as great in the CREP as in the continued pumping scenario, those losses continued during the 2005-2054 simulation. Retiring the Circle K Ranch water rights decreases the rate of aquifer storage loss and increases the average flow of the Arkansas River, but only to a limited extent in the general vicinity of the Ranch.

INTRODUCTION

The stretch of the Arkansas River from the Ford-Edwards county line to the confluence with Rattlesnake Creek in southwest Rice County is known within Kansas as the Middle Arkansas River. The Middle Arkansas subbasin is defined by the Kansas Department of Agriculture, Division of Water Resources (DWR) as the watershed for the Middle Arkansas River excluding the watersheds of the Pawnee River and Walnut Creek (Figure 1). The subbasin lies within the lower part of the Upper Arkansas basin as defined in the Kansas Water Plan. The subbasin is one of several in the Subbasin Water Resource Management Program (SWRMP) of DWR formed to address issues related to water resources concerns. The program is funded by the State Water Plan and "is designed to take a proactive approach in developing water management strategies that address declines in stream flows and groundwater levels" (SWRMP, 2004). A decline in ground-water levels in the High Plains aquifer and a decrease in flow of the Arkansas River have been observed during the last three decades within the Middle Arkansas subbasin.

Purpose of Project

The DWR and the Kansas Water Office (KWO) needed additional information regarding the aquifers, the nature of stream-aquifer interactions, and the impact of ground-water pumpage for planning and management of water resources in the Middle Arkansas subbasin. Stream-aquifer interactions in the vicinity of the Circle K Ranch were of particular interest. These state agencies requested that the Kansas Geological Survey (KGS) construct a ground-water flow model to determine the hydraulic relationships between the High Plains aquifer and the Arkansas River in the subbasin. The modeling was to include simulation of different scenarios of Arkansas River flow and ground-water pumpage. The subbasin is included in the Upper Arkansas basin section of the State Water Plan and stream-aquifer modeling is an activity identified in the Water Issue Strategic Plan. The modeling activity fits within the following Kansas Water Plan Objectives:

1. By 2015, achieve sustainable yield management of Kansas surface and ground water resources outside the Ogallala aquifer and areas specifically exempt by regulation,
2. By 2010, target data collection, research projects, and data sharing activities to address specific water resource issues as identified in the Kansas water planning process and to support and guide state water resource program operations (Kansas Water Authority, 2005).

The modeling project extended from July 2004 to April 2006; the calibrated transient model was completed by early February 2006, scenarios were run from early February to mid-March, and the draft report was completed in mid-April 2006.

Description of Study Area

The Middle Arkansas subbasin is 781,455 acres in extent and is located in portions of Barton, Edwards, Kiowa, Pawnee, Rice, Rush, and Stafford counties in south-central Kansas (Figure 1). Approximately three-fourths of the subbasin lies within Big Bend Groundwater Management District No. 5 (SWRMP, 2004). The Arkansas River flows into the southwest part of the subbasin, follows a general northeasterly path to Great Bend, and then curves to the east

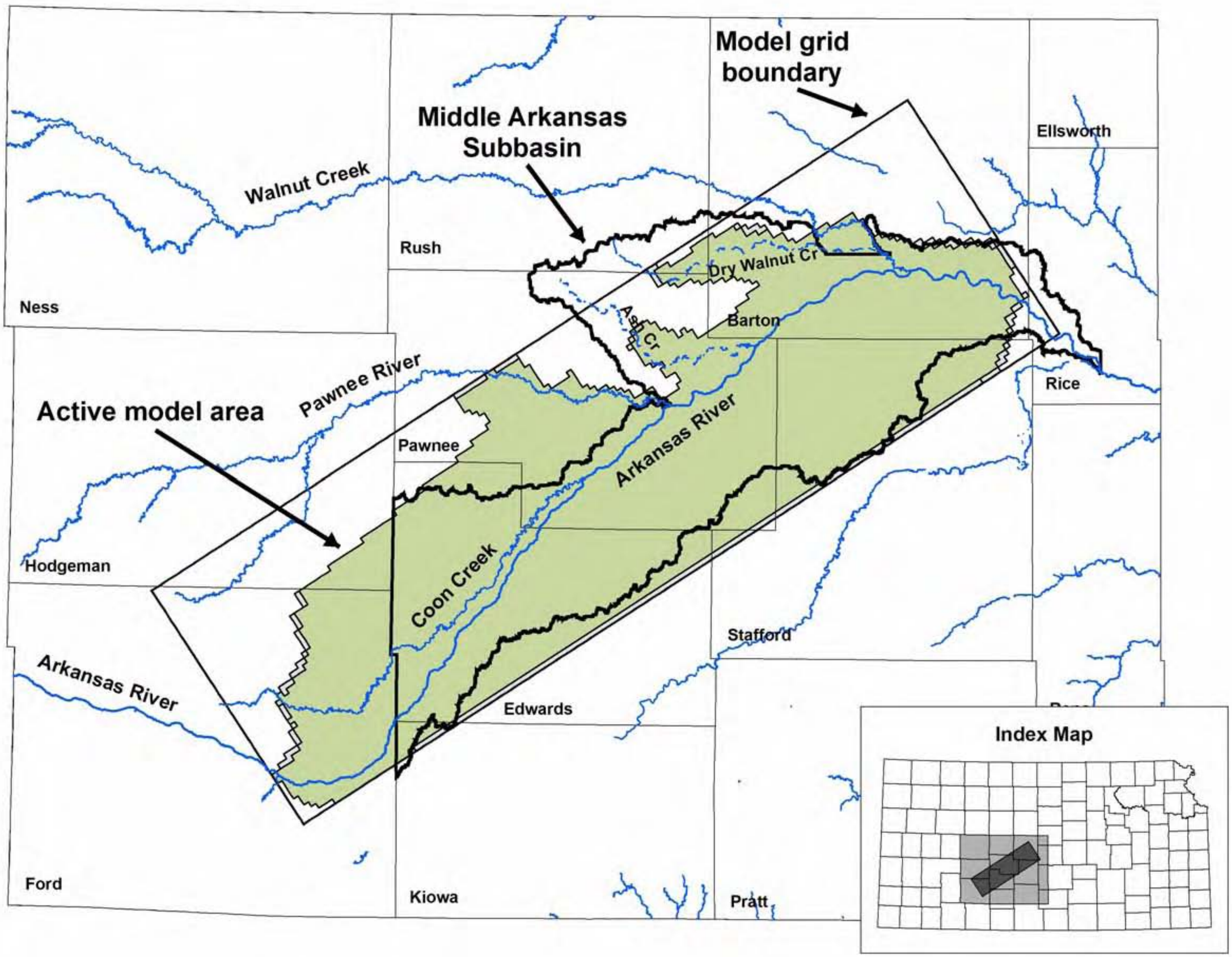

Figure 1. Boundary of the Middle Arkansas Subbasin and location of the model grid boundary and active model area.

and southeast before exiting the subbasin. The subbasins of the Pawnee River and Walnut Creek enter the western and northern sides of the subbasin, respectively. The study area included parts of the Upper Arkansas basin to the west of the subbasin in Ford and Hodgeman counties, the Pawnee River watershed in Edwards and Pawnee counties, the Rattlesnake Creek subbasin in Edwards, Pawnee, and Stafford counties, and the Walnut Creek subbasin in Barton County. The model grid boundary is shown in Figure 1 along with the area of active model cells. For the purposes of this report, we refer to the area within the model grid boundary as the model area and the area of active cells as the active model area.

Previous Geohydrologic Studies

Investigations of the geohydrology within the study area are described in a series of previous KGS bulletins and reports. McLaughlin (1949) reported on the geohydrologic conditions for Pawnee and Edwards counties, Latta (1950) for Barton and Stafford counties, and Waite (1942) for Ford County. Fader and Stullken (1978) described the geohydrology of the Great Bend Prairie, which included the area of the Middle Arkansas subbasin to the east and south of the Arkansas River. These studies include a substantial number of water-level measurements.

Sophocleous et al. (1993) constructed a numerical model of stream-aquifer relationships for the Kinsley to Great Bend reach of the Arkansas River as part of a KWO funded study. The model area did not include the portion of the Middle Arkansas subbasin upstream of Kinsley or downstream of Great Bend, but did extend to the boundary with the Rattlesnake Creek subbasin. The objectives of Sophocleous et al. (1993) were

1. To define the geologic and hydrologic relationship between ground water and surface water in the reach of the Arkansas River from Kinsley to Great Bend,
2. To evaluate the impacts of ground-water management alternatives on streamflows in the river reach, and
3. To evaluate recovery of regional ground water in response to increased streamflow in the river reach.

The active model area of Sophocleous et al (1993) was 472 square miles and had a grid cell size of one square mile. The model was calibrated for a predevelopment time of circa 1955 and a development period of 1955-1985, and was validated using pumping and streamflow stresses during 1985-1990 that were different from those used in the development calibration.

Sophocleous et al. (1993) reported that their model indicated that the level of ground-water pumping during 1990 “is not sustainable over the long term and that desirable streamflows cannot be maintained unless severe measures … are taken to protect and conserve the water resources of the region.” They also ran management scenarios for the period 1991-2010 for both continued and reduced pumping schedules in the model area and for corridors of different widths along the Arkansas River. Their results indicated that a pumping reduction of about 50% throughout the model area or a pumping moratorium within a 3-mile corridor along the river were needed to either stabilize or improve Arkansas River flow, given an average input flow at Kinsley for 1988-1990 conditions.

Model Oversight

The DWR and KWO formed a Technical Advisory Committee to oversee the project. The TAC met either in Topeka or by conference call three times during the second half of calendar 2004, and on an approximately monthly basis from January 2005 to February 2006. The DWR members of the TAC were Tina Alder, James Bagley, David Barfield, and David Zook. The KWO members were Susan Stover, Chris Gnau, and Earl Lewis. The TAC included participation by the Manager and a staff member of Big Bend Groundwater Management District No. 5 (Sharon Falk and Chad Milligan, respectively), and also a consultant for Water PACK, Andrew Keller of Keller-Bliesner Engineering, Logan, UT. The DWR arranged for review of the project by Steven Larson of S.S. Papadopulos & Associates, Bethesda, MD. The DWR and KWO provided the specifics of the management scenarios to be examined using the calibrated transient model. The KGS presented the results of the calibrated numerical model for the 1944-2004 simulations at the February 27, 2006 meeting, and of the scenario simulations at the May 4, 2006 meeting of the Basin Advisory Committee for the Upper Arkansas basin in Great Bend.

CHARACTERISTICS OF STUDY AREA

Physiographic Setting

The part of the active model area (Figure 1) along and to the south of the Arkansas River, and to the north of the river in the Great Bend area, lies within the physiographic provinces known as the Arkansas River lowlands and the Great Bend Prairie. The lowermost portion of the Pawnee River valley and the lower parts of two tributary valleys (Ash and Dry Walnut creeks) are also within the Arkansas River lowlands physiographic province. This area is generally flat-lying and there are no significant tributaries entering the south side of the river within the subbasin. The active model area to the north of the Arkansas River in northeastern Ford, southeastern Hodgeman, and northwestern Edwards counties, and southwestern Pawnee County south of the Pawnee River is within the High Plains physiographic province. The land is either nearly flat or has gentle slopes extending to higher elevations above the Arkansas River. The area within the model grid boundary but outside of the active model area in Hodgeman, Edwards, Pawnee, and western Barton counties lies in the Smoky Hill physiographic province. This area consists of gently-sloped hills dissected by tributaries to the Pawnee River and Walnut Creek, and within the upper watersheds of Ash and Dry Walnut creeks.

Soils

Soils data and coverages are available from the Natural Resources Conservation Service of the U.S. Department of Agriculture. The data are mainly based on county surveys: Dodge et al. (1981) for Barton County, Roth (1973) for Edwards County, Dodge et al. (1965) for Ford County, Haberman et al. (1973) for Hodgeman County, Dodge and Roth (1978) for Pawnee County, and Dodge et al. (1978) for Stafford County. The character of the soils ranges widely across the active model area, from level, poorly drained soils where there is a substantial clay content to hummocky, excessively drained soils developed on sand dunes. Soils in the Arkansas River valley developed on alluvial sediments and are level to nearly level, sandy to loamy to clayey in texture, and well to poorly drained. In general, the sandier soils tend to be located in the southwest part of the model area and the more clayey soils in the bottomlands in the northeast portion of the model area. Soils in the Pawnee River valley and the lower parts of the Dry Walnut and Walnut Creek valleys are nearly level, well drained to moderately well drained, and can have a silt loam to silty clay subsoil.

A band of pronounced sand dunes lies to the south of the Arkansas River valley from the southwest part of the model area up to Barton County. The band is widest in Edwards County and thins to the northeast. The soils that developed on the hummocky to undulating dunes are sandy and are well to excessively drained. To the south of this band and to the south of the Arkansas River valley in Barton County, the soils range from nearly level to undulating, depending on whether there are low sand dunes or areas between the dunes where the materials have a higher silt and clay content. Thus, the soils range from sandy texture and well drained to loamy and well to somewhat poorly drained.

Soils in the upland north of the Arkansas River valley in northeast Ford, southeast Hodgeman, northwest Edwards, central Pawnee, and southwest Barton counties within the active model area but outside the valleys of the Pawnee River and Dry Walnut and Walnut creeks range from nearly level to gently sloping, and are generally loamy in texture and moderately to well drained. Some areas have silt loam to silty clay loam subsoil.

Precipitation

The long-term mean annual precipitation across the active model area during the 65-year period 1940-2004 is 24.59 inches. The model area was divided into the six recharge zones that are displayed in Figure 2 (zonation described later in the section on recharge-precipitation relationships under the transient model; initially there was a zone 5 that was combined with zone 4 during the modeling process). Annual precipitation data (obtained from the National Climatic Data Center) for the region within and surrounding the model area were used to prepare a precipitation surface from which mean values were computed for each year for each recharge zone. The mean precipitation for the recharge zones ranged from a minimum of 9.93 inches during 1956 in zone 4 in the southwest portion of the model area, to a maximum of 43.38 inches during 1973 in zone 1 in the northeast part of the model. The mean precipitation for 1940-2004 increased from the southwest to the northeast: 23.43 inches in zone 4, 24.07 inches in zone 2, 24.30 inches in zone 6, 24.71 inches in zone 3, 25.40 inches in zone 7, and 25.65 inches in zone 1. Figure 3 shows that the precipitation patterns during dry and wet years in each recharge zone correspond relatively well, such as during the wet year 1973 and the dry year 1988. However, there was a substantial difference in precipitation across the model area in some years, for example, the wet year 1993 in which the mean annual precipitation ranged from 28.97 inches in zone 2 to 38.12 inches in zone 1, and the dry to near average year 2002 in which the precipitation ranged from 16.96 inches in zone 4 to 23.20 inches in zone 1. The standard deviation in the annual precipitation for 1940-2004 over the six recharge zones is 6.12 inches.

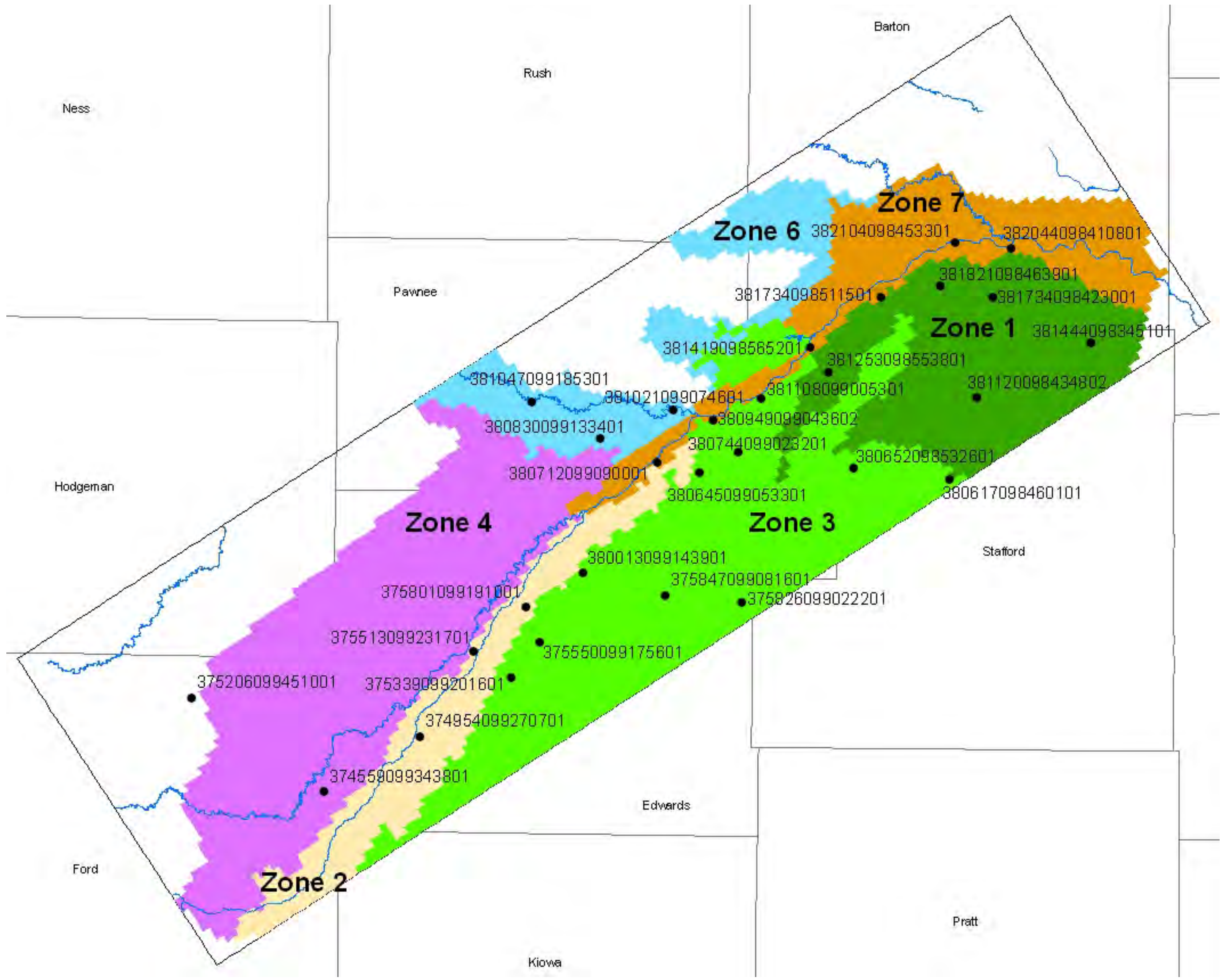

Figure 2. Recharge zones in the active model area. See Figure 1 for names of rivers and creeks (blue lines). The black dots (with USGS identification numbers) represent the locations of wells with long-term hydrographs used in the calibration process.

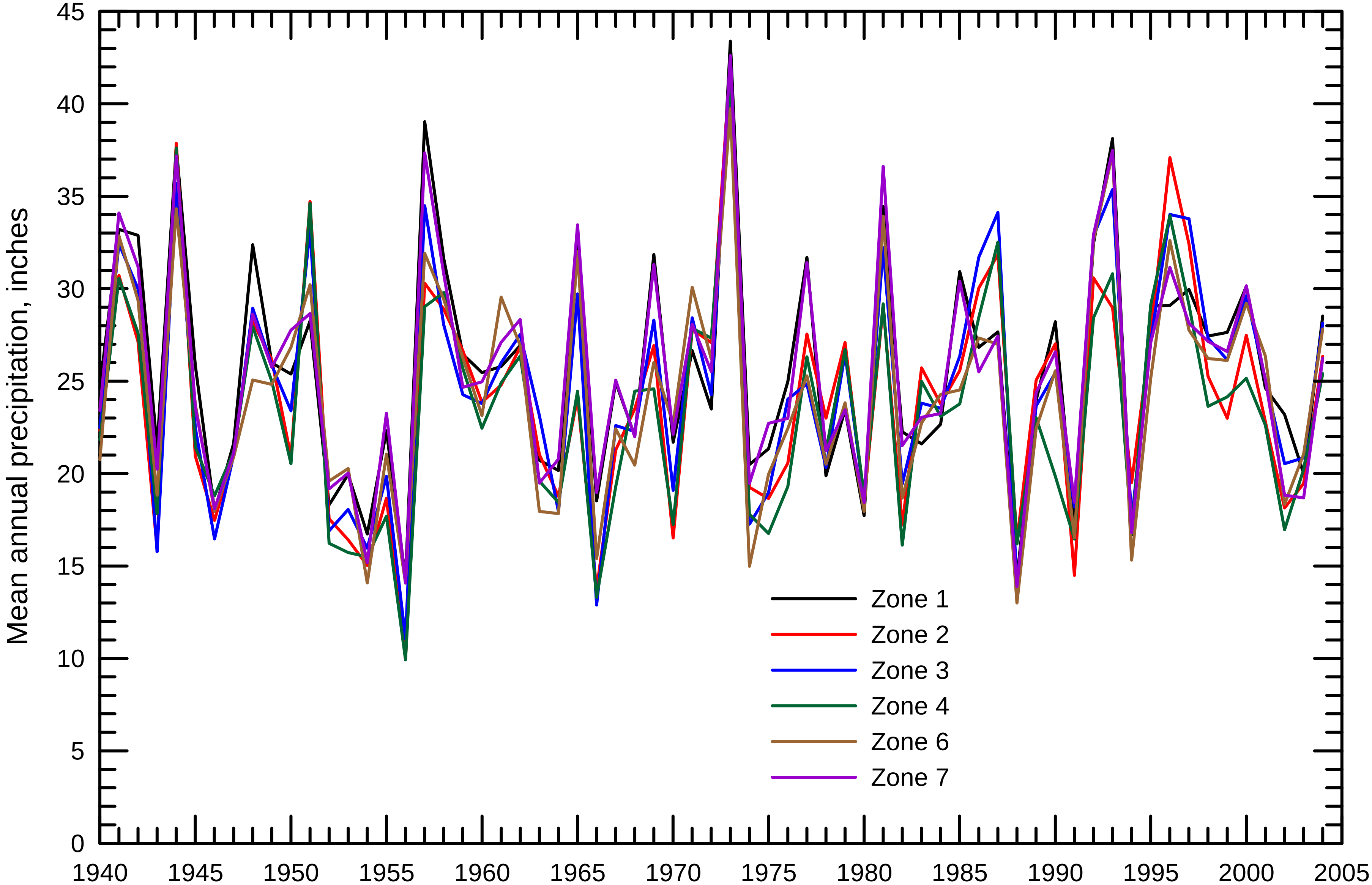

Figure 3. Mean annual precipitation during 1940-2004 for the six recharge zones in the active area of the transient model.

Streamflow

The streams with generally the greatest flow within the model area are the Arkansas and Pawnee rivers and Walnut Creek (Figure 1). The Arkansas River extends in a general southwest to northeast direction across the model area. The Pawnee River flows from the west and enters the Arkansas River at Larned in east-central Pawnee County. Walnut Creek flows from the northwest into the model area and joins the Arkansas River downstream of Great Bend in south-central Barton County. Coon Creek has intermittent flow, largely parallels the Arkansas River in the southwest to central part of the model area, and enters the Arkansas River in southwest Pawnee County near the town of Garfield. Ash and Dry Walnut creeks only flow after substantial rainstorms; their valleys trend from a west to east direction. Ash Creek joins the Arkansas River near the town of Pawnee Rock in the northeast corner of Pawnee County. Dry Walnut Creek enters Walnut Creek to the northeast of Great Bend.

The U.S. Geological Survey (USGS) has been gaging streamflow on the Arkansas River at three stations within the model area. The record for the gage to the east of Kinsley in west-central Edwards County started September 1, 1944, for the gage northeast of Larned on October 1, 1998, and for the gage at the south side of Great Bend on October 1, 1940. A gaging station for the Pawnee River is located at the town of Rozel at the north-central boundary of the active model area in west Pawnee County. The Pawnee flow record at Rozel started in 1924. From June 3, 1959 to June 6, 1990, the flow was measured at a site 5.8 miles downstream of the Rozel station. No flow data were recorded for either of these sites from October 1, 1987 to September 30, 1988. The flow for the Pawnee River was estimated in this modeling study for these 365-days of missing data based on a relationship that was derived between flows in Walnut Creek near the town of Albert and those for the Pawnee River. Walnut Creek has been gaged at Albert, which is just upstream of the northern model boundary, in western Barton County since June 1, 1958. Flow in the Arkansas River has been continuously measured upstream of the western boundary of the model at Dodge City since September 1944.

The mean annual flow over the period 1945-2005 for the Arkansas River near Kinsley and at Great Bend, and for the Pawnee River at Rozel, are displayed in linear and log formats in Figures 4 and 5, respectively. In general, both high and low annual flows have decreased during this period. However, the relative discharge decrease during the low flow years is much greater than that for the high flow years as illustrated in Figure 5. The sources of the high annual flows vary between gaging stations. High annual flows near Kinsley result from substantial snowmelt runoff and precipitation in the Arkansas River basin in Colorado that fill John Martin Reservoir, leading to large releases downstream to Kansas. The decline in ground-water levels in the High Plains aquifer in the Arkansas River corridor of southwestern Kansas has resulted in an increasing amount of recharge of high flows received from Colorado, thereby decreasing the amount of water reaching the Middle Arkansas River over time and reducing the occurrence of high flow years. Large annual flows in the Pawnee River are related to wet years in the Pawnee watershed. High annual flows in the Arkansas River at Great Bend are produced by either the large flows from Colorado, substantially above normal precipitation falling over the Pawnee River watershed and the rest of the Middle Arkansas subbasin, or a combination of both.

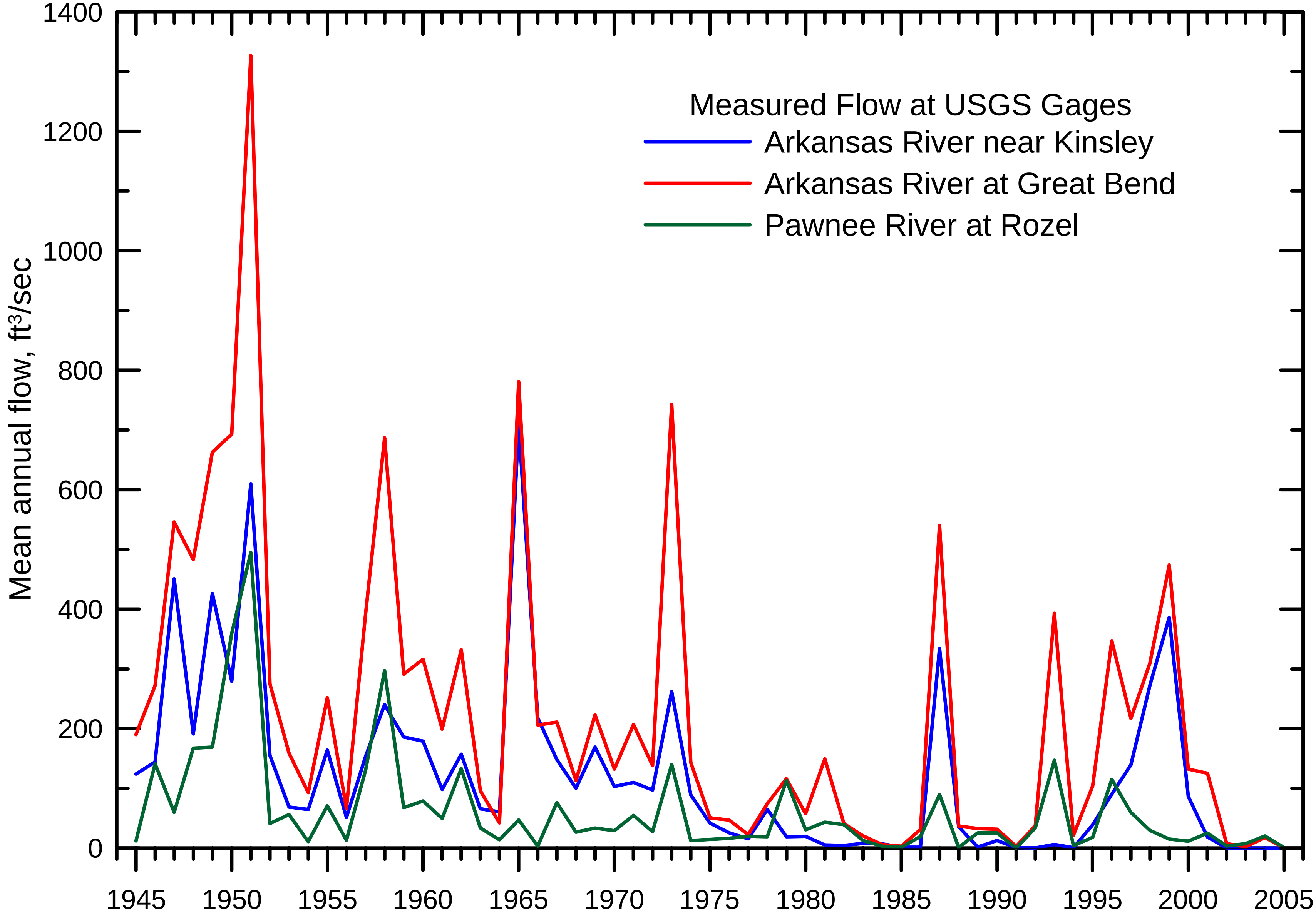

Figure 4. Mean annual flow (linear flow axis) in the Arkansas and Pawnee rivers in the model area.

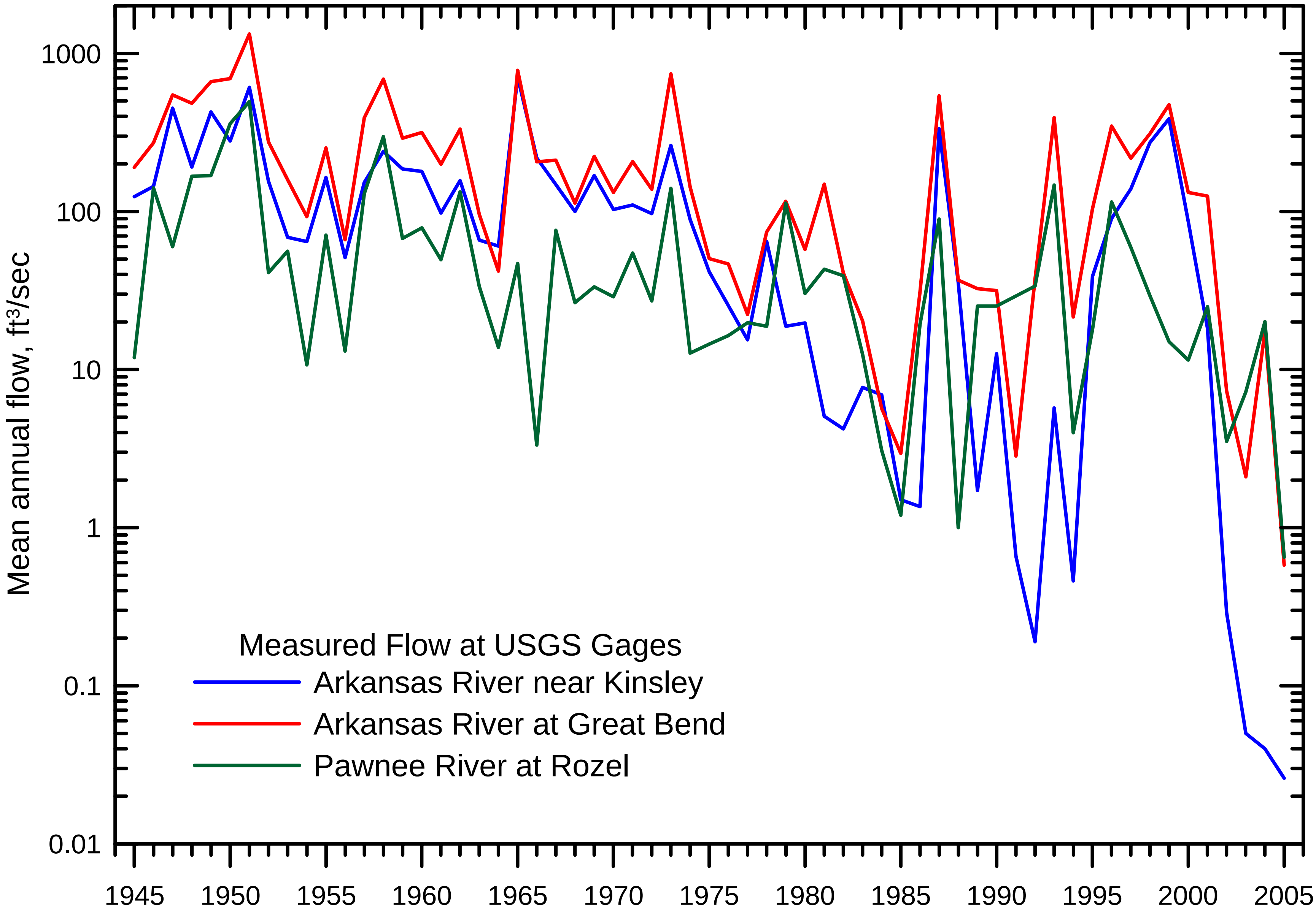

Figure 5. Mean annual flow (log flow axis) in the Arkansas and Pawnee rivers in the model area.

Dundee Diversion

The State of Kansas acquired the land for Cheyenne Bottoms and constructed dikes to impound water in five pools there during the 1940s and 1950s. To provide additional water for the pools, the State built dams and canals to divert water from the Arkansas River and Walnut Creek. A low-head dam was constructed on the Arkansas River about one mile directly south of the town of Dundee in southwest Barton County. Water diverted from the dam follows a canal to the Dry Walnut Creek bed, then, after flowing through about two miles of the creek channel, is diverted through a half-mile aqueduct to Walnut Creek. Water is diverted from Walnut Creek, several miles downstream of the aqueduct entrance, into a canal to Cheyenne Bottoms.

The first diversion from the Dundee dam began in 1957. Diversions continued during portions of each year through 1990. No diversions were recorded for the years 1991-1996. Water began to be diverted again in 1997 and continued into 2004 (Figure 6). Diversion flows generally increased from 1957 to a maximum in 1970 and have since decreased. The most recent substantial diversions occurred during the period of appreciable flows in the Arkansas River derived from Colorado in 1996-2000.

Channel Elevation Change

The stream channel of the Arkansas River has shifted downwards due to erosion during the period of USGS flow gaging. Since the late 1800s, substantial amounts of water have been diverted from the Arkansas River in eastern Colorado, with additional, but not as large, volumes diverted in southwest Kansas. Storage of water in John Martin Reservoir starting in the early to mid 1940s appreciably changed the flow characteristics of the river entering Kansas. The decreased flow and reservoir regulation changed the morphology of the riverbed from a very broad, shallow channel to a much narrower and somewhat deeper channel. This is apparent as a present channel entrenched several feet into the older wide channel along the river.

The USGS has changed the gage datum three times at the Garden City station on the Arkansas River (the first station downstream of all substantial river diversions in southwest Kansas). They lowered the gage datum by 3.0 ft on July 9, 1964, by 3.0 ft on April 8, 1976, and by another 3.0 ft on September 30, 1986, indicating a total of 9 ft of channel entrenchment. The USGS measured flow in the river at the Dodge City station during 1902-1906 at a site 0.7 mile downstream from the present site; the gage datum for this location was lowered 4.0 ft in 1944 when flow gaging began again. On September 30, 1975, the datum was lowered another 1.0 ft. On March 16, 1981 the USGS lowered the datum another 3.0 ft and moved the station to its present location. At the Arkansas River station near Kinsley, the USGS lowered the gage datum by 3.0 ft on December 31, 1975. At the Great Bend station, the USGS lowered the gage datum by 4.0 ft on October 1, 1975. With some additional erosion since the 1970s, the total channel entrenchment in the Middle Arkansas River is expected to be currently about 3-6 ft.

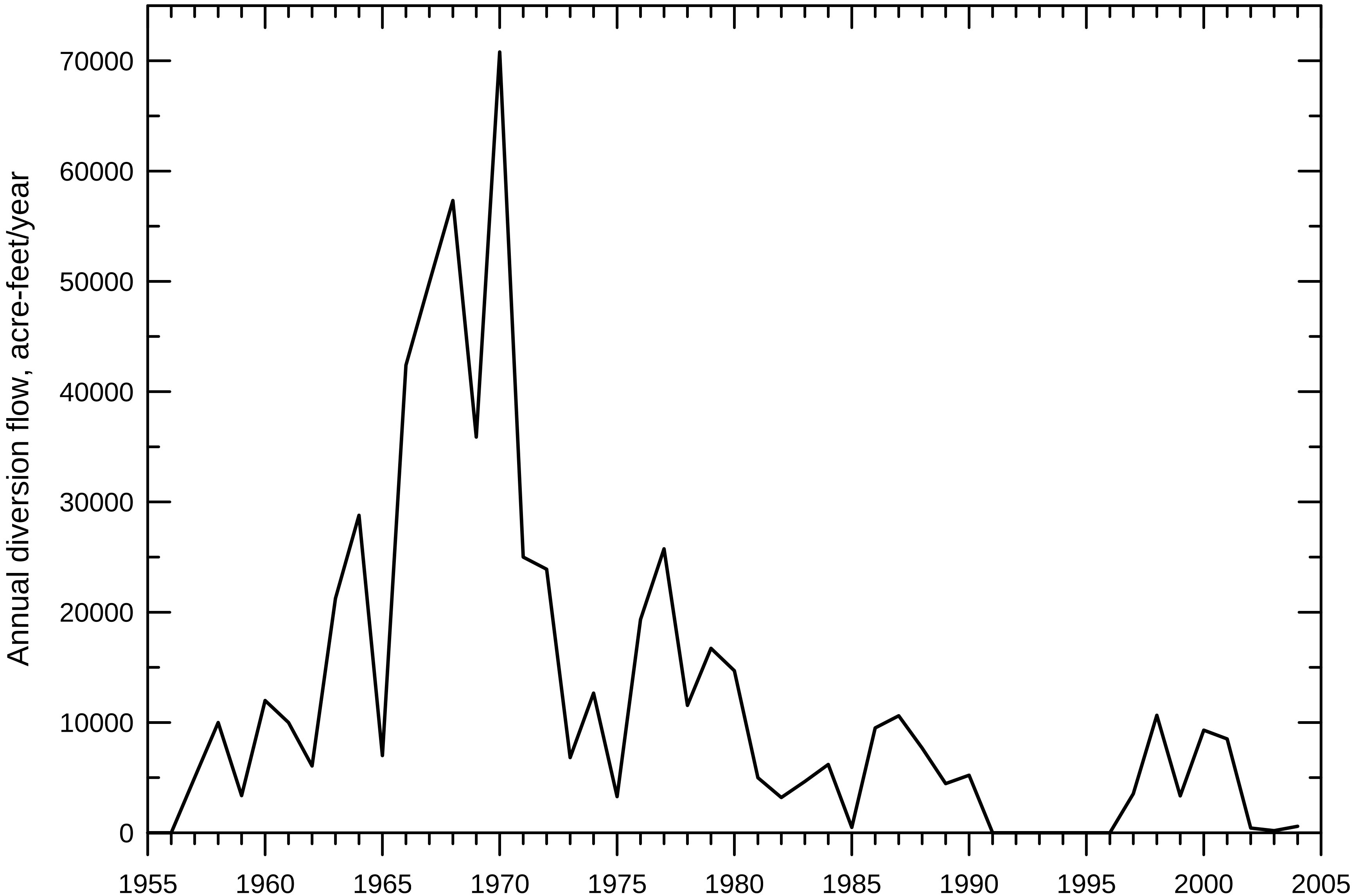

Figure 6. Annual diversion flow from the Arkansas River at the Dundee diversion dam.

Geology

Bedrock

Permian strata do not outcrop within the model area but underlie the unconsolidated deposits in the northeastern part of the model area in northeastern Stafford County and the southernmost part of southeastern Barton County. These strata include the Cedar Hills Sandstone and the Salt Plain Formation, which consist of sandstone, silt, and shale generally colored red by iron oxides (Fader and Stullken, 1978).

Cretaceous rocks outcrop in portions of the western and northern parts of the area within the model grid boundary but outside the active model area, except for a very small outcrop along the valley wall north of the Arkansas River in northeastern Ford County. These include the lower Cretaceous Dakota Formation composed of shale, siltstone, and sandstone. The Graneros Shale and Greenhorn Limestone, which are Upper Cretaceous formations, overlie the Dakota Formation and outcrop along portions of the northernmost parts of the area within the model grid boundary. The Dakota Formation and other undifferentiated lower Cretaceous shales, siltstones, and sandstones underlie the unconsolidated deposits over most of the active model area.

Unconsolidated Deposits

The Ogallala Formation of Tertiary age is at the surface or underlies loess deposits within the southwestern part of the active model area in northeast Ford, southeast Hodgeman, and northwest Edwards counties. The Ogallala Formation consists mainly of silt, sand, and gravel with caliche deposits (McLaughlin, 1949).

Quaternary sediments comprise most of the unconsolidated deposits across the active model area. These consist of Pleistocene and recent deposits of clay, silt, sand, and gravel. The thick deposits underlying the Arkansas lowlands and the Great Bend Prairie are interbedded alluvial sediments. These include the recent alluvium along the river. Terrace deposits at higher elevations north of the Arkansas River in the southwestern parts of the model area tend to be finer grained (silts and clays). Fine dune sands cover the alluvial deposits over most of the model area south of the Arkansas River. These dune deposits range from a broad band of hummocky dunes along the south side of the river in Edwards and northeasternmost Ford counties to thinner dunes scattered across the Great Bend Prairie.

Land Use

Most of the land and water use across the model area is for agriculture. Cropland comprises the majority of the agricultural land (Figure 7). A substantial acreage of the lowlands in the Arkansas River valley, the Great Bend Prairie, and the lower valleys of the Pawnee River and Ash, Dry Walnut, and Walnut creeks consists of irrigated cropland. Grasslands used for pasture or enrolled in the Conservation Reserve Program are scattered across the model area. The most prominent zone of grasslands within the active model area is in the band of pronounced sand dunes along the south side of the Arkansas River in east-central Ford, the northwest corner of Kiowa, southwest to north-central Edwards, and southwest to east-central Pawnee counties.

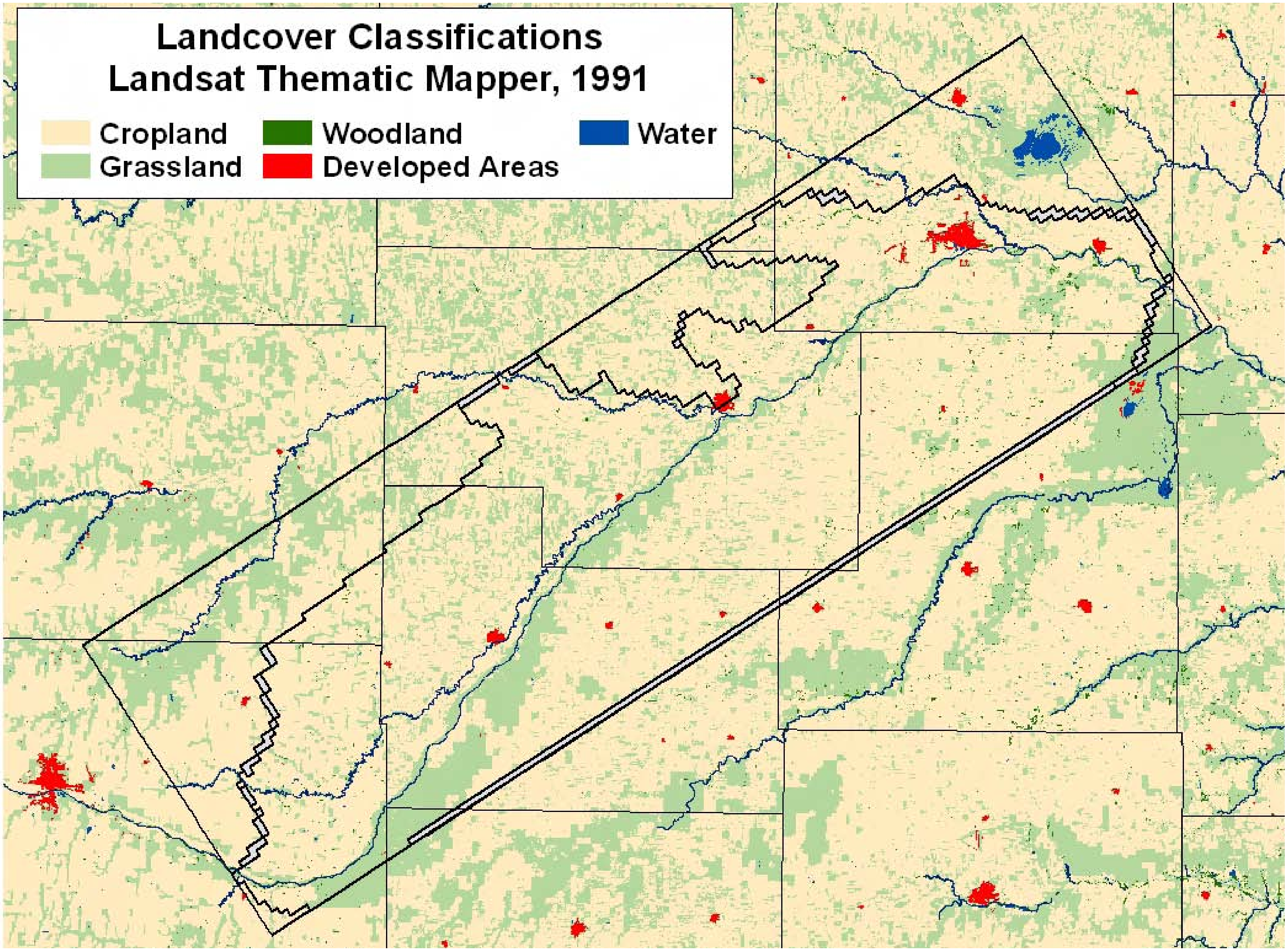

Figure 7. Landcover classifications in the model region based on Landsat Thematic Mapper, 1991.

The area of the Circle K Ranch in southwest Edwards County is visible on Figure 7 as an area of cropland along the south side of the Arkansas River cut into the grassland of the sand dune zone.

Water Use

There are a large number of wells permitted by the DWR to withdraw water across the model area (Figure 8). A very high percentage of these wells are used for irrigation. Other wells are used for municipal, industrial, stock, and recreational water supplies. Although some of the municipal wells produce annual quantities comparable to those for irrigation wells, most of the other wells shown in Figure 8 extract smaller annual quantities than the irrigation wells. The locations of the wells generally outline the most productive aquifer areas. The total quantity of ground water pumped in 2004 from permitted wells in the active model area was 174,270 acre-ft.

The number of water rights and the amount of ground water pumped from permitted wells in the model area increased gradually from the 1940s to the mid-1960s (Figure 9). The number of water rights and the annual volume of ground-water pumped then increased substantially to the early 1980s, followed by a gradual rise to the present. The increase in ground-water pumpage was a result of the large increase in crop irrigation as indicated by the change in harvested irrigated acres for the model area in Figure 9. There is no general trend in the harvested irrigated acres from the mid-1980s to the most recent data. If the change in the harvested irrigated acres, which is based on Farm Fact data for the entire counties in which the model is located, is representative of the change over the model area, it could suggest that the amount of ground-water pumped during the mid-1980s (1990 was the first year that the water use data underwent a quality control and assurance program administered by the State) is underestimated. Additional information on water use for the Middle Arkansas subbasin is summarized for the period 1988-2000 in a report by the Subbasin Water Resource Management Program (2004).

Aquifer Characteristics

Although the Dakota Formation is used for water supply in a few locations within the active model area, the numerical model simulated ground-water flow in only the unconsolidated deposits that form the High Plains aquifer. The upper part of the High Plains aquifer within the river and creek valleys includes recent alluvium. The rest of the High Plains aquifer in the model area consists primarily of Pleistocene sediments. All water-level and water-right data known to be associated with bedrock strata (the Dakota aquifer) were removed before calculations were performed for the model.

High Plains and Alluvial Aquifers

As shown in Figure 10, the High Plains aquifer has sufficient saturated thickness to yield water to wells over most of the active model area. Figure 10 also shows the location of the recent alluvial deposits within the High Plains aquifer. Parts of the southwest model area north of the Arkansas River include High Plains aquifer deposits with little or no saturated thickness.

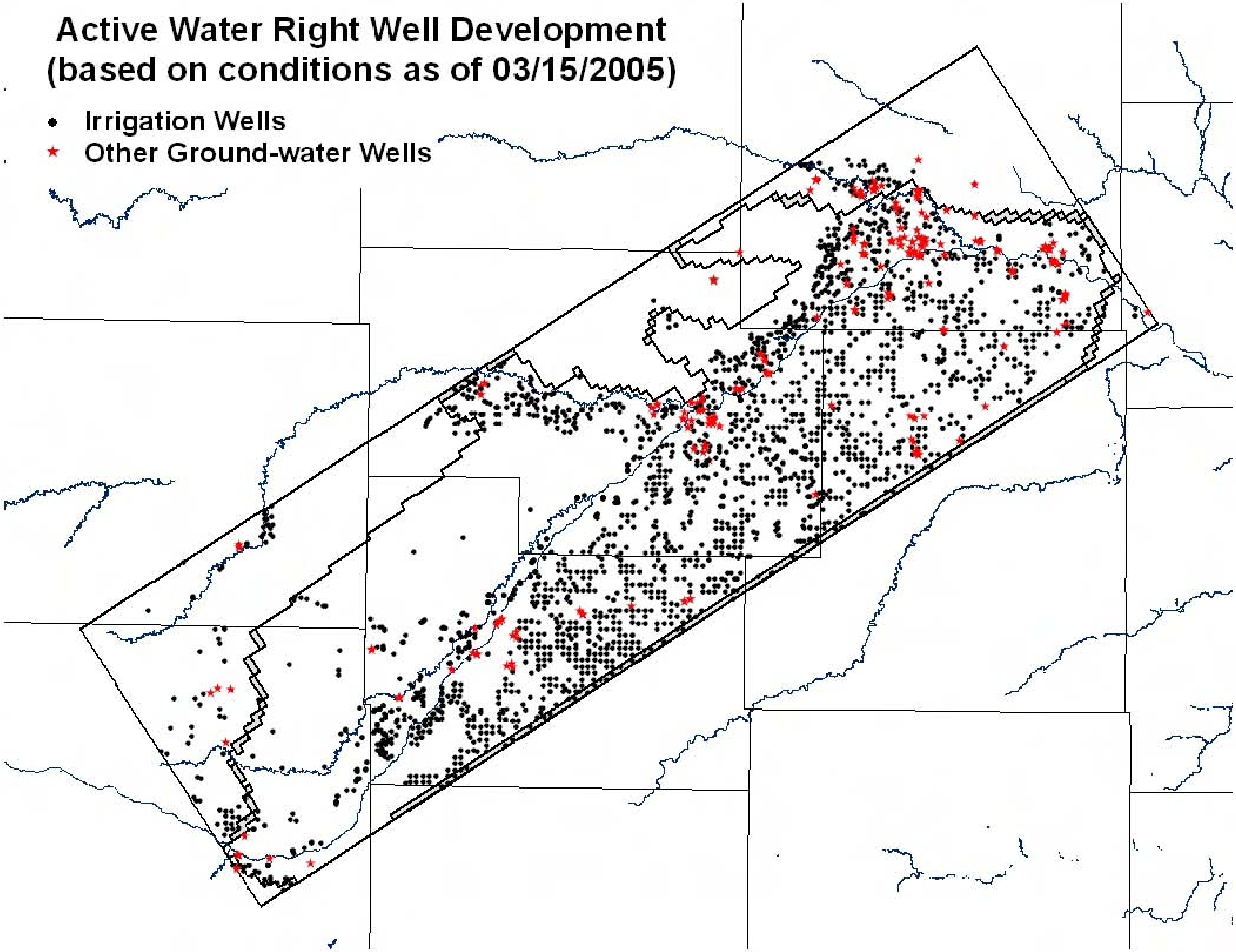

Figure 8. Locations of wells permitted to withdraw ground water within the model grid boundary.

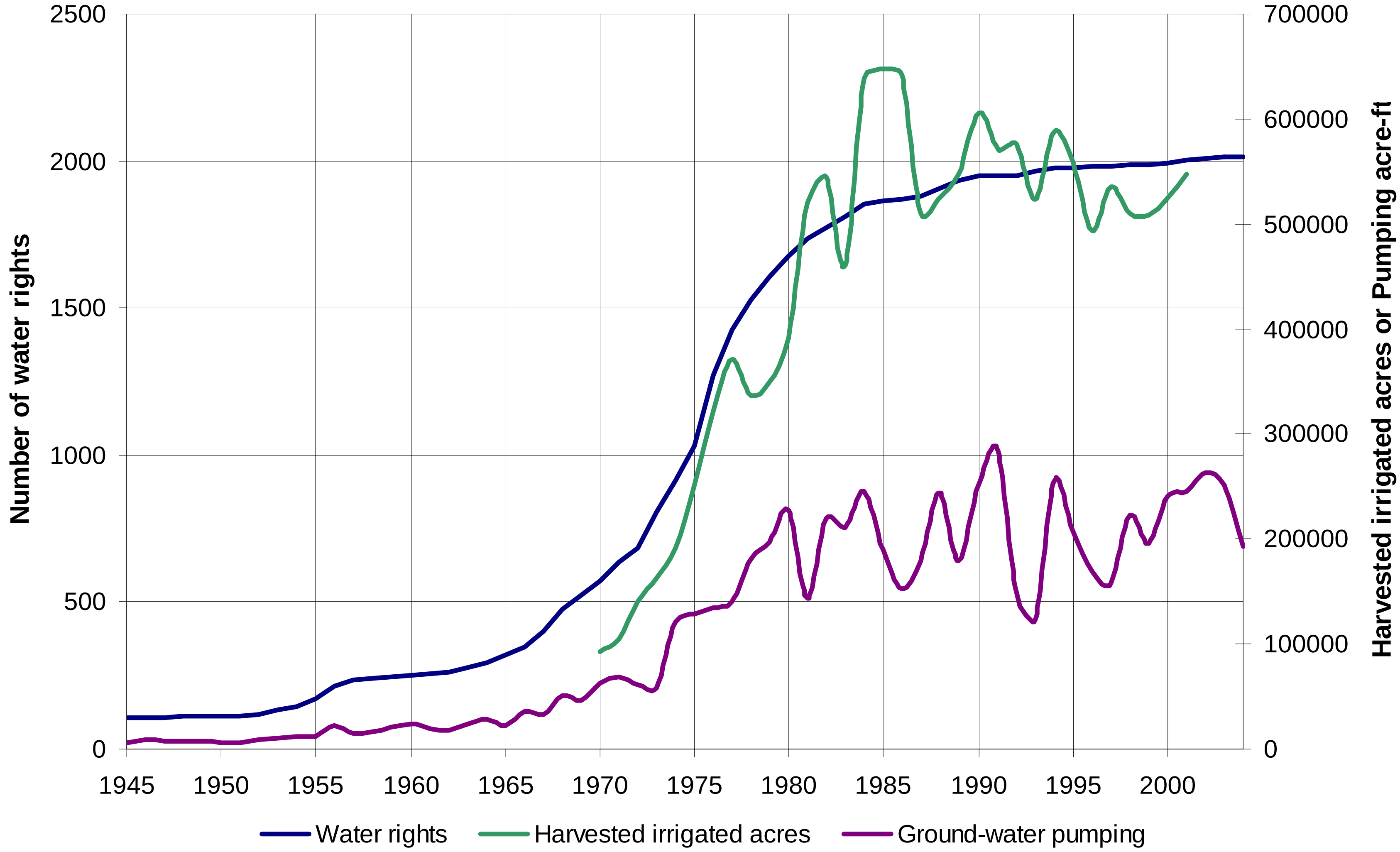

Figure 9. Change in number of water rights and amount of ground-water pumping in the model area, and in harvested irrigated acres in the counties of the model area.

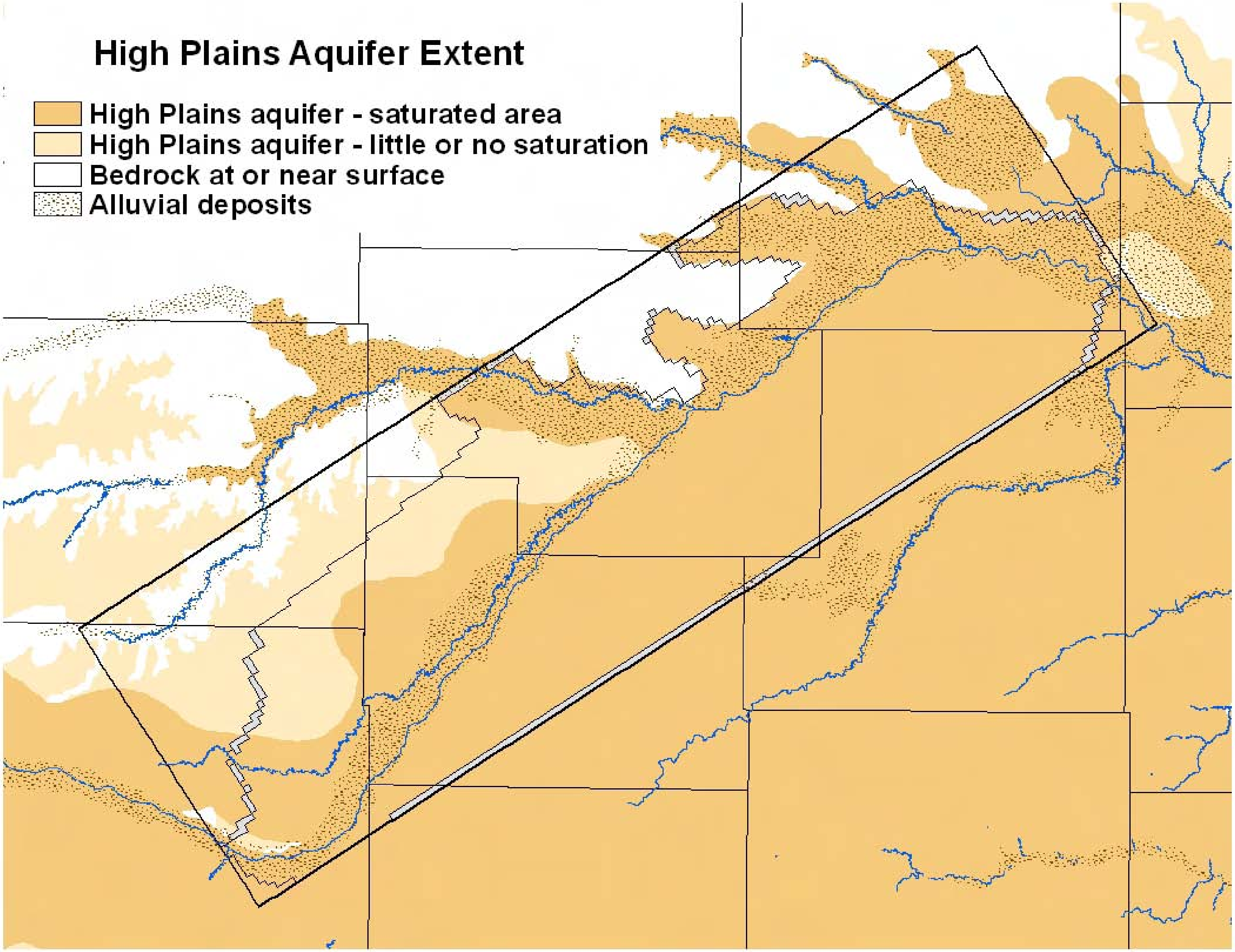

Figure 10. Extent of the High Plains aquifer and recent alluvial deposits in the model region.

In order to examine the aquifer characteristics of the High Plains aquifer along the Arkansas River valley, a color-coded lithologic cross section along the river in the model area was produced using the methods of Young et al. (2000). Published logs of wells and test holes were used where available, but the main source of lithologic information was Water Well Completion Records (WWC-5 logs) submitted to the Kansas Department of Health and Environment (KDHE) and filed at the KGS. Only logs judged to have relatively good lithologic information were used for the cross section. Well and test hole locations are listed in Table 1 and shown in Figure 11. The range of colors corresponding to the different textural classifications of the sediments in the cross section is shown in Figure 12. The coarser, more permeable, sediments are lighter and the fine-grained sediments are darker in color.

The base of the columns in the lithologic cross section (Figure 13) is an approximate representation of the bedrock surface. The appearance of an uneven bedrock surface is partly real and partly an artifact of the amount, location, quality, and depth of available well logs. The bedrock surface does consist of valleys and ridges, and the elevation of the bedrock surface varies considerably over short distances.

As illustrated in the cross section along the Arkansas River (Figure 13A), the permeable alluvium is well defined along most of this stretch of the river. Its thickness varies, but its composition of sand and gravel is relatively homogenous. The alluvium ranges in thickness up to about 50 ft. Some of the coarse alluvial deposits are capped by finer sediments. Based on the available logs, there appears to be little high-permeability material below the Arkansas River alluvium except in Barton County and eastern Pawnee County.

At the western extent of the model area, the aquifer is composed of up to about 40 ft of permeable sand and gravel overlying a lesser amount of fine-grained sediment. The alluvium is thinner – typically not more than about 20 ft thick – throughout most of eastern Ford County, and rests on shallow bedrock (Dakota Formation).

The thickness of the unconsolidated deposits increases in Edwards County (Figure 13A). The alluvium is generally relatively thick – a few tens of feet in most of Edwards County – and is typically underlain by a substantial thickness of mostly fine-grained deposits. There is some permeable material below the fine-grained interval, but it is unclear whether this material is laterally continuous, and it does not appear to exceed a couple tens of feet in thickness. The alluvium thins near the Edwards-Pawnee County line, as does the entire sequence of unconsolidated deposits. The alluvium is underlain by an interval of almost entirely fine-grained deposits. There does not appear to be a water-producing horizon below the fine grained sediment.

Figure 13B is a lithologic transect displaying the character of the sediments perpendicular to the Arkansas River in the area of the Circle K Ranch. The transect illustrates the substantial increase in the thickness of the sediments from northwest to southeast across the river valley in the vicinity of the Ranch. The coarsest sediments that form the aquifer in this area lie between finer materials nearer the surface and clayey sediments above the bedrock.

Table 1. Locations of wells and test holes used in the lithologic cross section and transect.

Cross Section along the Arkansas River		Circle K Ranch Transect
Ford County	Pawnee County	Edwards County
28S 22W 05 ADC	23S 18W 31 D	25S 20W 24 CCB
28S 22W 04 BC	23S 18W 29 C	25S 20W 26 A
28S 22W 10 AC	23S 18W 27 CCB	25S 19W 31 DAD
28S 22W 11 BDB	23S 18W 12 BA	25S 19W 32 CBC
28S 22W 11 BD	23S 18W 13 AAB	26S 19W 04 B
27S 22W 36 AAD	23S 18W 01 DCD	26S 19W 04 A
27S 22W 36 ADD	23S 17W 06 C	26S 19W 03 C
27S 21W 32 CCC	22S 17W 22 AB	26S 19W 09 A
27S 21W 29 AAC	22S 17W 14 CDA	26S 19W 15 BAA
27S 21W 26 BB	22S 17W 24 BD	
27S 21W 10 DCC	22S 16W 05 DD	
26S 21W 36 BCB	22S 16W 04 C	
26S 21W 36 B	22S 16W 02 CBC	
26S 21W 25 DCD	21S 15W 30 ABA	
	21S 15W 29 BAB	
Edwards County	21S 15W 21 A	
26S 20W 30 DDD		
26S 20W 19 AAA	Barton County	
26S 20W 05 CCC	20S 15W 36 A	
26S 20W 21 ACB	20S 14W 31 B	
26S 20W 15 C	20S 14W 29 B	
26S 20W 15 CAA	20S 14W 20 C	
26S 20W 10 CCD	20S 14W 16 BB	
25S 19W 19 DDD	20S 14W 21 D	
25S 19W 15 DBA	20S 14W 16 AAA	
25S 19W 10 CC	20S 14W 01 AA	
24S 19W 33 DDC	19S 13W 32 BBB	
24S 19W 34 AC	19S 13W 36 DCC	
24S 19W 36 BBB	19S 13W 36 DC	
	19S 12W 31 DC	
	19S 12W 32 CCA	
	19S 12W 29 DD	
	20S 12W 03 C	
	19S 11W 31 DDA	
	19S 11W 29 BB	
	20S 11W 12 BB	

The total sediment thickness increases substantially in the central part of Pawnee County, where the river crosses over a paleochannel near the confluence of the Pawnee and Arkansas rivers. Bedrock maps by both Becker et al. (1998) and Sophocleous and Stern (1993) indicate this paleochannel. Here the sediments beneath the Arkansas River are at their maximum thickness in the model area of about 160 ft. The alluvium appears to thicken in this vicinity as

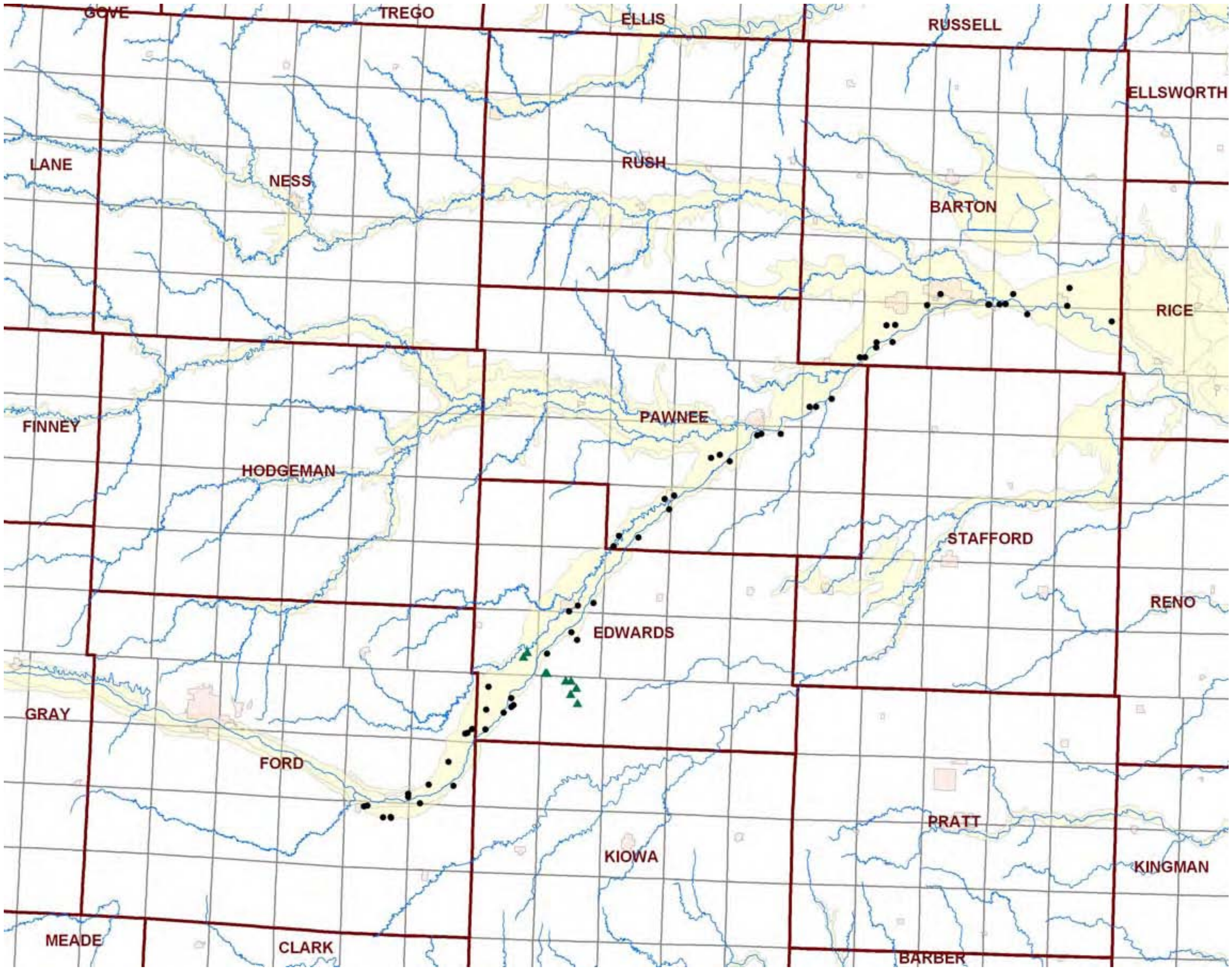

Figure 11. Locations of wells and test holes used in the lithologic cross sections. The lithologic columns in cross sections A and B in Figure 13 are represented by the black filled circles and green triangles, respectively.

well. A deeper permeable aquifer zone is present at the base of the paleochannel. A thick layer of fine-grained material separates the Arkansas River alluvium from the deeper permeable zone. East of the paleochannel, throughout eastern Pawnee and Barton counties, the thickness of unconsolidated sediments below the river remains fairly uniform, up to about 140 ft. The amount and percentage of coarse-grained materials increases in Barton County. The matrix is composed of mostly sand and gravel with interspersed clay layers and lenses. The shallow alluvium is difficult to differentiate from deeper deposits in parts of Barton County. The aquifer thins in extreme east Barton County nearing an outcrop of the Kiowa Formation.

The upper part of the alluvial sediments of the Pawnee River valley consists predominantly of clay and silt containing some sand (Fishel, 1952). This silt and clay zone ranges in thickness from about 15 to 50 ft and has an average thickness of 30 ft (McLaughlin, 1949). Fishel (1952) indicated that these fine-grained deposits retard and limit the amount of ground-water recharge from precipitation. Sand and gravel underlie the lower permeability zone and form the alluvial aquifer of the Pawnee River valley.

The alluvial deposits in the study area are not consistently underlain by low permeability sediments separating them from the main part of the High Plains aquifer, so it was difficult to characterize the transition from the alluvial aquifer to the main High Plains aquifer. Consequently, the alluvium was not represented as a separate layer in the numerical model.

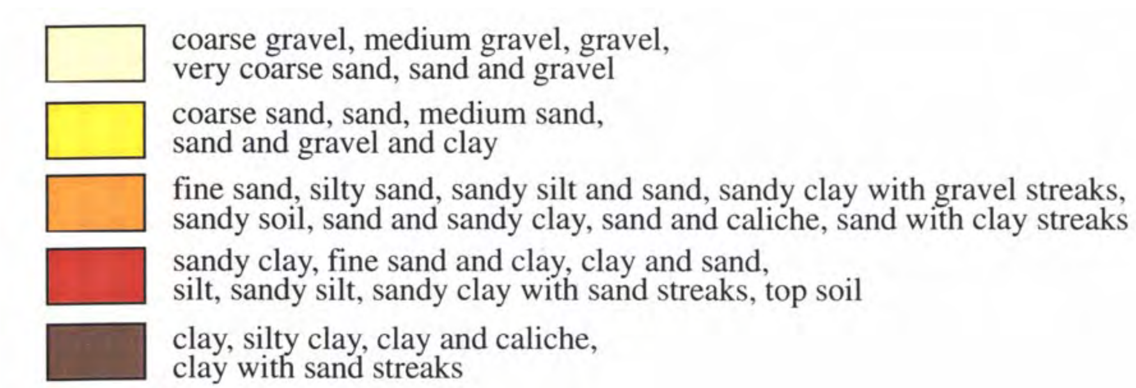

Figure 12. Color codes identifying different sediment textures in the lithologic cross sections shown in Figure 13.

Water Levels and Saturated Thickness of the High Plains Aquifer

There are substantial amounts of published water-level data for the counties in the study area for 1940-1945 (Fishel, 1952, Latta, 1950, McLaughlin, 1949, and Waite, 1942). A water-level surface for this period was prepared to represent predevelopment conditions for use in the steady-state model. The saturated thickness of the High Plains aquifer for the predevelopment period is displayed in Figure 14. The water-level surface for this map was interpolated from observations in the model area and the surrounding region. The bedrock surface used to generate

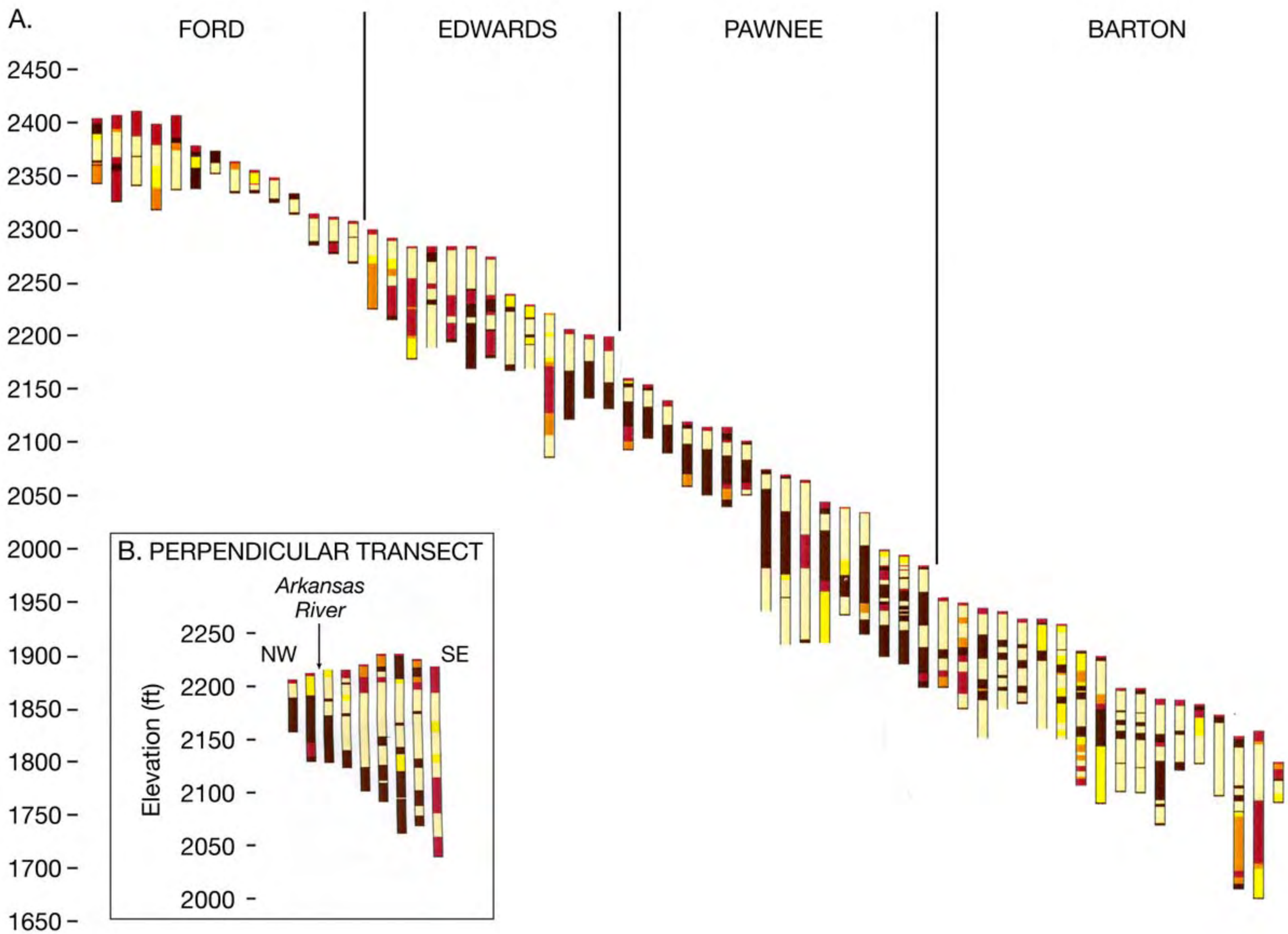

Figure 13. A. Lithologic cross section along the Arkansas River through the model area. B. Lithologic cross section perpendicular to the Arkansas River in the area of the Circle K Ranch. Figure 11 shows the location of the data used in the cross sections.

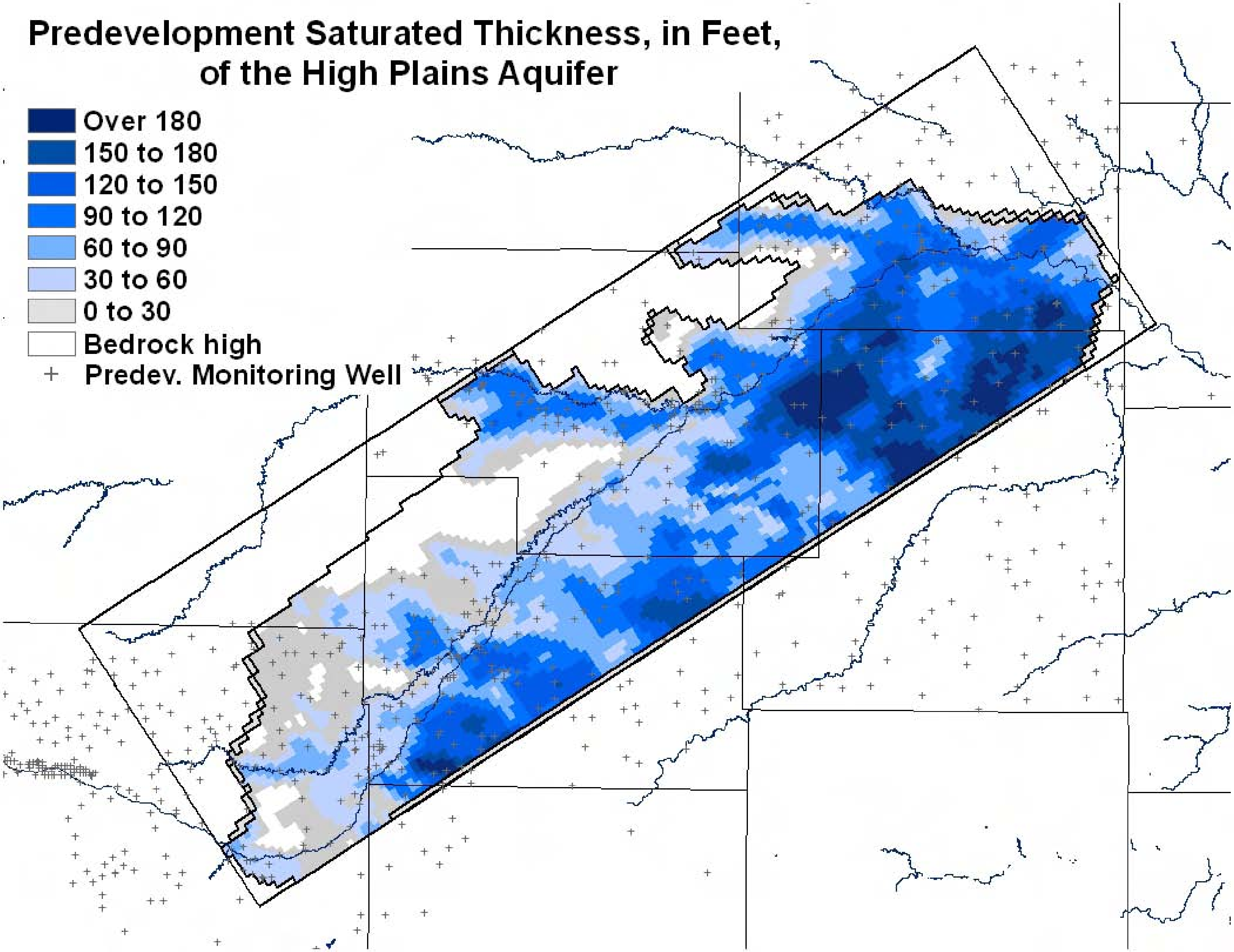

Figure 14. Saturated thickness of the High Plains aquifer in the model area during 1940-1945 used in the steady-state model.

this and other saturated thickness maps in this report was based on a combination of data from multiple sources. A region with substantial saturated thickness (>90 ft) lies within the northeast part of the model area in southern Barton, northern Stafford, and eastern Pawnee counties. Portions of the model area in Edwards County with substantial saturated thickness are distributed as somewhat disconnected zones predominantly south of the Arkansas River.

The number of winter water-level measurements within the model area and the surrounding region was low from the middle 1940s up to 1960 (Figure 15). Winter measurements are defined here as measurements in the period from December to February; these are generally referenced as "January" for the purposes of the model. The number of winter measurements began to slowly rise after 1960 and then fluctuated markedly until the early 1980s. The 1974 spike in the measurement number is related to the geohydrologic study of the Great Bend Prairie by Fader and Stullken (1978). After 1983, the number of winter observations remained between 500 and 590 except for dipping to a little over 400 in 1988.

The water-level surface for winter (January) 2005 for the active model area is displayed as a contour map in Figure 16. The general direction of ground-water flow is from the southwest to the northeast. The water-level contour along the southwest boundary of the active model area in northeast Ford County is approximately north-south, indicating a west to east direction of ground-water flow along the west-east direction of the southern bend of the Arkansas River. The contours rotate counter-clockwise and are approximately perpendicular to the Arkansas River in the middle of the model area. The contours then rotate in a clockwise direction through the northern bend of the Arkansas River in southern Barton County.

The saturated thickness of the High Plains aquifer based on interpolated January 2005 water-level measurements is displayed in Figure 17. The pattern in saturated thickness is similar to that for the predevelopment period (Figure 14) except that the areas with substantial saturated thickness are smaller. The water-level change from the predevelopment period (early to mid 1940s) to January 2005 is shown in Figure 18, which also represents the change in saturated thickness for the model area. The areas in Figure 18 for which there is the greatest confidence in actual water-level changes are those where there are observations for both the predevelopment and 2005 periods. There are no recent water-level data for the model area extending from the northeast corner of Ford County through the southeast corner of Hodgeman County to northwest Edwards County and into southwesternmost Pawnee County. This resulted in a large water-level decline shown in this area in Figure 18 that may not be accurate. This is the area of little or no saturated thickness in the High Plains aquifer. In addition, there are no 2005 data for the upstream portions of Ash and Dry Walnut creek valleys, resulting in apparent water-level declines that may not be as great as indicated.

Figure 18 indicates that water-level changes from the predevelopment period to 2005 in the High Plains aquifer are relatively small in the southwest and northeast ends of the active model area. The most pronounced water-level declines in the High Plains aquifer lie south of the Arkansas River and extend from southwest Edwards County to northwest Stafford County. A large area with greater than 20 ft of decline stretches from central Edwards through southeast Pawnee to west-central Stafford counties. Although the water-level declines along the Arkansas River are predominantly less than 10 ft, a change of even 5 ft is significant in reducing baseflow

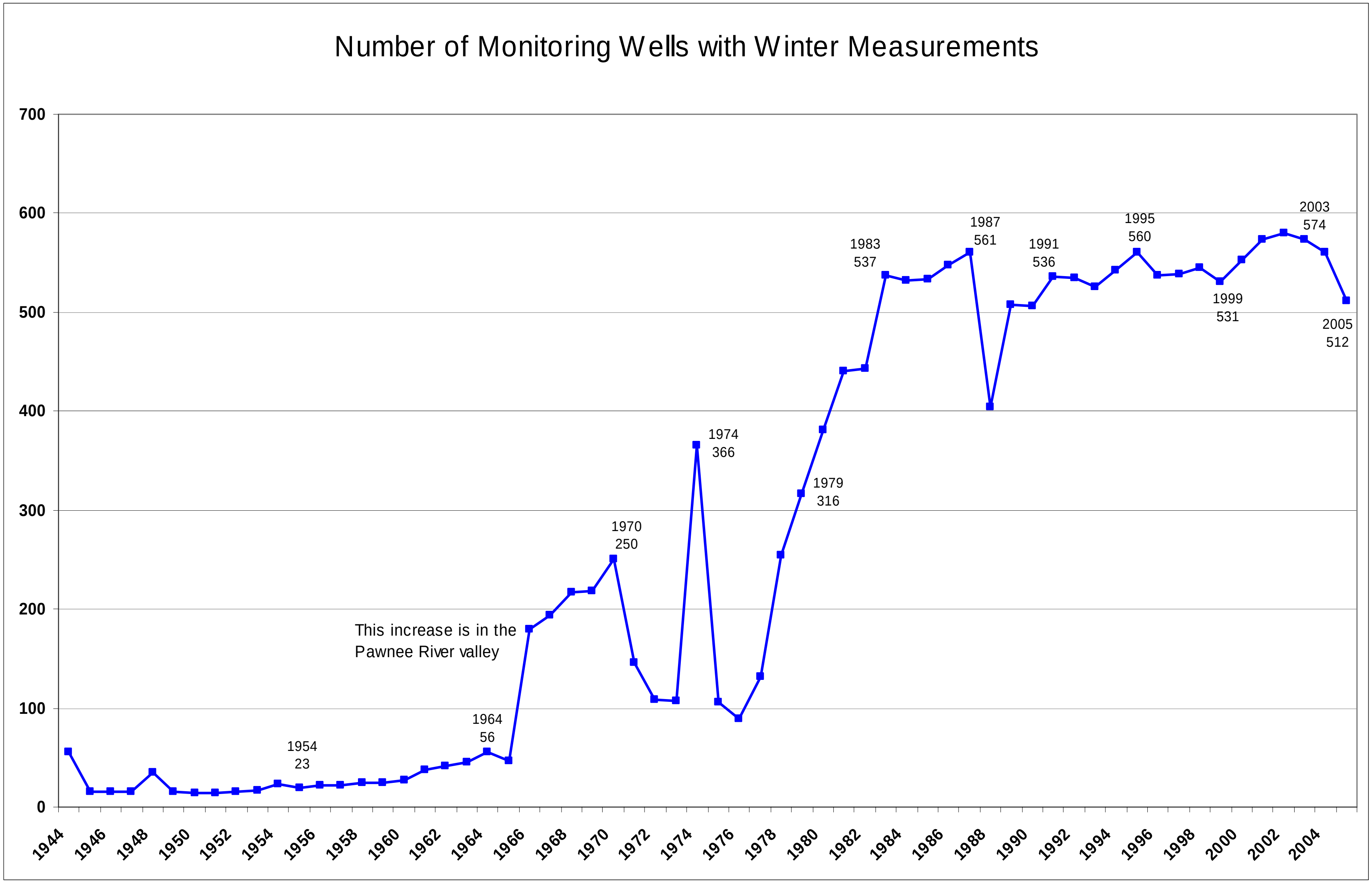

Figure 15. Time distribution of winter water-level measurements in the model area and the surrounding region.

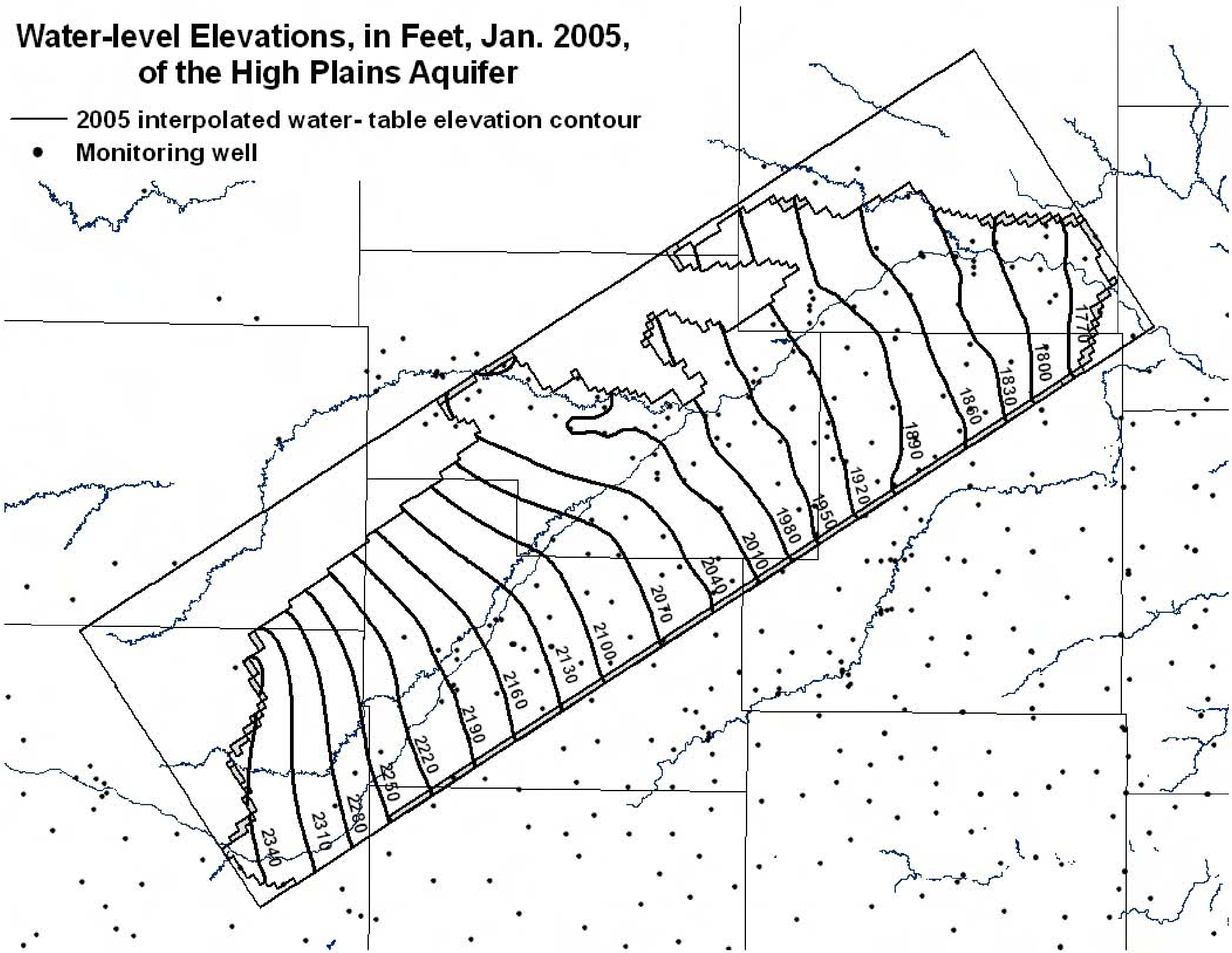

Figure 16. Water-level surface map with locations of observations for January 2005 . Contour intervals are 30 feet.

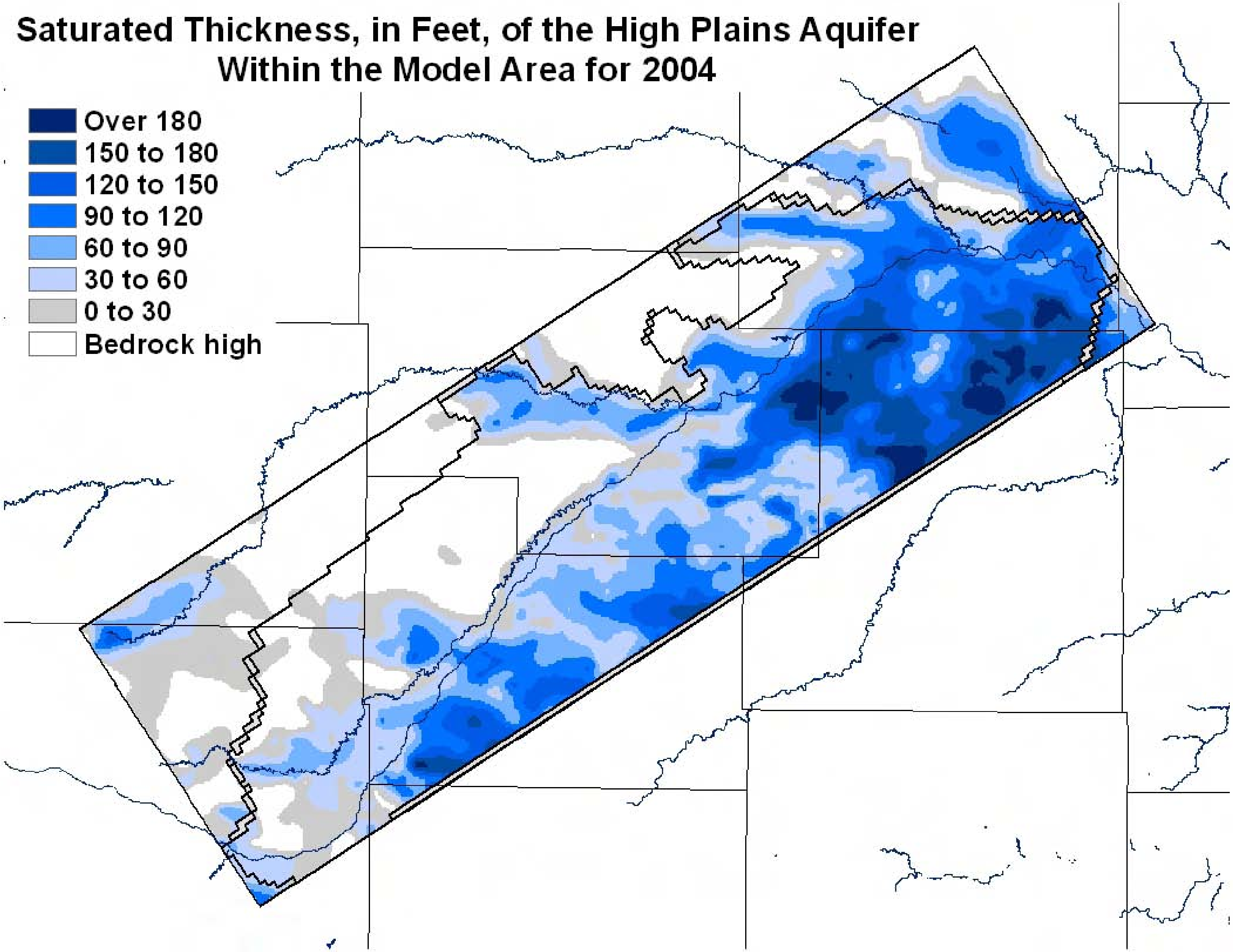

Figure 17. Saturated thickness of the High Plains aquifer based on water-level measurements for January 2005.

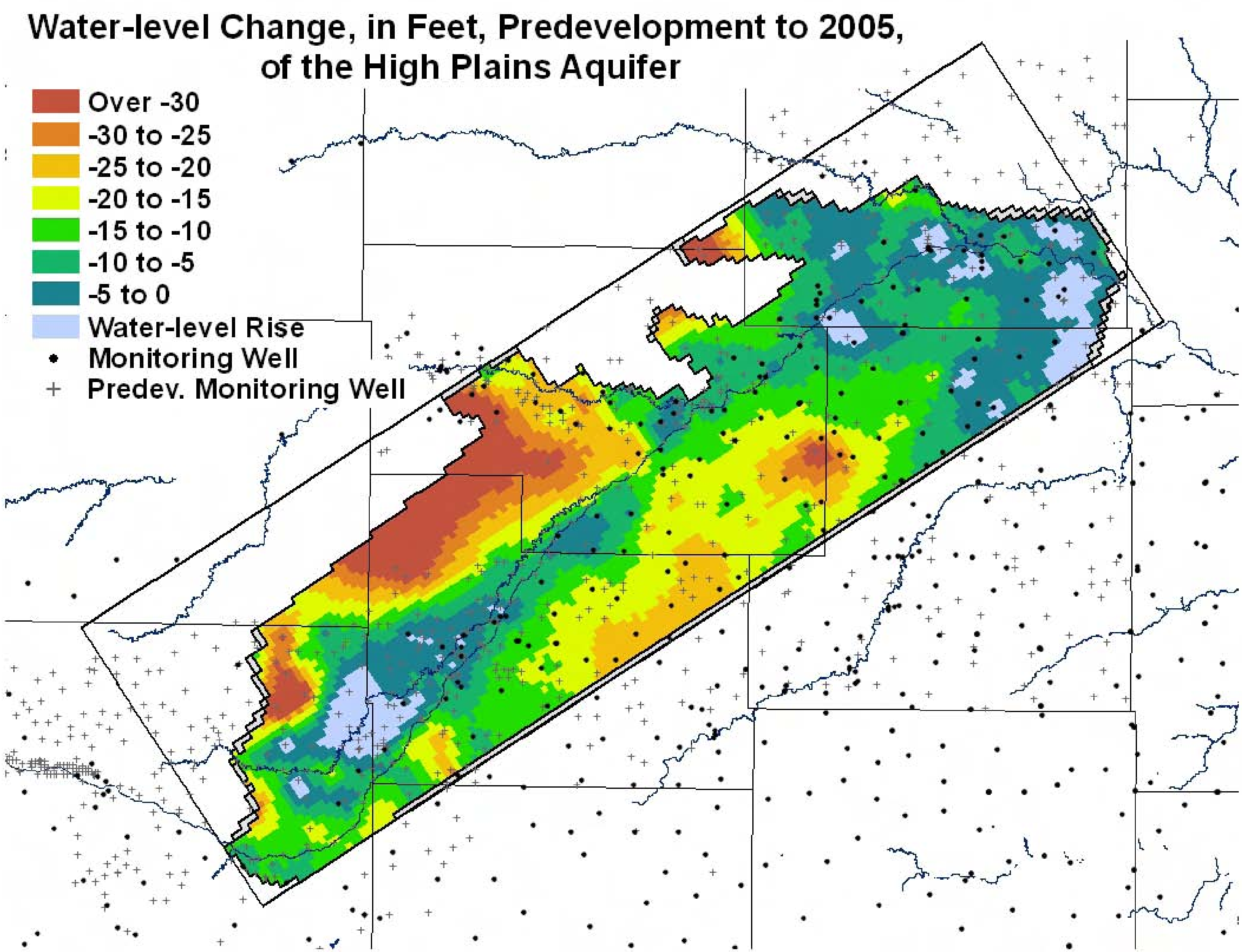

Figure 18. Change in the water-level surface from the pre-development period to January 2005 based on observations.

to the river and causing moderate flows in the river to recharge the alluvial aquifer. The area of water-level declines in Figure 18 in southeast Hodgeman, northwest Edwards, and adjacent portion of southwest Pawnee counties is an artifact related to the absence of recent data.

Stream-Aquifer Interactions

Ground-water levels in the alluvial aquifer of the Arkansas River respond relatively rapidly to fluctuations in river stage based on measurements recorded by pressure transducers in wells installed by the KGS for the DWR at the USGS station locations near Kinsley and Larned and at Great Bend, and as part of KGS studies on phreatophytes and stream-aquifer interactions at the Larned Research Site. Ground-water levels rise as a result of lateral migration of river water into the alluvial aquifer during rises in river stage, and fall during declining stage as ground water discharges to the river. Because ground-water levels have remained at or below the bottom of the river channel for most of the last few years, little to no baseflow has occurred. Ground water in the alluvial aquifer now moves either along or across the river channel area.

During the past two decades there have been periods during which substantial flows derived from Colorado have reached the Middle Arkansas subbasin (see section on streamflow earlier in this report). If the river channel is been dry in the subbasin, the river inflow recharges the alluvial aquifer until the ground-water level rises to the bottom of the channel and flow in the river begins. Recharge continues until the river stage and adjacent water level in the alluvial aquifer are equal. If the river channel is not dry, then some of the high flow derived from Colorado recharges the alluvial aquifer until the ground-water level reaches the approximate level of the river stage. Then essentially all of the inflow passes through the subbasin. Thus, substantial, continuous flow in the Arkansas River during the last two decades has not been produced by baseflow from the aquifer in the Middle Arkansas subbasin, but instead has been pass-through flow from Colorado. When the high river flows derived from Colorado decrease to the point where recharge to the alluvial and High Plains aquifers in southwest Kansas becomes greater than the flow rate crossing the state line, the river flows entering the Middle Arkansas subbasin decrease substantially. The river continues to flow at a higher rate within the Middle Arkansas subbasin than any pre-existing baseflow for a period of time as a result of discharge of the ground water recharged by the prior high river flows. The rate of decrease in this baseflow depends on the amount of areal recharge and ground-water pumpage in the river valley.

Heavy rains over the Pawnee River watershed can generate high flows that enter the Arkansas River valley near Larned. During the last two decades when ground-water levels have declined, these high flows have provided substantial recharge to the alluvial aquifer of the Arkansas River as well as that of the Pawnee River valley. Flow can also enter the Arkansas River from heavy rains over the watersheds of Coon, Ash, and Dry Walnut creeks. Some of the resulting ground-water recharge from these high flows discharges back to the river after the peak flows have passed. These periods of streamflow are much shorter in duration than those derived from Colorado. In general, the high flows occur on the order of days and the following discharge of bank storage water occurs on the order of weeks to a couple months. Thus, in the last several years, substantial flow in the Arkansas River has been dependent either on high flows received from Colorado or on peak flows from heavy precipitation events in watersheds of tributaries entering the north side of the Arkansas River.

NUMERICAL MODEL

The following sections describe the characteristics of the steady-state and transient models, and the results of the transient model runs for the 1944-2004 period and for the different management scenarios. Selected data and figures are included in this report; additional figures and data are available on the KGS web site for the Middle Arkansas River subbasin model that can be accessed by the Technical Advisory Committee.

Model Type

The ground-water flow model used in this project was MODFLOW 2000, which is based on a finite-difference approximation of the flow equation (Harbaugh et al., 2000). MODFLOW 2000 can simulate the effects of many processes, such as areal recharge, stream-aquifer interactions, drains, evapotranspiration, and pumpage. The finite-difference procedure requires that the aquifer be divided into cells (Anderson and Woessner, 1992). The aquifer properties in each cell are assumed uniform. The unknown hydraulic head in each cell is calculated at a point or node at the center of that cell. The head is calculated by iterating through the finite-difference equations for all nodes until the maximum head change from the previous iteration in any cell is less than a specified value. Once this criterion is met, the program advances to a new time step and the process of computing heads at each node is repeated.

The stream (STR) module was used to compute stream-aquifer interactions. Streams superimposed on the aquifer are divided into reaches and segments. A segment consists of one or more reaches. Streamflow is accounted for by specifying inflow for the first reach that enters the active model area and then computing streamflow to adjacent downstream reaches as equal to upstream inflow to the reach plus or minus leakage from or to the aquifer in the reach. Leakage is calculated for each reach based on the head difference between the stream and aquifer and a conductance term for the streambed. The stream stage in each reach is computed from the Manning formula under the assumption of a rectangular stream channel (Prudic, 1989).

The GMS pre- and post-processing program was initially employed to prepare model inputs and display the model results. Subsequently, the Groundwater Vistas post-processing program was used to prepare model results for display.

Model Area and Design

<u>Model Grid</u>

The cell grid, boundary of active cells, and active cell area used in the model are shown in Figure 19. The area within the grid boundary is 2,184 square miles and includes the Middle Arkansas subbasin plus an additional buffer area to the west of the southwest subbasin boundary. The grid is oriented in a southwest to northeast direction along the general direction of the Arkansas River valley and the regional ground-water flow in the High Plains aquifer (Figure 16). Each cell in the grid is a square (0.5 mile on a side) with an area of a quarter square mile. There are 52 rows and 168 columns, giving a total of 8,736 cells within the grid. The rows are ordered from north to south and the columns from west to east. The model has only one layer because

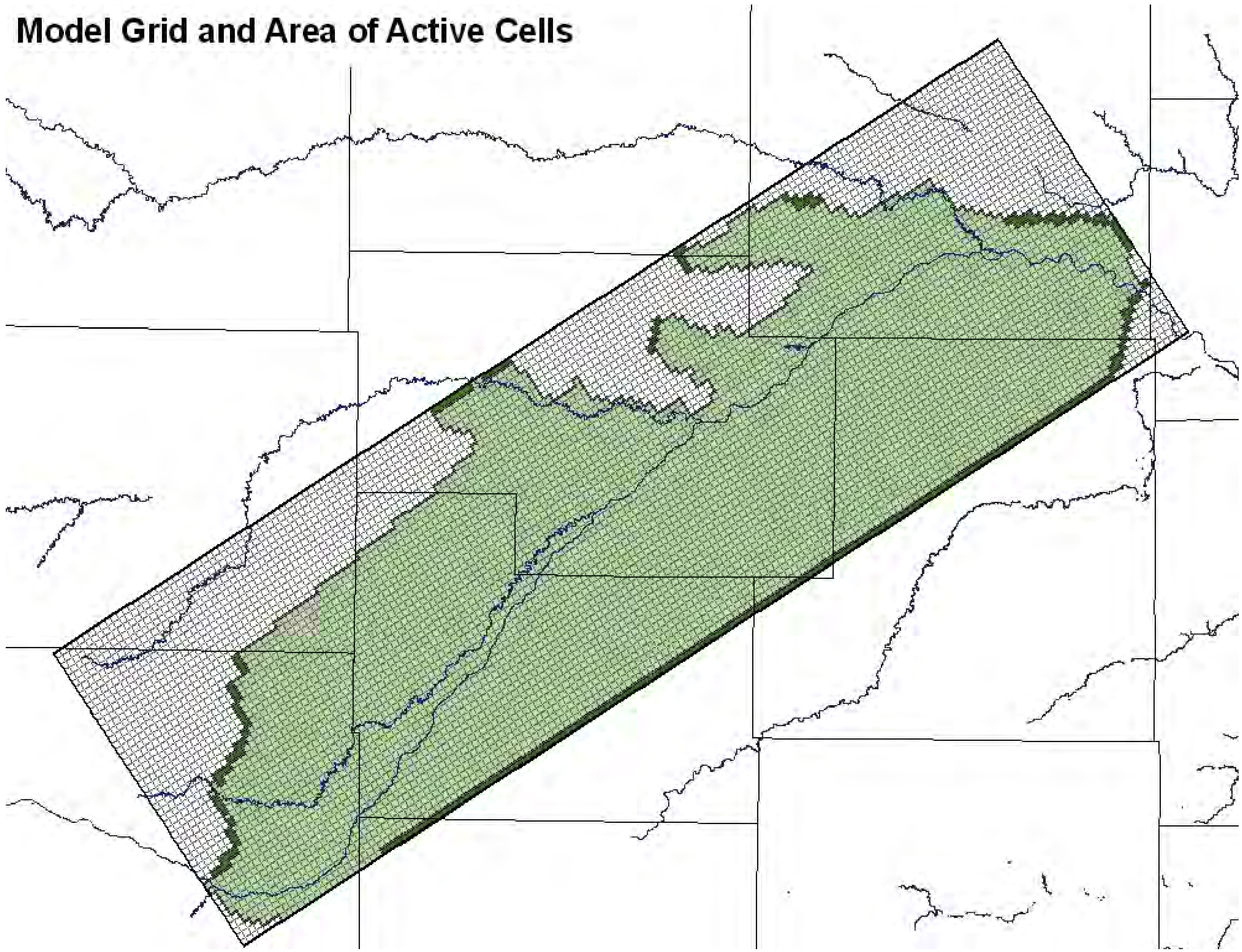

Figure 19. Cell grid, boundaries of active cells, and active cell area (light green) of the numerical model. The dark green shaded cells are specified head cells.

the difference between the alluvial aquifer and the main part of the High Plains aquifer is not sufficiently distinct across the model area to warrant a separation into two layers in the absence of a more extensive lithologic characterization.

Model Cell Boundaries

The number of active cells (cells in which calculations are performed) is 6,209. The definition of the active model area (1,552.25 square miles) was based on water-level contours for different periods and the hydrogeology in the Middle Arkansas subbasin. The boundaries for the active model area are discussed in this section.

The southwestern boundary of the model was chosen a distance upgradient of the southwestern boundary of the subbasin in a region where impacts of pumping have been relatively small. Water-level contours in eastern Ford County were found not to have changed substantially over time, so the southwestern boundary of the active model area was defined there as a constant head boundary.

The southern boundary of the model grid was selected to be at the edge of the protrusions of the southern boundary of the Middle Arkansas subbasin from northwest Kiowa County to north-central Stafford County. The southern boundary of the active model area used for the steady-state model did not extend completely to the southern grid boundary, but was extended to the southern grid boundary for the transient model. The southern boundary is defined as a time-varying constant head boundary (constant within a time step but can change between steps) to better represent the changing water levels produced by ground-water development in the vicinity of that boundary. The southwestern most part of the southern boundary was a flow-line (no-flow) boundary, and is in an area where there are no substantial water rights (pumping wells) to significantly impact that boundary.

The northern boundaries in the areas of the Pawnee River and Ash, Dry Walnut, and Walnut Creek valleys either coincide with the extent of the High Plains aquifer (see Figure 10) or the location of a stream gaging station. The northern boundary through southeast Hodgeman, northwest Edwards, and southwest Pawnee counties is along a ground-water flow line, and is thus defined as a no-flow boundary (there is no flow perpendicular to that flow line). The portions of the northern boundary north and northeast of that no-flow boundary are either defined as no flow (outcropping bedrock), or constant head. The eastern boundary across the Arkansas River valley parallels the water-level contours in that area (see Figure 16) and is defined as a time-varying constant head boundary.

Steady-State Simulation

In order to define the initial, equilibrium conditions for the transient model, a steady-state model was first developed for predevelopment conditions using a compilation of available ground-water levels and average climatic conditions for 1940-45. The steady-state model was also employed to zone and calibrate the model for initial recharge and hydrogeologic parameters for use in the transient model.

Model Characteristics

The steady-state model was developed for 1940-1945 because there is a considerable amount of water-level data for this period in KGS bulletins. The model incorporated zones for hydraulic conductivity, recharge, and evapotranspiration. The active streams in the model were the Arkansas River and its tributaries, the Pawnee River and Walnut Creek. The initial elevation of the streambeds was determined for each cell from USGS 7.5 minute topographic maps. Drains were incorporated to simulate ephemeral streams along Coon, Ash, and Dry Walnut creeks because no stream gaging stations exist on those creeks. The drain package uses two variables as input, drain elevation (land surface elevation) and streambed conductance. Water-level, precipitation, pumpage, and streamflow data for the region were used in the model computations.

As indicated previously and shown in Figure 10, there is little or no saturated thickness within the extent of the High Plains aquifer in areas of northeast Ford, southeast Hodgeman, northwest Edwards, and southwest Pawnee counties. In order to avoid the generation of dry cells, which can cause numerical instabilities, a minimum saturated thickness limit of 5 ft was defined for these areas.

There is relatively little information about hydraulic conductivity variations over the model area so a simple hydraulic conductivity zonation was utilized. Two zones were defined: one highly conductive zone along the Arkansas River valley, and another less conductive zone representing the rest of the model area. The effective hydraulic conductivity of the alluvial valley of the Arkansas River was defined as 160 ft/day, and that of the rest of the area as 110 ft/day. These values were based on an examination of values used in previous models of the High Plains aquifer in the region and on the calibration of the current model.

The evapotranspiration package uses three variables as input, land surface elevation, maximum evapotranspiration at the surface, and extinction depth (i.e. average root zone depth, 6 ft). The evapotranspiration decreases linearly from a maximum value at the surface to zero at the extinction depth. The zone for evapotranspiration computation was one model cell on either side of the Arkansas River, giving a total width of one mile.

Recharge Estimation Methodology

The definition of the spatial and temporal variations in recharge is often one of the more difficult tasks for a numerical modeling investigation. The recharge zonation used in the steady-state model in this study is based on a combination of the following four components:

a) A multiple regression equation for recharge estimation that is a function of total annual precipitation, soil-profile available water capacity, and spring-time average shallowest depth to water (Table 2). The derived multiple regression equation was based on detailed storm-by-storm data collection from 1985 to 1993 at a number of sites throughout the Big Bend Groundwater Management District 5 (GMD5) region, which encompasses the model study area. Sophocleous (1992) noted a threshold precipitation value of approximately 15 in/yr, below which no noticeable recharge takes place in the region. Figure 20 shows the cell-by-cell recharge values calculated with the regression equation

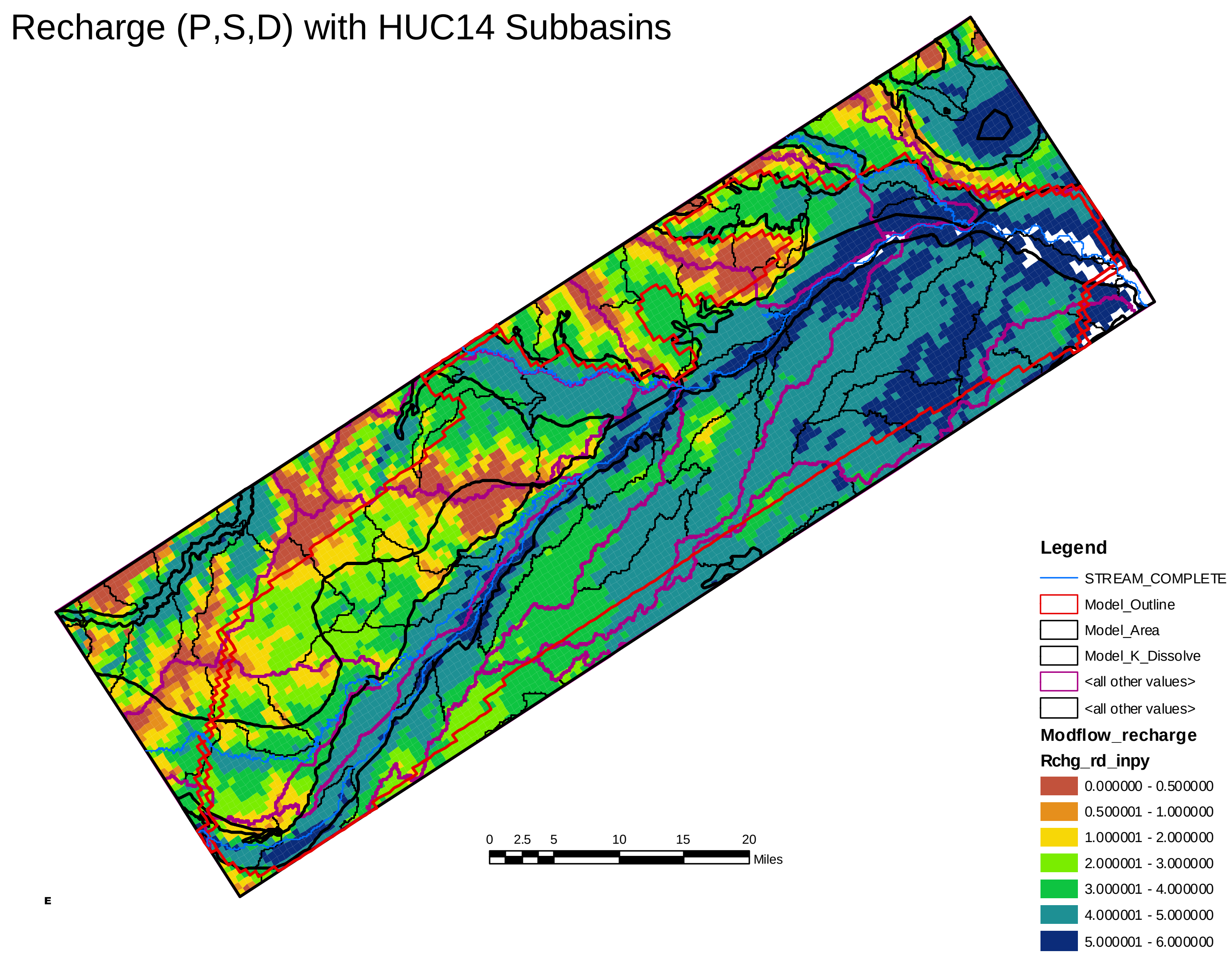

Figure 20. Cell-by-cell recharge values based on the recharge regression equation of Sophocleous (1992).

using predevelopment (steady-state) conditions (1940-45 average precipitation) in the study area.

b) Topographic subbasins based on the USGS Hydrologic Unit Code (HUC) basins (HUC11 and 14), as shown in Figure 20.

c) Land-use cover based on Landsat Thematic Mapper images, as shown in Figure 21.

d) The geology and hydrogeologic conditions of the study area, with special attention paid to areas of bedrock outcrops, limited saturated thickness, and unsaturated areas (Figure 22).

The resulting recharge zonation map used in the steady-state model based on precipitation, soil properties (available water capacity), depth-to-water, HUC basins, land cover, and hydrogeology is shown in Figure 23.

Table 2. Recharge Regression Equation (from Sophocleous, 1992)

$$R = -9.3727 + 0.2459\,PCPt - 0.0819\,Smax - 5.2387\,WLmax \qquad \text{MultR***}=86.95\%$$

(34.2)** (33.1809)* (0.0396)* (0.0267)* (1.7663)*

Explanation of variables:

R is the annual recharge (mm),
PCP_t is the total annual precipitation (mm),
S_{max} is the average maximum soil-water storage (mm) in the upper 2.75 m of the soil profile for the recharge season (spring), and
WL_{max} = average shallowest depth to water table (m) for the recharge season (spring).

* standard error of the regression coefficients (mm)
** standard error of the recharge estimate (mm)
***MultR = multiple correlation coefficient

Model Calibration

The general process of model calibration involves adjusting the values of selected input parameters (for example, recharge, hydraulic conductivity, stream width and conductance) within plausible ranges for the sediments of the area in order to improve the match between field-observed and model-calculated ground-water levels. For the steady-state model, the model was calibrated in a sequential fashion by fixing one set of parameters (e.g., hydraulic conductivity) and adjusting the others until a reasonable agreement between measured and calculated predevelopment water levels was achieved. Because of uncertainties in streambed elevations, they were also adjusted during the calibration process to further improve the agreement.

Transient Simulation

The transient model was run for a 61-year stress period (1944-2004) using many of the characteristics of the steady-state model. The variables that change in time were appropriately

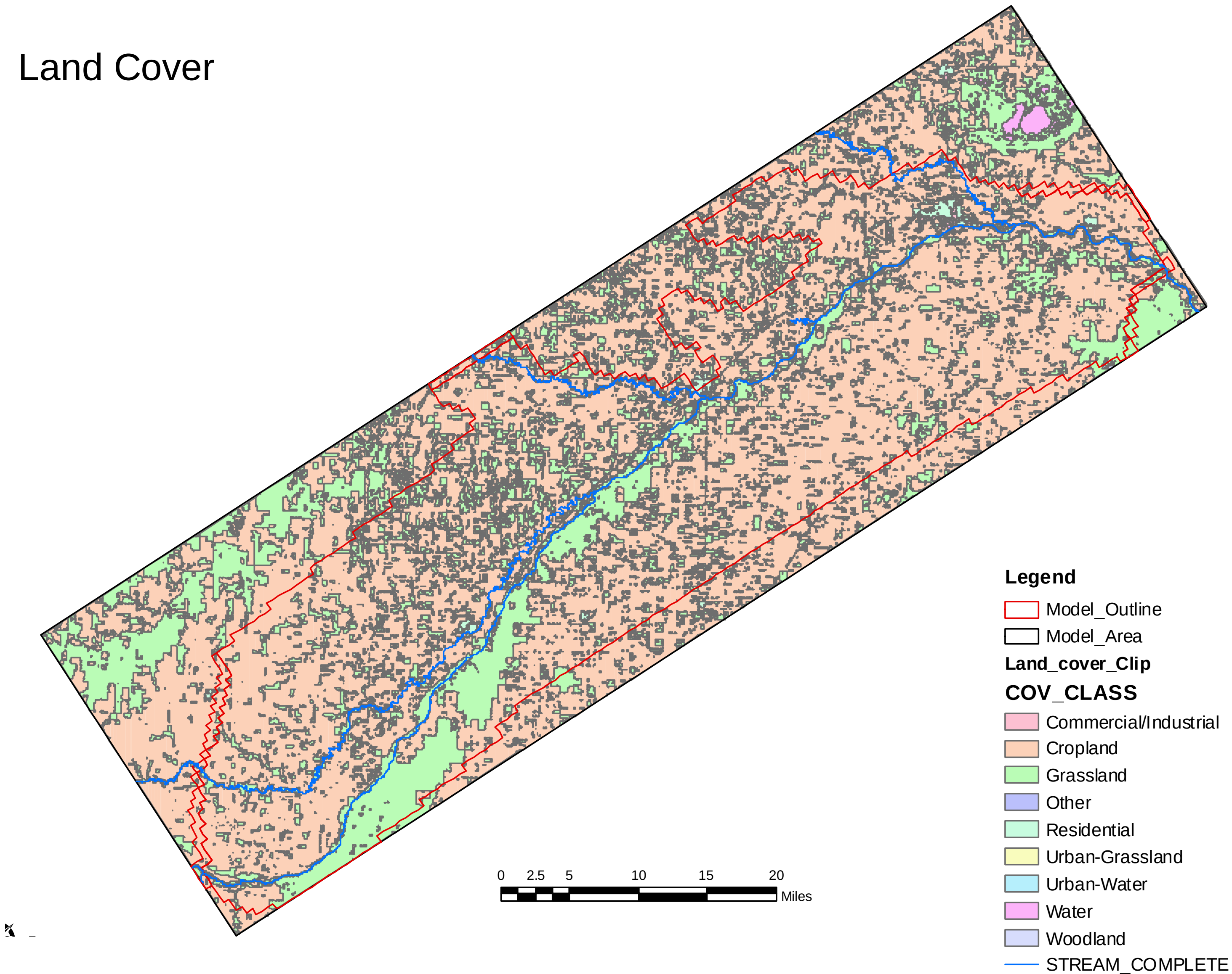

Figure 21. Land-use cover based on Landsat Thematic Mapper images and used in the recharge estimation methodology.

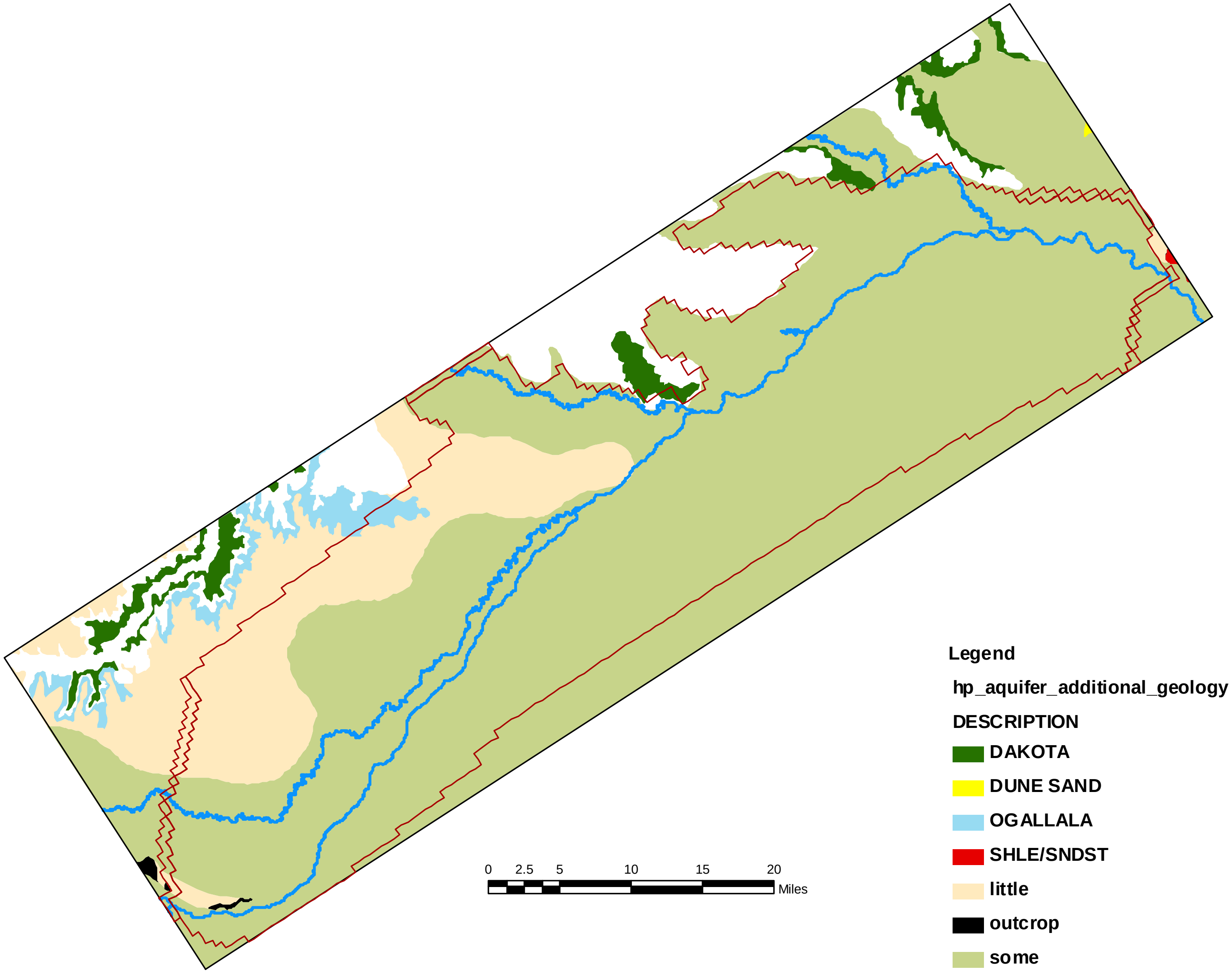

Figure 22. Geologic and hydrogeologic conditions within the model grid area used in the recharge estimation methodology. In the legend, “little” refers to little or no saturated thickness and “some” refers to the main part of the High Plains aquifer.

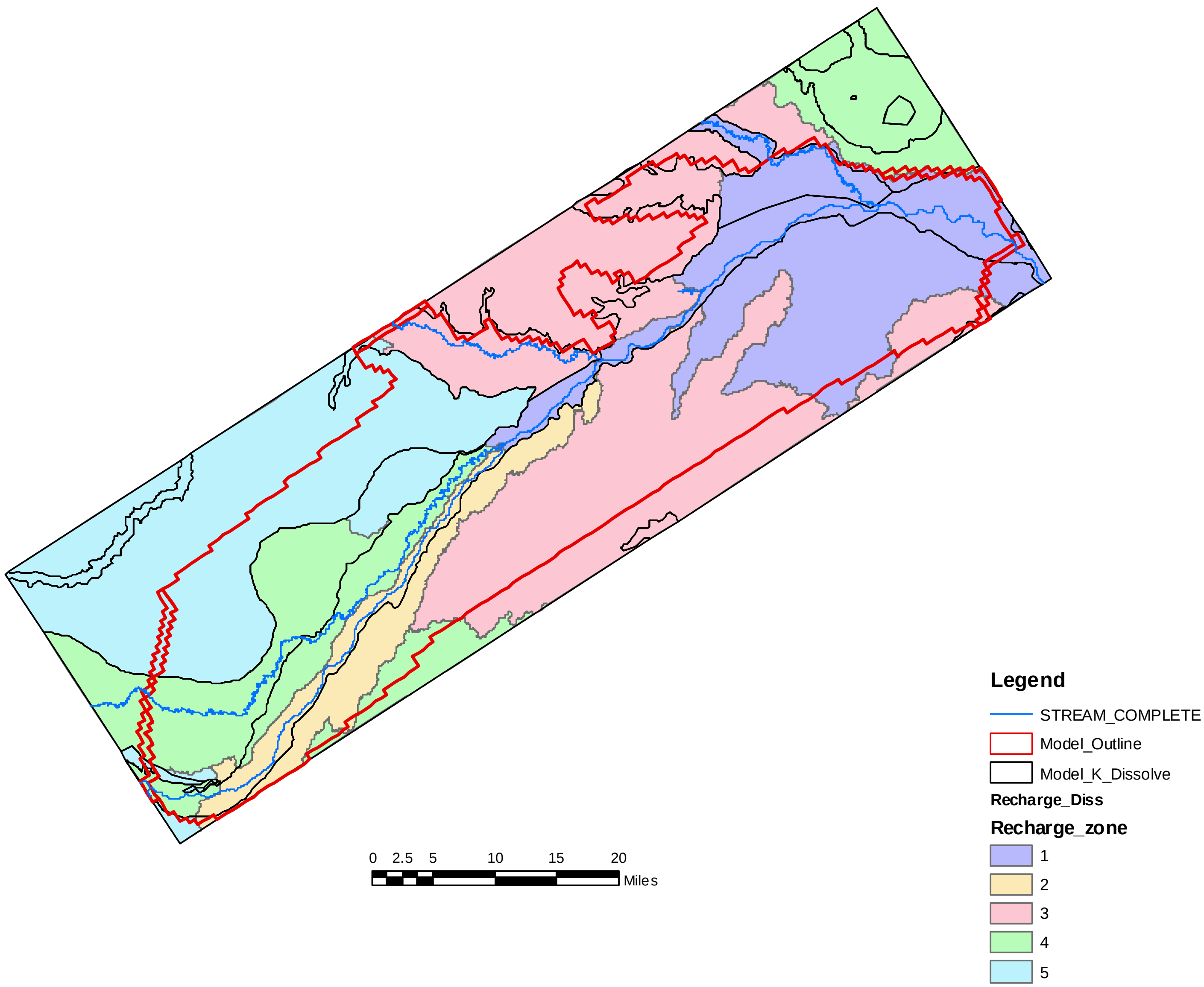

Figure 23. Recharge zones used in the steady-state model. See Figure 2 for the recharge zones used in the transient model.

modified for the transient modeling. The ground-water level data for the transient period were extracted from the KGS WIZARD database.

Model Boundaries

Time-varying specified-head boundaries were used for many portions of the active model boundaries. The time-varying heads for the southern and eastern boundaries were the average head for every few to several years for the pre-1970 period and annual values for 1970-2004. Due to the limited data for certain periods in the area along the southern boundary in the northeast part of the model and along the east boundary, the interpolated water-level surface along sections of the boundaries was above or very close to the land surface for some years. This occurred where there are valleys or depressions in the land surface. Available water-level records were closely examined and a long-term hydrograph from a well in the northeast corner of the model area was selected as a surrogate for annual water-level fluctuations. The annual variations in this hydrograph were used to adjust the time-varying heads for the locations along the boundary where the interpolated water levels were above or very close to the land surface. The adjustment also considered the annual variations in the time-varying heads along the adjacent parts of the boundary where the water levels were below the land surface. This not only produced depths-to-water that were more realistic along the boundary but also that followed the relative water-level variations that occurred in the general area.

Hydraulic Conductivity and Specific Yield

The two hydraulic conductivity zones used in the steady-state model were further refined during the transient model calibration process with the result that four hydraulic conductivity zones were defined (Figure 24): bedrock area and thinly saturated High Plains aquifer (50 ft/day), side alluvial valleys (80 ft/day), main High Plains aquifer area (120 ft/day), and the alluvial aquifer and underlying High Plains aquifer in the Arkansas River valley (160 ft/day). A specific yield of 0.22 was used throughout the model area for the transient runs.

Precipitation- Recharge Relationships

The final recharge zonation used in the transient model is shown in Figure 2. During calibration of the transient model, the recharge zones of the steady-state model were modified. Recharge zones 4 and 5 in the steady-state model (Figure 23) were combined into one zone (zone 4 in Figure 2), zone 1 north of the Arkansas River was split into two zones (zones 1 and 7 in Figure 2), the portion of zone 4 south of zone 2 was combined with zone 3, and the portion of zone 3 in the northeast part of the active model area and along the southern model boundary was combined with zone 1. The general characteristics of each recharge zone are as follows:

Zone 1, northeast part of the main High Plains aquifer in the model area, nearly flat lying area with gently sloped fine sand dunes and silt at the surface with thick soils,

Zone 2, upper Arkansas River valley, sandy alluvium along the river, sand dunes with moderate to steep slopes and thin developed soils away from the river.

Zone 3, southwest and middle part of the main High Plains aquifer in the model area, nearly flat lying area with gently sloped fine sand dunes and silt at the surface with thick soils,

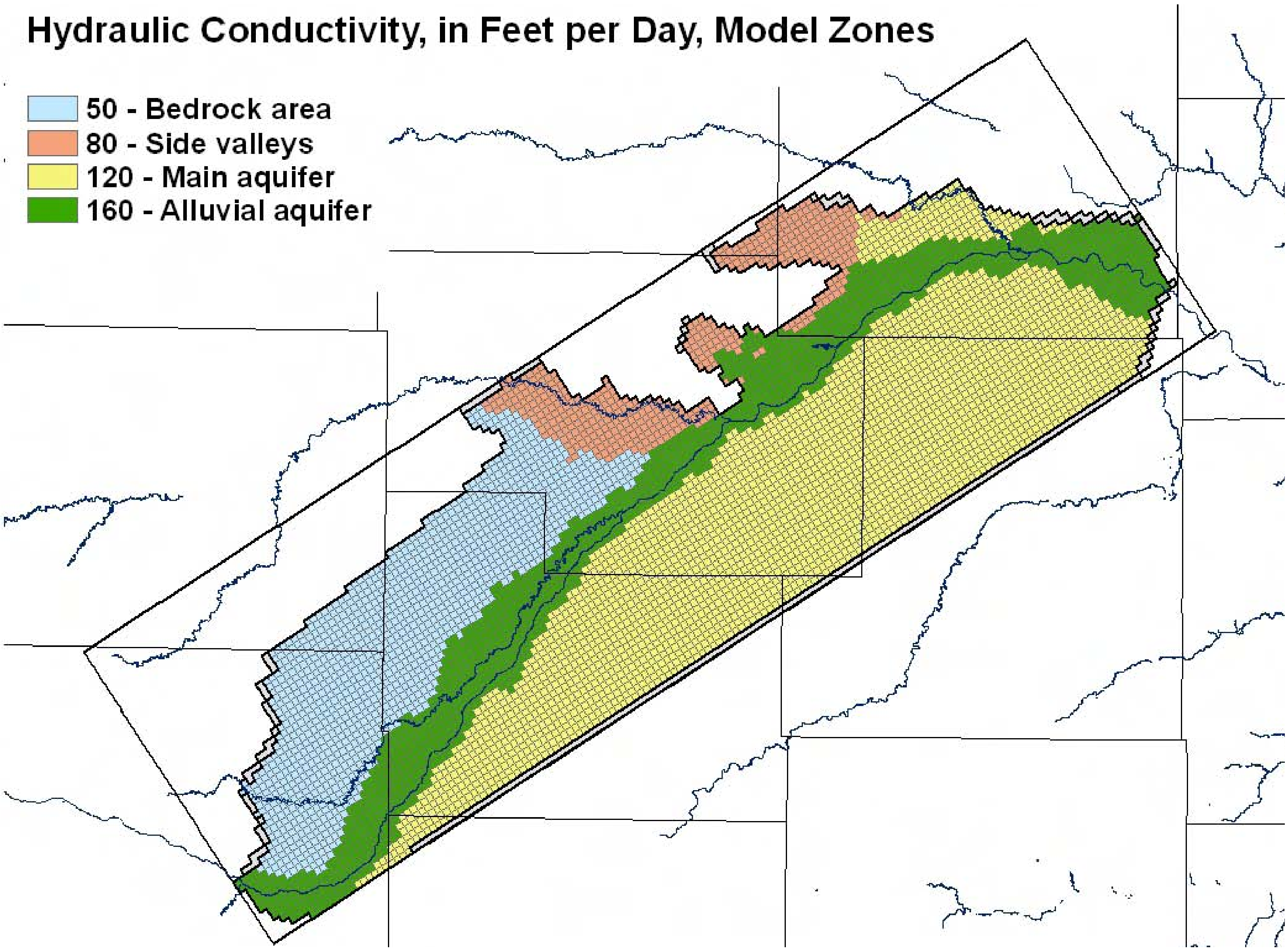

Figure 24. Hydraulic conductivity zones used in the transient model.

Zone 4, bedrock and terrace deposits area with some thinly saturated High Plains aquifer, terrace deposits principally composed of silt and clay at the surface,
Zone 6, tributary valleys on the north side of the Arkansas River – Pawnee River, Ash Creek, and Dry Walnut Creek upstream of the Arkansas River valley, fine-grained alluvium at and near the surface,
Zone 7, lower Arkansas River valley, sandy alluvium along the river, nearly flat lying area away from the river with gently sloped fine sand dunes and silt at the surface with thick soils,

Segmented linear relationships between recharge and precipitation were used during calibration of the transient model. The segments were adjusted to further minimize the mean residuals (difference between observed and simulated water level) for 1980, 1990, 1995, 2000, and 2004. The segmented recharge functions used in the final calibrated model for each zone are shown in Figure 25. The segmented recharge curves show a break point at a precipitation below which there is essentially no recharge, then show increasing recharge with increasing precipitation until a point is reached when the recharge rate (slope of recharge curve) remains constant or decreases as a result of soil saturation and increasing runoff. The optimized recharge-precipitation relationships (obtained using the parameter estimation program PEST [Doherty, 2004]) were used to calculate recharge during the transient runs for all model grid cells in each recharge zone based on the average annual precipitation for each recharge zone.

The recharge estimated by the linear segments (Figure 25) for recharge zones 1, 3, and 7 for low to average annual precipitation for the study area is similar to that based on 1985-1993 values (Figure 26) estimated from measurements at four recharge sites close to the study area (sites 1, 2, 3, and 5 of Sophocleous [1992, 1993, 2000] and Sophocleous et al. [1996]). At higher annual precipitation, the linear segments for these three recharge zones estimate a higher rate of recharge than in Figure 26. The lower recharge estimated by the linear segments for recharge zones 4 and 6 compared to Figure 26 is expected because the soils and sediments are generally less permeable in these zones than in the main aquifer area of GMD5 where the recharge sites are located. The substantially greater recharge estimated by the linear segments for recharge zone 2 for most of the precipitation range compared to Figure 26 is also expected due to the high permeability of the river valley and sand dune deposits in that area.

Stream Characteristics

There are 11 stream segments in the transient model:

1-2) Arkansas River from the western model boundary to the confluence with Coon Creek,
3) Coon Creek from the western model boundary to the confluence with the Arkansas River (Coon Creek was converted from a drain in the steady-state model to a stream in the transient model),
4) Arkansas River from the confluence with Coon Creek to the confluence with the Pawnee River
5) Pawnee River from the northern model boundary to the confluence with the Arkansas River,

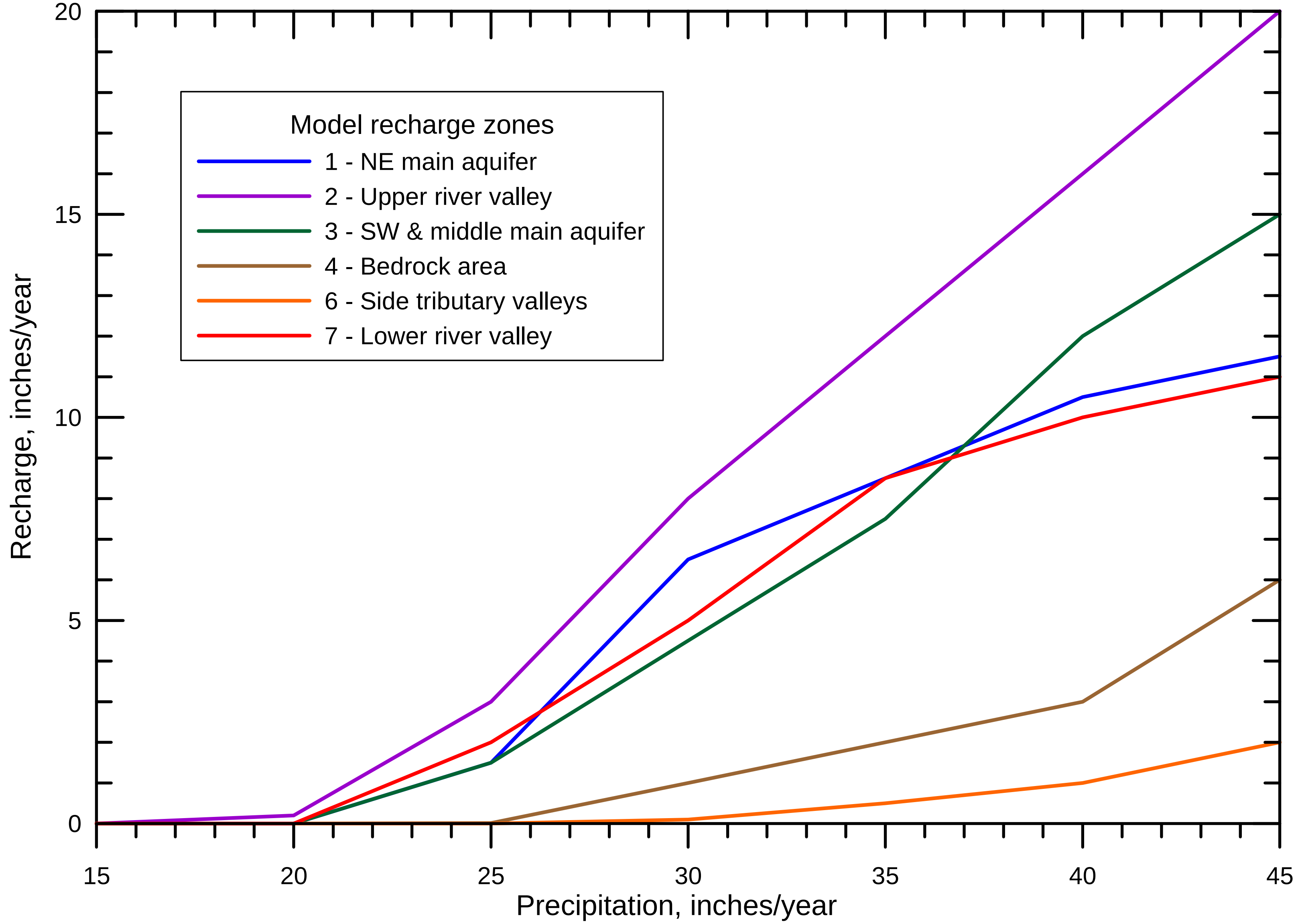

Figure 25. Segmented recharge-precipitation relationships for model recharge zones used in the final transient model.

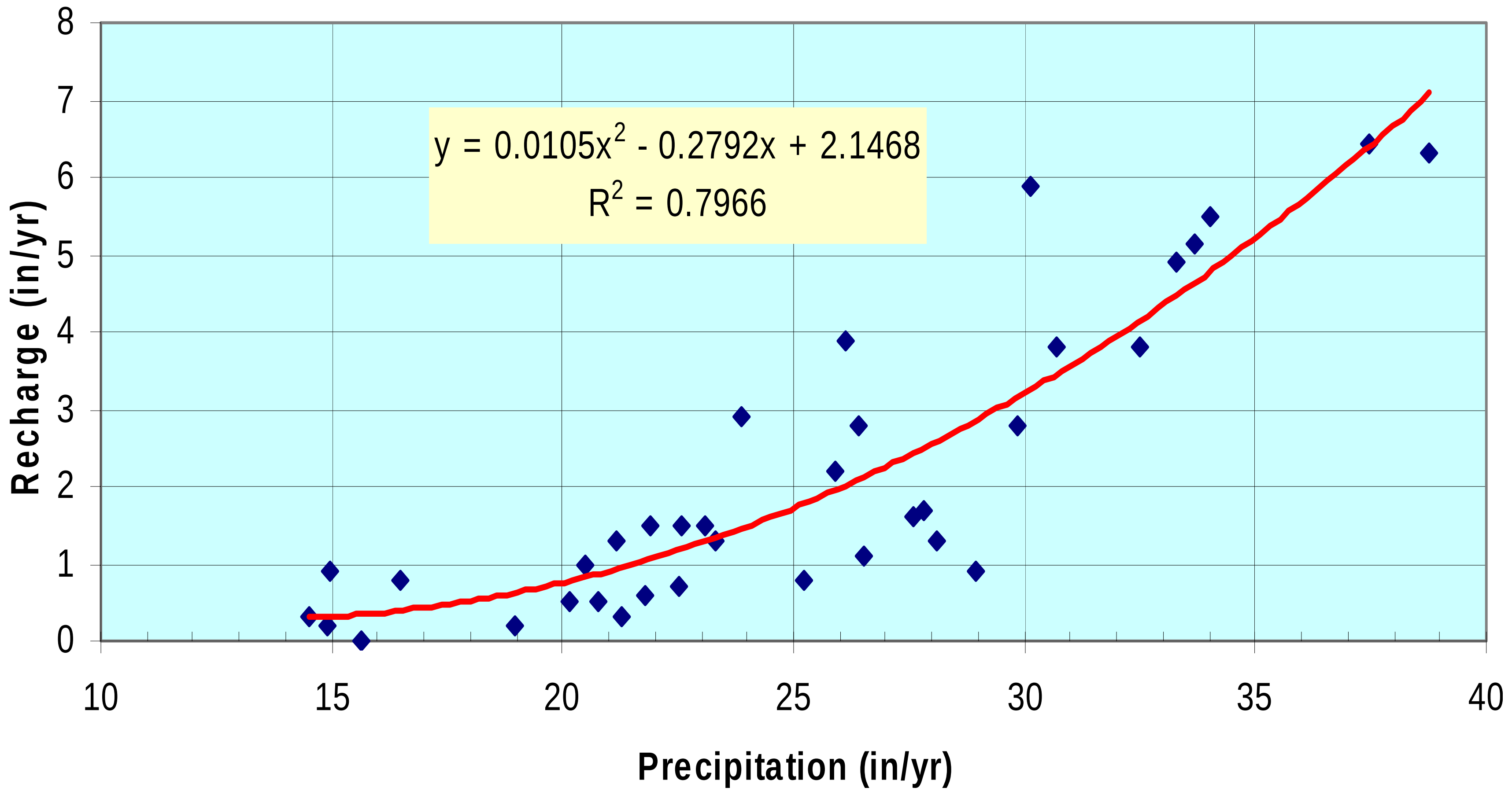

Figure 26. Recharge-precipitation relationship based on measurements of Sophocleous (1992, 1993, 2000) and Sophocleous et al. (1996) at recharge sites located in the area of the High Plains aquifer in Big Bend Groundwater Management District No. 5.

6) Arkansas River from the confluence with the Pawnee River to the confluence with the Ash Creek drain,
7) Arkansas River from the confluence with the Ash Creek drain to the Dundee diversion,
8) Dundee diversion
9) Arkansas River from the Dundee diversion to the confluence with Walnut Creek,
10) Walnut Creek from the northern model boundary to the confluence with the Arkansas River,
11) Arkansas River from the confluence with Walnut Creek to the eastern model boundary.

The USGS gage station near Kinsley is located in reach 86 of stream segment 2, the station near Larned is in reach 20 of segment 6, and that at Great Bend is in reach 21 of segment 9.

The model was optimized for stream width and conductance during the calibration process using PEST. The streams are simulated as rectangular channels with an underlying streambed. A streambed width of 131 ft (40 m) was used, which is approximately the current width of the entrenched Arkansas River channel observed in the stretch of the river upstream and downstream of the USGS gaging station near Larned. An estimated streambed thickness of 3.28 ft (1.0 m) and a hydraulic conductivity of the streambed of 1.31 ft/day (0.4 m/day) were used.

As described in the earlier section on channel elevation change, the channel of the Arkansas River became entrenched through time due to flow reduction related to upstream regulation and diversions. A two-step entrenchment was used in the transient model. The streambed elevations for the steady-state model were used for the stress period 1944-1954. For 1955 to 1964, the elevation of the streambed of the Arkansas River channel was lowered by 1.64 ft (0.5 m) from the western boundary to the confluence with the Pawnee River, by 3.28 ft (1.0 m) at Great Bend, by a linear function related to the stream reach lengths between the confluence with the Pawnee River and Great Bend, by 1.64 ft (0.5 m) from the confluence with Walnut Creek to the eastern model boundary, and by a linear function related to the stream reach lengths between Great Bend and the confluence with Walnut Creek. For 1965 to 2004, the elevation of the Arkansas River streambed was lowered by twice the amount for the 1955-1964 period, giving a total of 3.28 ft (1.0 m) along most of the river channel, 6.56 ft (2.0 m) at Great Bend, and entrenchment values from 3.28 ft (1.0 m) to 6.56 ft (2.0 m) between the confluence with the Pawnee River and Great Bend, and between Great Bend and the confluence with Walnut Creek. The values used for the entrenchment were derived from an examination of the streambed elevations used in the steady-state model, the channel elevations of the Kinsley, Larned, and Great Bend gaging stations on USGS 7.5 minute topographic quadrangles, the date of the quadrangle survey, the construction of John Martin Reservoir in the early 1940s, and field observations of the channel morphology in different parts of the subbasin.

<u>Streamflow</u>

The input streamflow for the Arkansas River at the western boundary was calculated using an interpolation of the mean annual flows recorded at the USGS gaging stations at Dodge City and near Kinsley. The interpolation was based on the river channel length between the Dodge City and Kinsley gages. The channel distance between the model boundary and the

Kinsley gage is 0.642 of the total distance between the two gages. Thus, 0.642 of the difference between the annual flows at the two gages was subtracted from the flow at the Kinsley gage to give the annual flow at the boundary. The inflows for the Pawnee River and Walnut Creek at the model boundaries were the annual flows recorded at the USGS gaging station at Rozel and Albert, respectively. The boundary inflow for Coon Creek was estimated from the size of the watershed outside the boundary and the stream discharge and watershed area relationships for different parts of Kansas based on data in a USGS report (Perry et al., 2004). A value of 1.6 ft^3/sec was used for the mean annual inflow of the creek.

Dundee Diversion

The Dundee diversion is described in a previous section. Data for the annual diversions from the Arkansas River were provided by the DWR. The diversion flow was removed from the Arkansas River at stream segment 8 in the transient model. The diverted water is piped approximately a mile and a half to the other side of Highway 56 east of Dundee. Another pipe carries the water from Dry Walnut Creek to Walnut Creek. No seepage was simulated for these transfer pipes. Seepage from the unlined portions of the diversion canal and sections where the water flows through Dry Walnut and Walnut creeks was simulated by injection wells within the cells crossed by the canal and the creek beds. The seepage used as recharge (well injection) for the unlined canal and streambeds was calculated as 1% of the annual diversion flow per mile of canal or streambed. Water is diverted from Walnut Creek to Cheyenne Bottoms at a location along the northern model boundary in south-central Barton County. The total seepage loss of the diverted Arkansas River flow within the active model area was 14.9%.

Ground-Water Pumpage

Pumping data were obtained from self-reported water use records that are submitted annually to the DWR and stored in the Water Rights Information System (WRIS) database. Water use reports may go back as far as 1958. However, reports were not required to be submitted to the DWR until the early 1980s, administrative enforcement of the requirement began in the late 1980s, and 1990 was the first year that the water-use data underwent a quality control and assurance program (originally administered by the KWO and now by the DWR). At the time of the model development, 2003 was the latest year for which data had undergone this quality control process. Water use reports from 1990 to 2003 were used to summarize total ground-water and total irrigation ground-water pumpage.

For the time period 1944 to 1989 and the year 2004, linear regression equations were used to calculate total ground-water and irrigation ground-water pumpage. The regression equations are based on the relationships between the ratio of average reported water use to average authorized annual quantity, and the average annual precipitation from 1990 to 2003, as explained below.

The WRIS database stores only the present day authorized annual quantity for water rights. Quantity summaries are based on water-right conditions as of March 21, 2005 and are assumed representative of past conditions. Based on the priority date for each water right in the model area, the annual authorized quantities were summarized by total ground-water and irrigation ground-water appropriations for each year from 1944 to present and then averaged over the model area for the development of the regression equations. Vested water rights, those water rights that have been in use before the 1945 Kansas Water Appropriation Act was established, were assigned a priority year of 1944.

The linear regression equations for total ground-water and irrigation ground-water pumpage are as follows:

$$WUSE/QTYt = 1.08687 + PCPa * -0.02408 \qquad R^2 = 0.768$$

$$WUSE/QTYi = 1.11703 + PCPa * -0.02525 \qquad R^2 = 0.771$$

where *WUSE/QTYt* is the average water use over average authorized quantity ratio,
WUSE/QTYi is the average irrigation water use over average authorized quantity ratio, and
PCPa is the average annual precipitation.

Based on the regression equations, the ratios of water use/authorized quantity were calculated from 1944 to 1989 and the year 2004. The ratios were multiplied by the annual authorized quantity to establish total ground-water and irrigation ground-water pumping amounts (Figure 27). The irrigation pumping amounts were then adjusted for irrigation return recharge for use as net pumpage in the model, as explained next.

Irrigation Return Recharge

The amount of recharge from irrigation water applied on fields was calculated using data for the distribution of irrigation system types in the Middle Arkansas subbasin, irrigated land acreage in Kansas, the beginning date of center pivot use, and estimates of recharge percentages for system types. The percentage of irrigation return recharge was calculated for each year of the 1945-2004 model period for three different zones in the active model area based on county data: the southwest (Ford and Kinsley counties), the middle (Pawnee County), and the northeast (Barton and Stafford counties). The values used for the recharge return by irrigation type were 25% for flood irrigation, 9% for center pivots with impact (top) nozzles, and 7% for center pivots with drop nozzles. Center pivot irrigation was estimated to have begun in the model area in 1955 and drop nozzles were used starting in 1988. The irrigation return flow for 1945 to 2004 decreased from 25% to 7.8% for the southwest, 9.4% for the middle, and 10.9% for the northeast zones. The average percentage for irrigation return recharge for the model area in 2004 was 9.48%. Additional information on the calculations is available on the TAC model web site.

Model Calibration and Verification

One of the most important steps in setting up a ground-water model is model calibration. Development of a computer model as a reliable simulator is based on the premise that if historic hydrologic phenomena can be satisfactorily approximated by the model, then so should future conditions. Calibration involves determining the magnitude and spatial distribution of the model parameters that reproduce the observed states (for this study, hydraulic heads and streamflows)

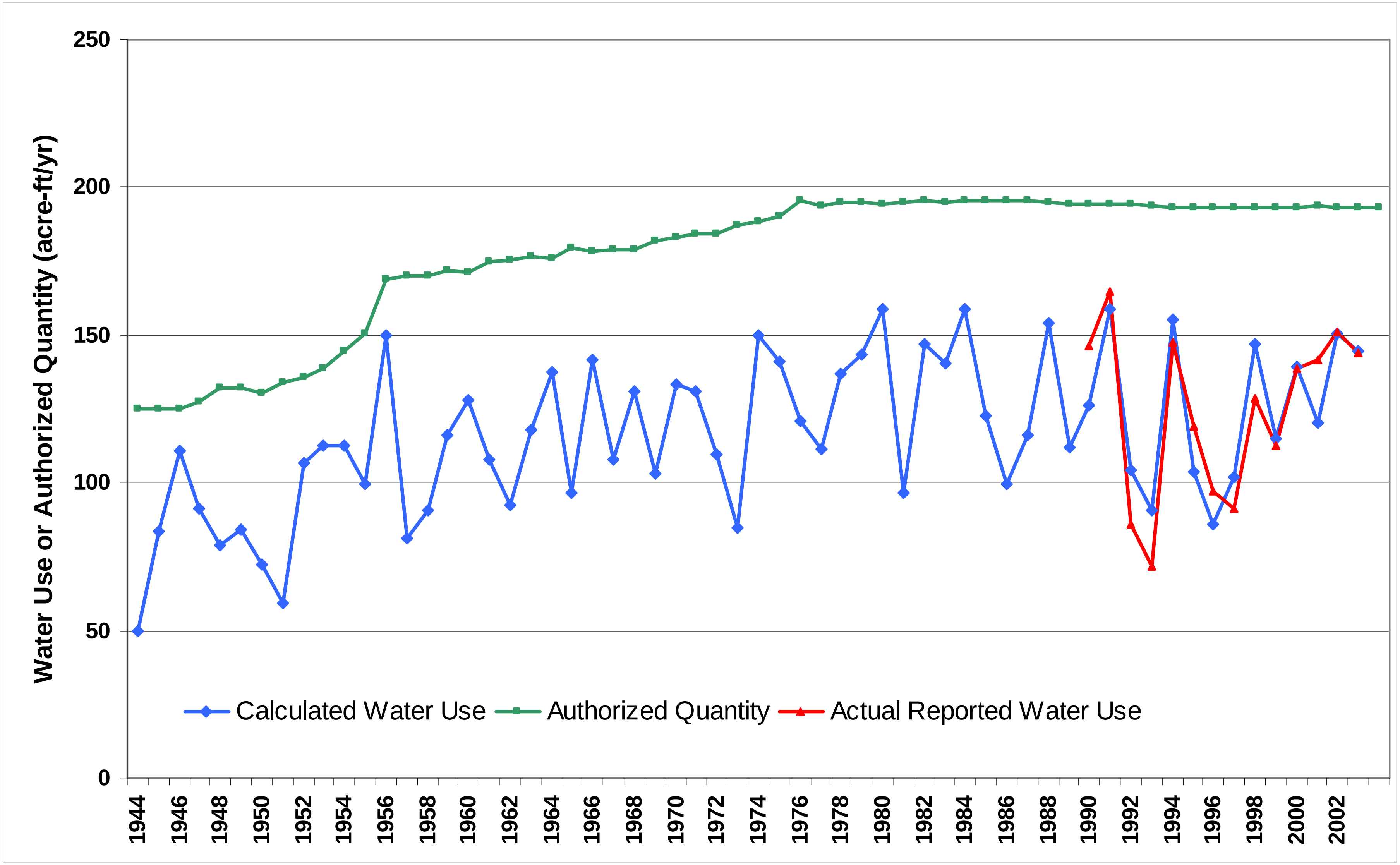

Figure 27. Comparison of average regressed water use and average actual reported water use.

with time. To assist in calibration, a parameter optimization package known as PEST (for Parameter ESTimation; Doherty, 2004) was used.

The historic ground-water levels for the target years of 1980, 1990, and 2000 were selected as target data for the transient calibration. In addition, 26 wells with long-term well hydrographs, spread throughout the active model area (Figure 2), were selected as target hydrographs to ensure that the model also reproduces the observed trends in water levels in a satisfactory manner. The observed annual streamflows at the Kinsley, Larned, and Great Bend stream gaging stations were also used as calibration targets for the simulated streamflows. The streamflows were log transformed and then weighted by a factor of two so that the large fluctuations in streamflow were not the primary control on the calibration process. The parameter estimation program PEST was employed to optimize parameters during the calibration process.

After a set of calibrated parameters was obtained, the final model was run with 1.25 times the recharge in zones 1 and 7 for the years 1993 and 1998 to reduce the change in the mean residual during the period 1980-2004. An increase in recharge in these two years was needed to make the water level rises in a few computed hydrographs in the northeast portion of the active model area closer to the observed rises for these years.

Model verification is the process of demonstrating that the calibrated model is an adequate representation of the physical system (Anderson and Woessner, 1992). Given that the model calibration was performed with relatively sparse data in some locations and for a certain set of boundary conditions and hydrologic stresses, the set of calibrated parameter values may not be appropriate for modeling the system under all possible conditions. Model verification helps establish greater confidence in the calibration by comparing model results with observed data for time steps other than those used as calibration targets. This permits an additional verification of model performance. In this study, model verification consisted of comparing calibrated model results for the years 1995 and 2004 with the observed data for those years.

The mean and mean absolute residuals for the target and verification years are listed in Table 3. The mean residuals are given as measured minus simulated values. The mean residuals for all of the individual target and verification years are less than 1.0 ft, and the average mean residuals for the target and verification years are both less than 0.5 ft. The mean absolute residuals are all less than 3.8 ft except for 1980, which is 4.07 ft. The number of water-level measurements for the active model area is substantially smaller for 1980 (64 values) than for the other years (1990 – 112, 1995 – 102, 2000 – 138, and 2004 – 136). The relative mean absolute error, which is the mean absolute residual divided by the maximum difference in observed water-level elevation across the active model area times 100, is 0.63% or less for all target and verification years except for 1980, which is 0.71%. The average relative mean absolute error for 1980, 1990, and 2000 is 0.61% and that for 1995 and 2004 is 0.62%. This indicates that the errors in the model are quite small compared to the total head loss of 598 ft in the observation wells across the active model area. The mean absolute residual for the simulated and observed hydrographs is 3.4 ft (Table 3).

Table 3. Mean and mean absolute residuals (difference between observed and simulated water levels).

Residual or error	Value
Mean residual 1980	-0.94 ft
Mean residual 1990	-0.81 ft
Mean residual 1995	0.07 ft
Mean residual 2000	0.11 ft
Mean residual 2004	0.91 ft
Change in mean residual 1980 to 2000	1.04 ft
Change in mean residual 1980 to 2004	1.85 ft
Change in mean residual 1995 to 2004	0.84 ft
Mean absolute residual 1980	4.07 ft
Mean absolute residual 1990	3.48 ft
Mean absolute residual 1995	3.58 ft
Mean absolute residual 2000	3.55 ft
Mean absolute residual 2004	3.73 ft
Mean absolute residual for hydrographs	3.43 ft

Figure 28 is a comparison of the simulated versus observed water-level elevations for the three target years, the straight line is for a one-to-one relationship. Figure 29 is the residual plot for these same target years. Most of the differences are less than 6 ft and nearly all of the differences are less than 12 ft. Only eight out of the 314 residual values are greater than 12 ft, with a maximum of 17.1 ft. The mean absolute residual for the simulated and observed hydrographs is 3.4 ft (Table 3).

The agreement between the observed and annual streamflow for the Arkansas River at the Kinsley, Larned, and Great Bend gages is relatively good (Table 4). The mean and mean absolute residuals (differences between the observed and simulated flows) calculated for low flows in the Arkansas River at Kinsley and Great Bend are relatively small (Table 4), particularly when considering that a change in river stage of only 0.1 ft results in a flow change of about 13 ft^3/sec in the model stream channel (width of 131 ft) for a flow velocity of approximately 1 ft/sec. The record for Larned is too short (1998-2004) for a meaningful residual calculation.

Sensitivity Analysis

Sensitivity analysis is an approach for assessing the impact of uncertainty on modeling results that involves analyzing the sensitivity of the computed results to perturbations in the model parameters (Anderson and Woessner, 1992). If the model results are sensitive to a parameter perturbation, then that parameter needs to be estimated as reliably as possible. The influence of a number of key parameters on the simulation results was examined in this project.

The most sensitive parameters were found to be ground-water recharge and ground-water pumping. The next most sensitive parameters were hydraulic conductivity, streambed elevation,

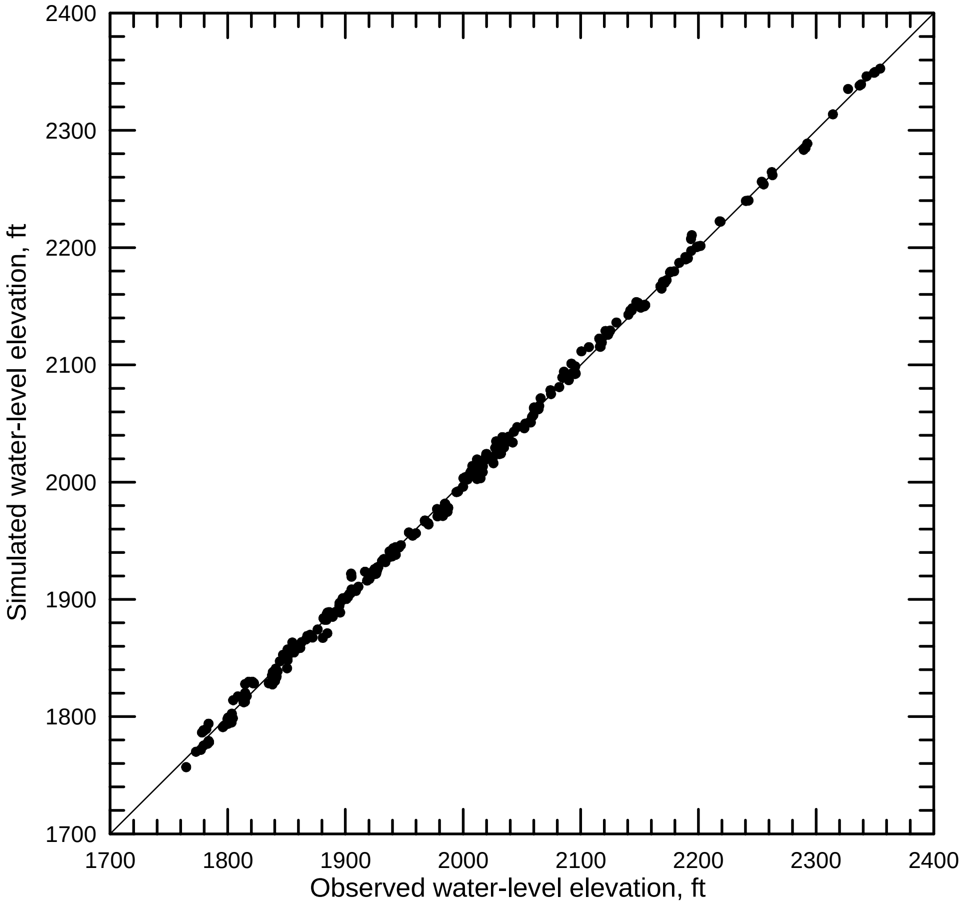

Figure 28. Simulated versus observed water-level elevations for 1980, 1990, and 2000.

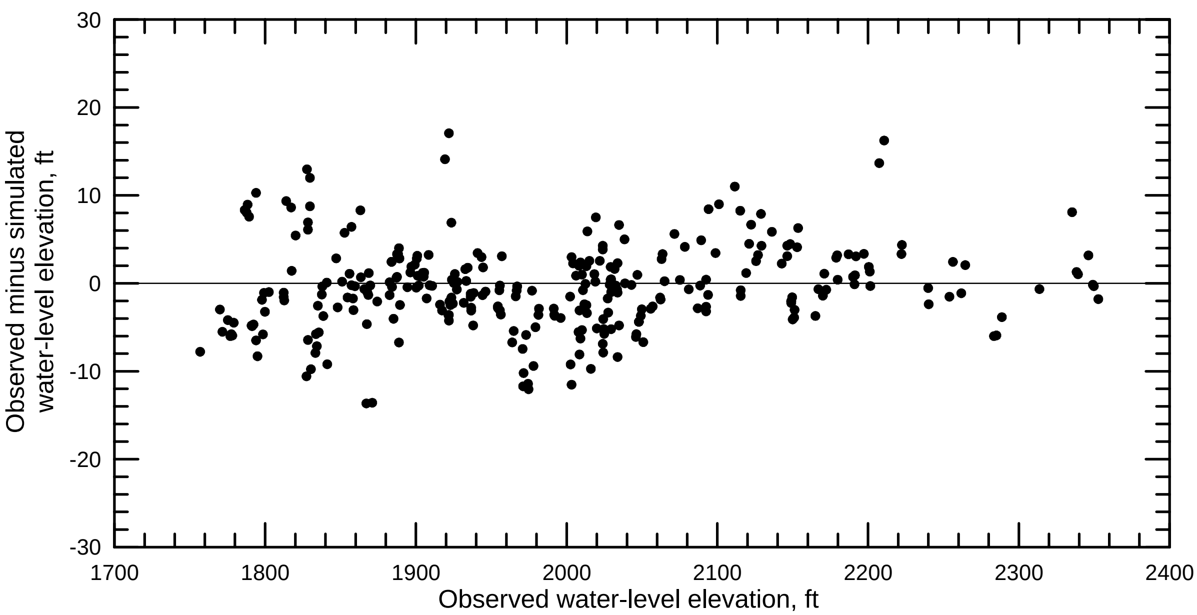

Figure 29. Differences between observed and simulated water-level elevations for 1980, 1990, and 2000.

Table 4. Correlation between observed and simulated flows, and mean and mean absolute residuals calculated using observed and simulated flows in the Arkansas River.

Correlation or residual	Value
Observed versus simulated flow, Kinsley	R^2 = 0.983
Observed versus simulated flow, Larned	R^2 = 0.981
Observed versus simulated flow, Great Bend	R^2 = 0.948
Mean residual for observed flow <40 ft^3/sec, Kinsley	5.0 ft^3/sec
Mean residual for observed flow <40 ft^3/sec, Great Bend	12.1 ft^3/sec
Mean absolute residual for observed flow <40 ft^3/sec, Kinsley	6.1 ft^3/sec
Mean absolute residual for observed flow <40 ft^3/sec, Great Bend	13.2 ft^3/sec
Mean residual for observed flow <10 ft^3/sec, Kinsley	0.25 ft^3/sec
Mean residual for observed flow <10 ft^3/sec, Great Bend	2.0 ft^3/sec
Mean absolute residual for observed flow <10 ft^3/sec, Kinsley	1.2 ft^3/sec
Mean absolute residual for observed flow <10 ft^3/sec, Great Bend	3.7 ft^3/sec

and stream conductance. Model results were found to be relatively insensitive to storativity and Manning's roughness coefficient. As a result, particular effort was made in checking and refining the ground-water recharge and pumping inputs to the model.

Transient Model Results

Water Levels

The simulated water-level surface for the end of 2004 matches well the observed surface for January 2005 (Figure 30), especially in areas of relatively plentiful water-level data. The greatest differences are in the southwest region of the active model area where there are few measured water levels, especially in the area of bedrock and thinly saturated High Plains aquifer from northeast Ford County to southwesternmost Pawnee County.

The short-term variations and long-term trends in the simulated water levels also match well the water-level changes in the 26 well hydrographs. Figures 31 and 32 compare eight simulated and observed long-term hydrographs from the alluvial and main High Plains aquifer areas in recharge zones 1, 2, 3, and 7. The 15-digit USGS identification number indicates the locations of the wells in Figure 2. The observed and simulated hydrographs are available on the TAC model web site.

Streamflows

The model simulated very well the mean annual flow for the Arkansas River near Kinsley during both high- and low-flow periods (Figure 33). The model simulated well the mean annual flow for the Arkansas River at Great Bend during moderate to low flows, but the simulated high flow tended to be low (Figure 34). The main reason for the underprediction of high flows at Great Bend is that the model does not incorporate the simulation of surface runoff within the

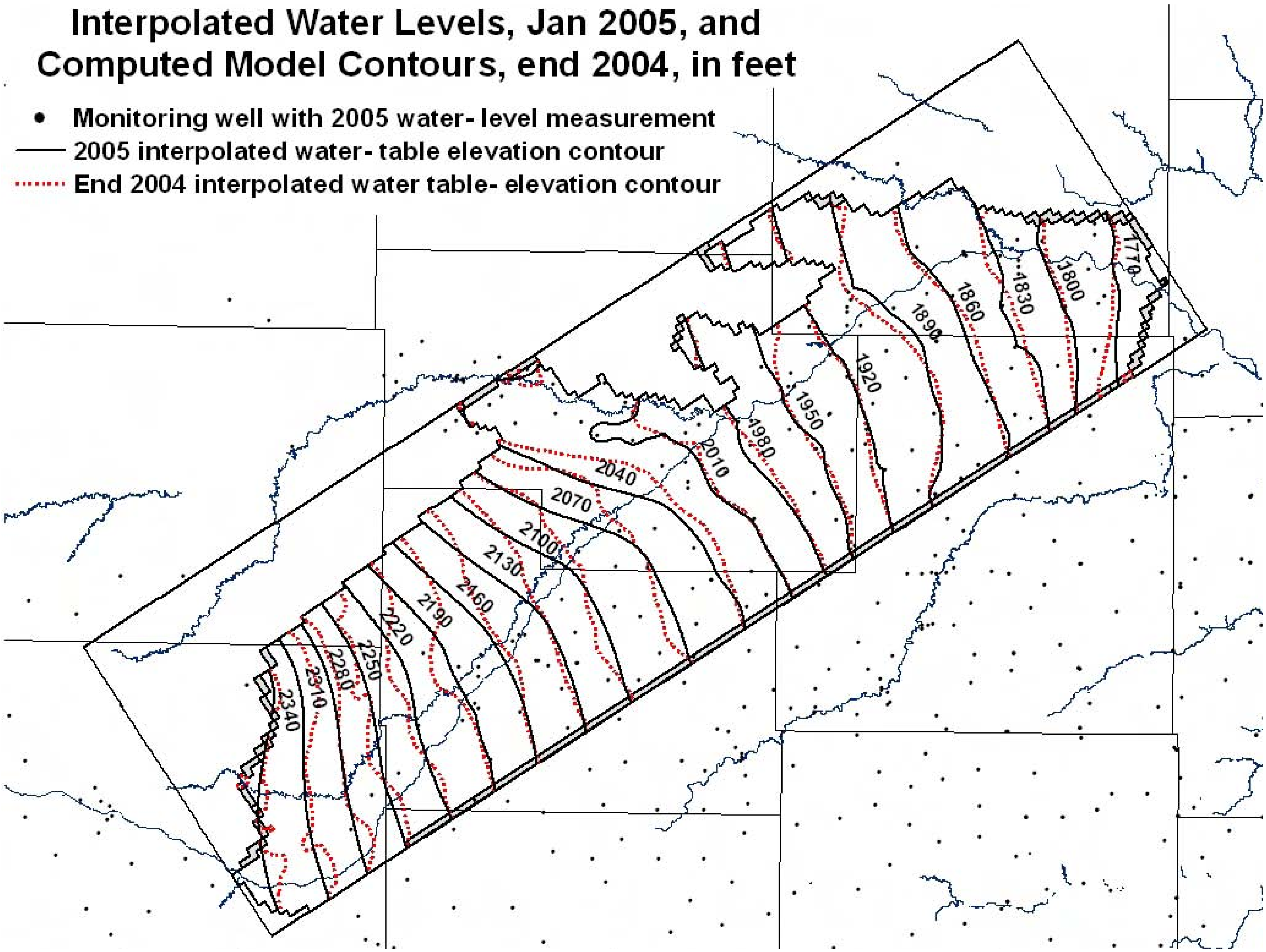

Figure 30. Comparison of simulated (end of 2004) and observed (January 2005) water-level surfaces. The contour interval is 30 ft.

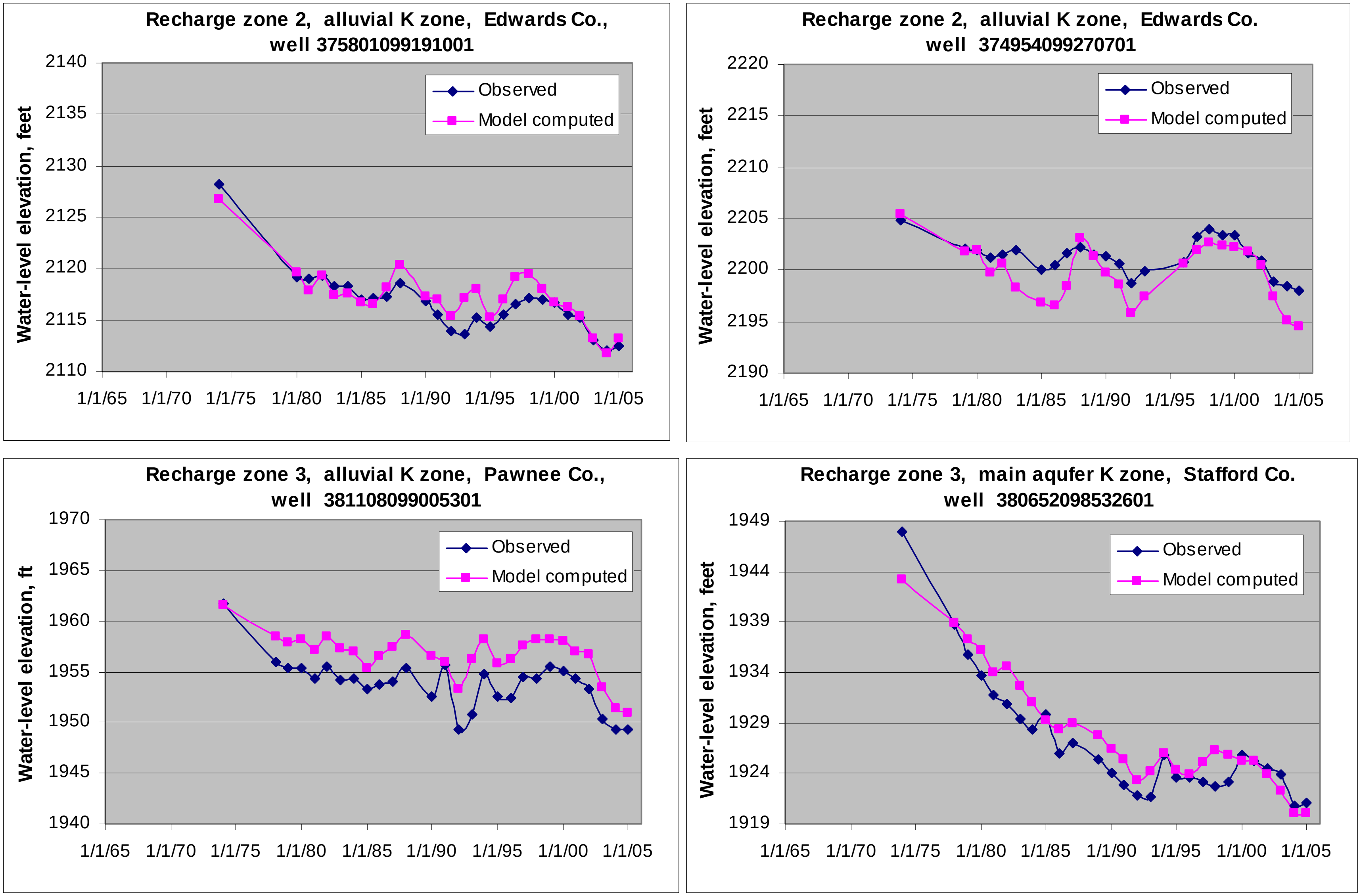

Figure 31. Comparison of simulated and observed hydrographs for recharge zones 2 and 3.

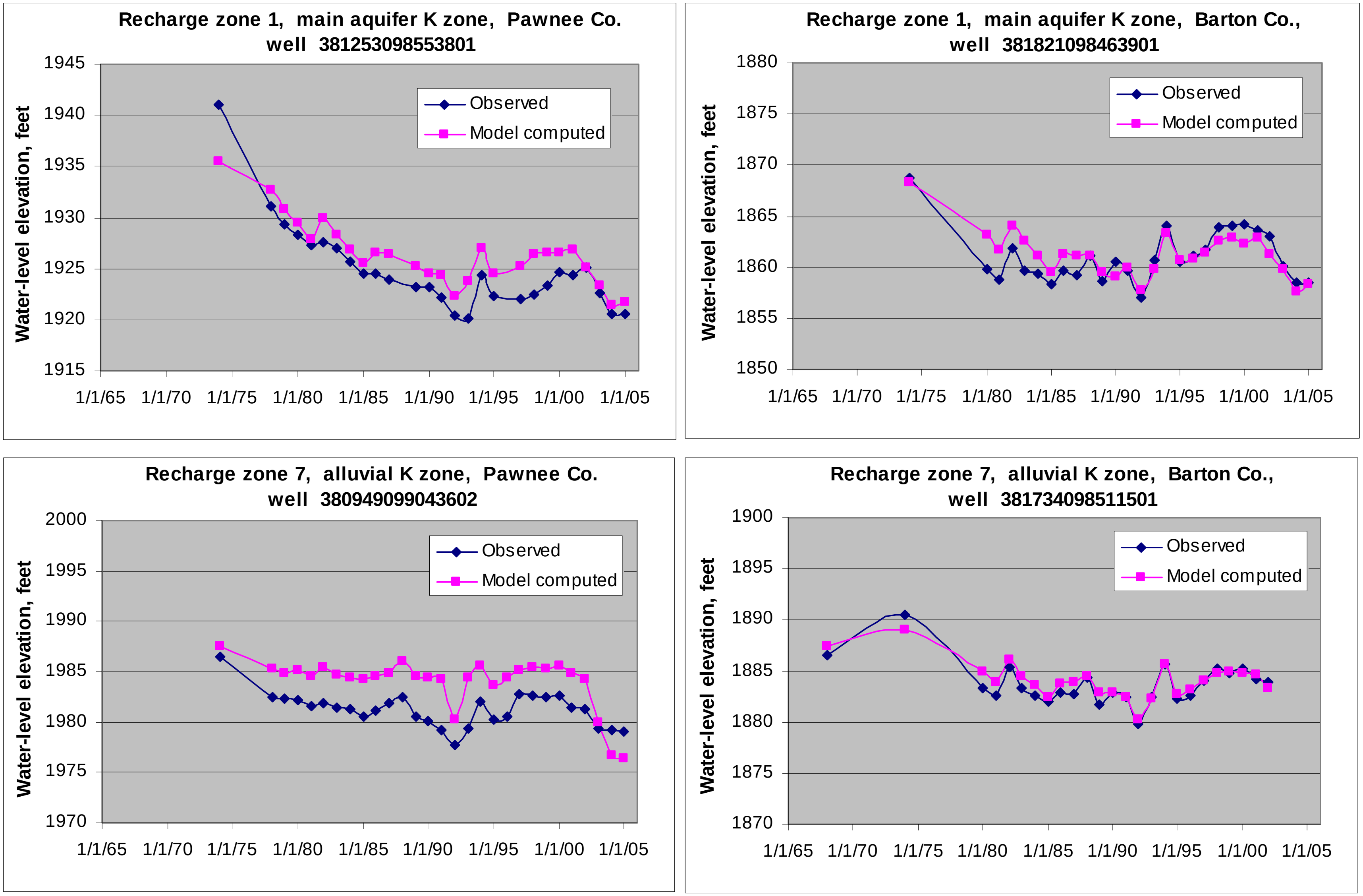

Figure 32. Comparison of simulated and observed hydrographs for recharge zones 1 and 7.

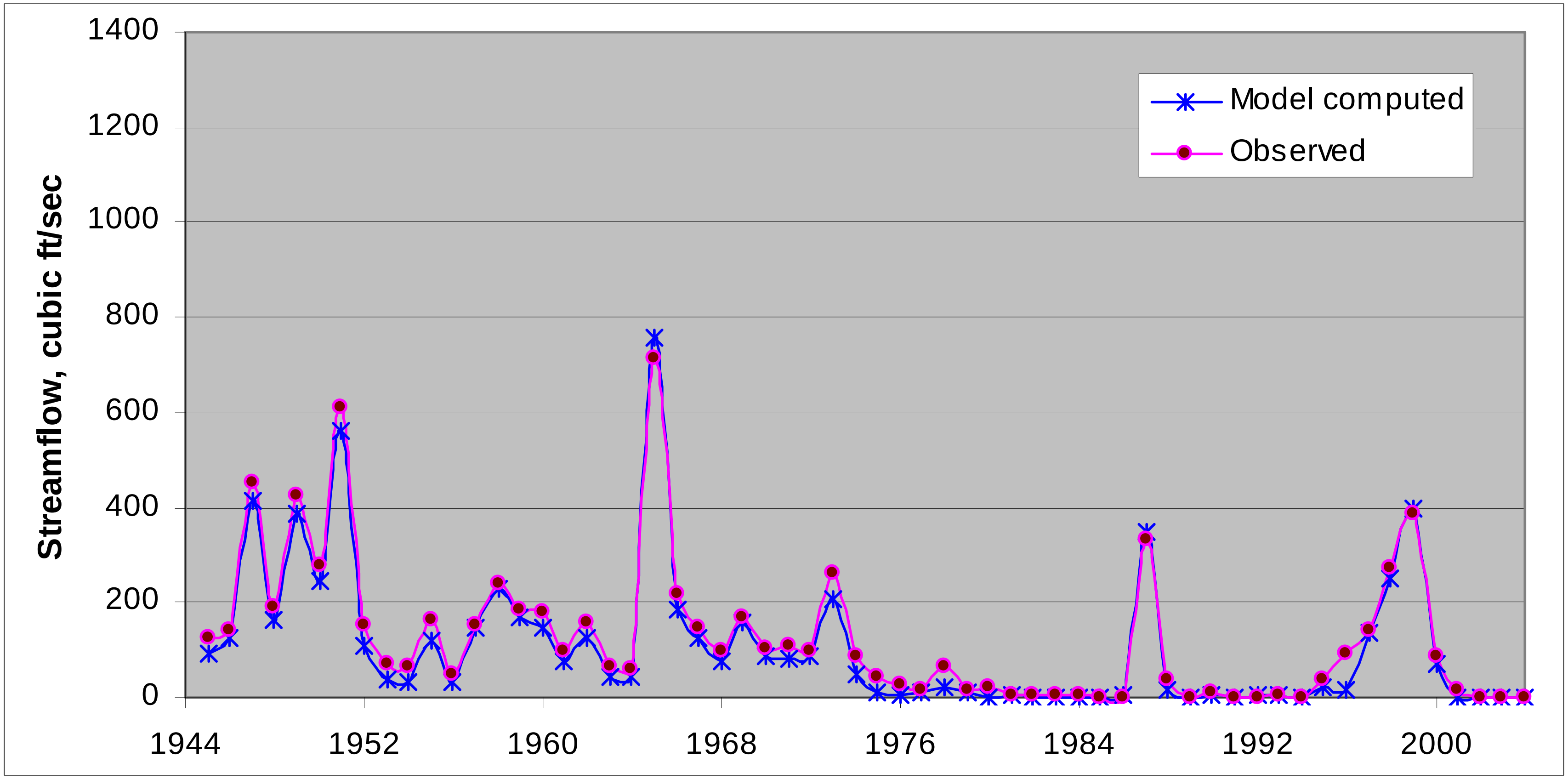

Figure 33. Observed and simulated annual flows of the Arkansas River at the USGS gaging station near Kinsley.

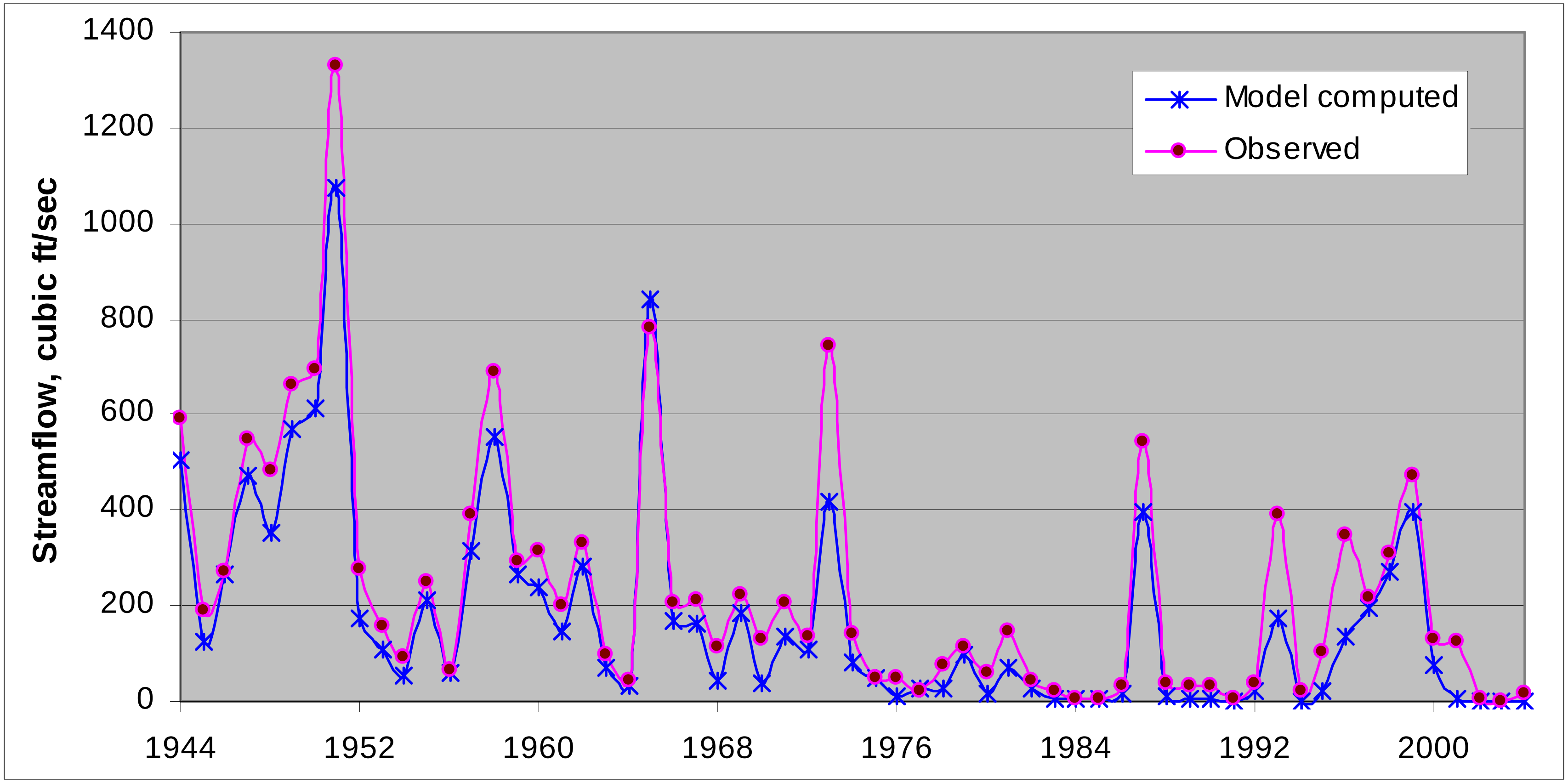

Figure 34. Observed and simulated annual flows of the Arkansas River at the USGS gaging station at Great Bend.

active model area. Thus, short-term runoff events, which could contribute substantial pass-through flow to the Arkansas River, are not included in the simulation. However, to the extent that the short-term runoff events recharge the aquifer enough to affect the winter water levels, those events are accounted for in the model.

Figure 35 displays the simulated mean annual streamflow along the Arkansas River channel through the model area for every decade during the model period as well as for 2004. The flows in 1950, 1960, and 1970 were substantial in the river channel throughout the Middle Arkansas subbasin. The increases in the flow where the Pawnee River and Walnut Creek join the Arkansas River are readily apparent. The decrease in flow from the Dundee diversion first appears in 1960. In 1980, the flow was substantially lower than for the previous decadal lines in the figure, and the pumping in the area of the Circle K Ranch decreased the flow to below 1 ft^3/sec. In 1990, the flow was also low and the model indicates that there was little to no flow in the river channel in the area of the Circle K Ranch. In 2000, the flow was substantial, as a result of appreciable flow releases from the John Martin Reservoir in Colorado. Only a very small dip in the flow occurs in the area of the Circle K Ranch in 2000. In 2004, the flow was very low and the relative flow increase caused by the inflow from Walnut Creek was appreciable.

Water Budget

The components of the water budget are net aquifer storage, net lateral ground-water flow, well pumpage, drains, evapotranspiration, areal precipitation recharge, and flow to and from streams. The changes in these components for the simulation period 1944-2004 are shown in Figure 36. The definitions of the components are as follows: net storage gain is the difference between aquifer storage accumulation and depletion, net streamflow gain is the difference between ground-water discharge to the stream (baseflow) and stream-leakage loss, and net lateral flow is the difference between ground-water flow leaving the subbasin and that incoming. The two components with the greatest magnitude of variability are net aquifer storage gain and areal recharge. In general, these two components are well correlated, indicating the importance of precipitation recharge in adding water to the aquifer. During low precipitation years, areal recharge is small, and the ground-water discharge to rivers, net lateral outflow from the aquifer, and pumpage cause a substantial loss in aquifer storage. During periods of high recharge in the last 25 years, the pumping has been lower, indicating the smaller amount of irrigation needed for crops. Conversely, in periods of low recharge, pumping is greater due to the drier conditions. Since the early 1970s, the model simulates a general downward trend in streamflow gain because stream depletion provides water for some of the pumping in the active model area. There is also a small decline in net lateral outflow during the simulation period.

The cumulative change in net aquifer storage (Figure 37) shows a substantial downward trend starting in the late 1970s. If the aquifer water budget were in a sustainable near-equilibrium condition, the line for net aquifer storage would be expected to fluctuate about the zero line in Figure 37. The cumulative loss in aquifer storage was about 1,500,000 acre-ft by the end of the modeling period (2004). For a sustainable system, the cumulative net streamflow gain and lateral outflow would be expected to fluctuate along straight lines with a constant positive slope. Both the cumulative net streamflow gain and lateral outflow approximately follow straight-line increases up to the mid-1970s. Then the slopes of both the streamflow gain and

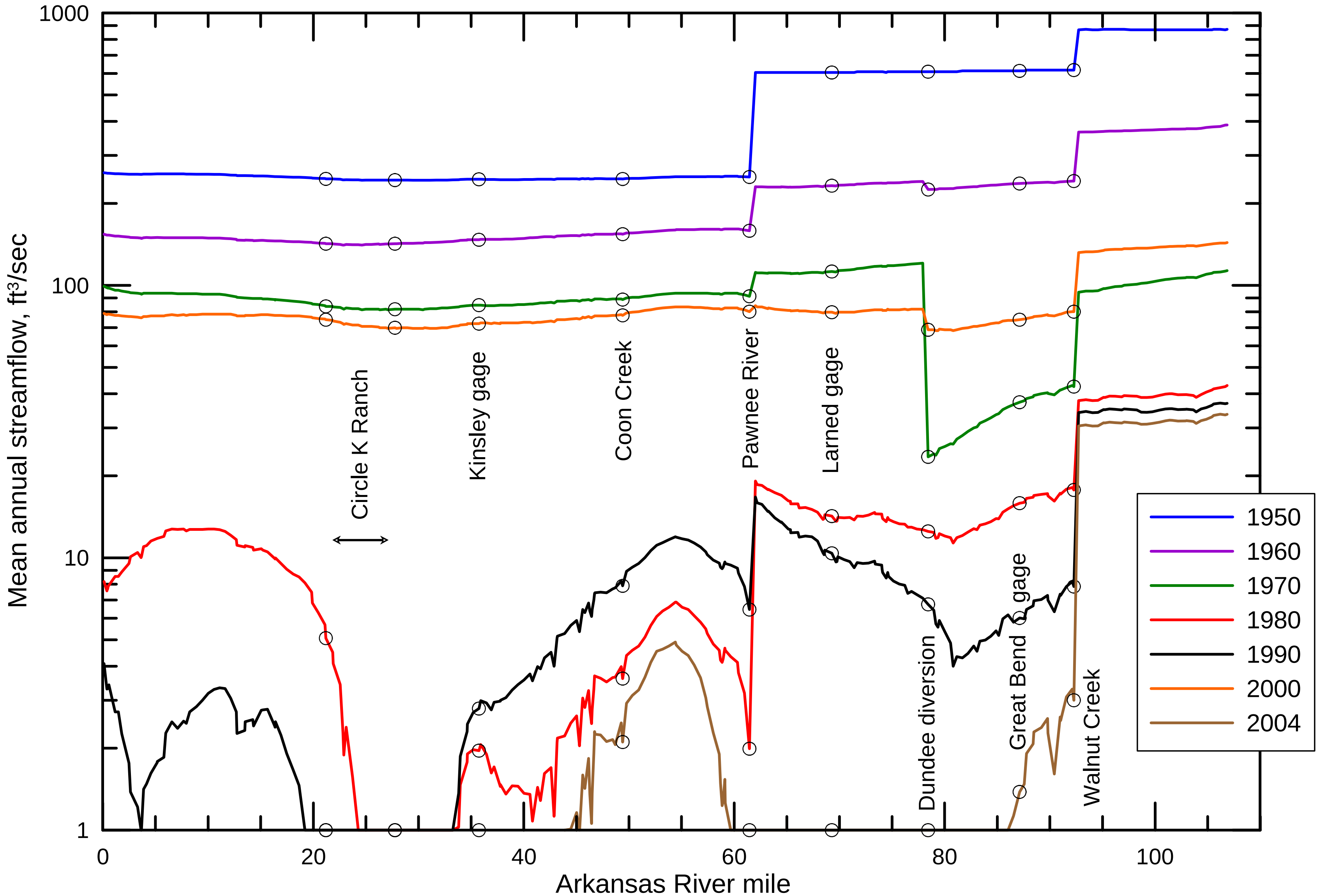

Figure 35. Simulated mean annual streamflow along the Arkansas River channel in the active model area. The circles show the beginning and the ending of the Circle K Ranch along the river, and the location of tributary confluences and gaging stations.

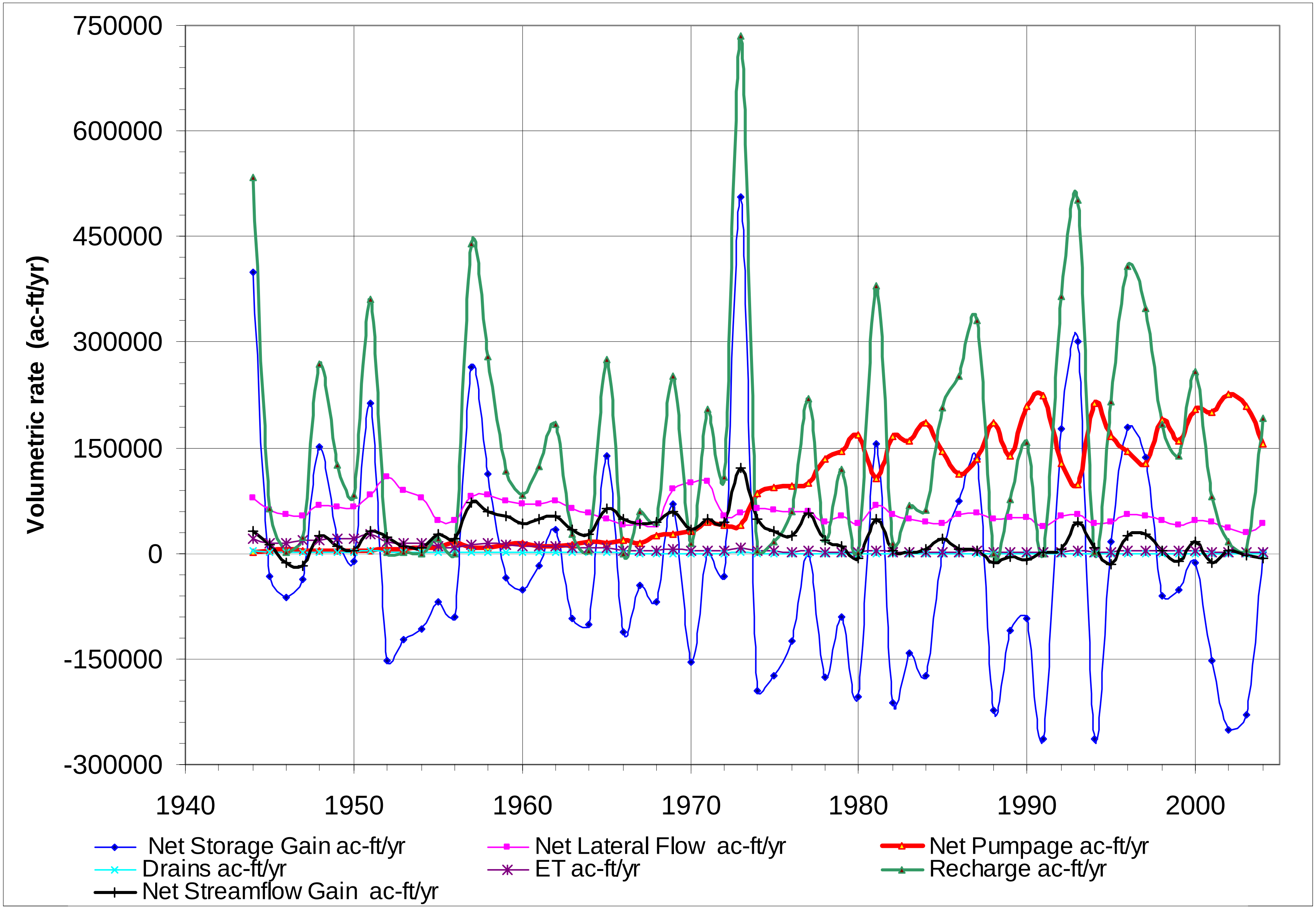

Figure 36. Water budget components for the 1944-2004 simulation period.

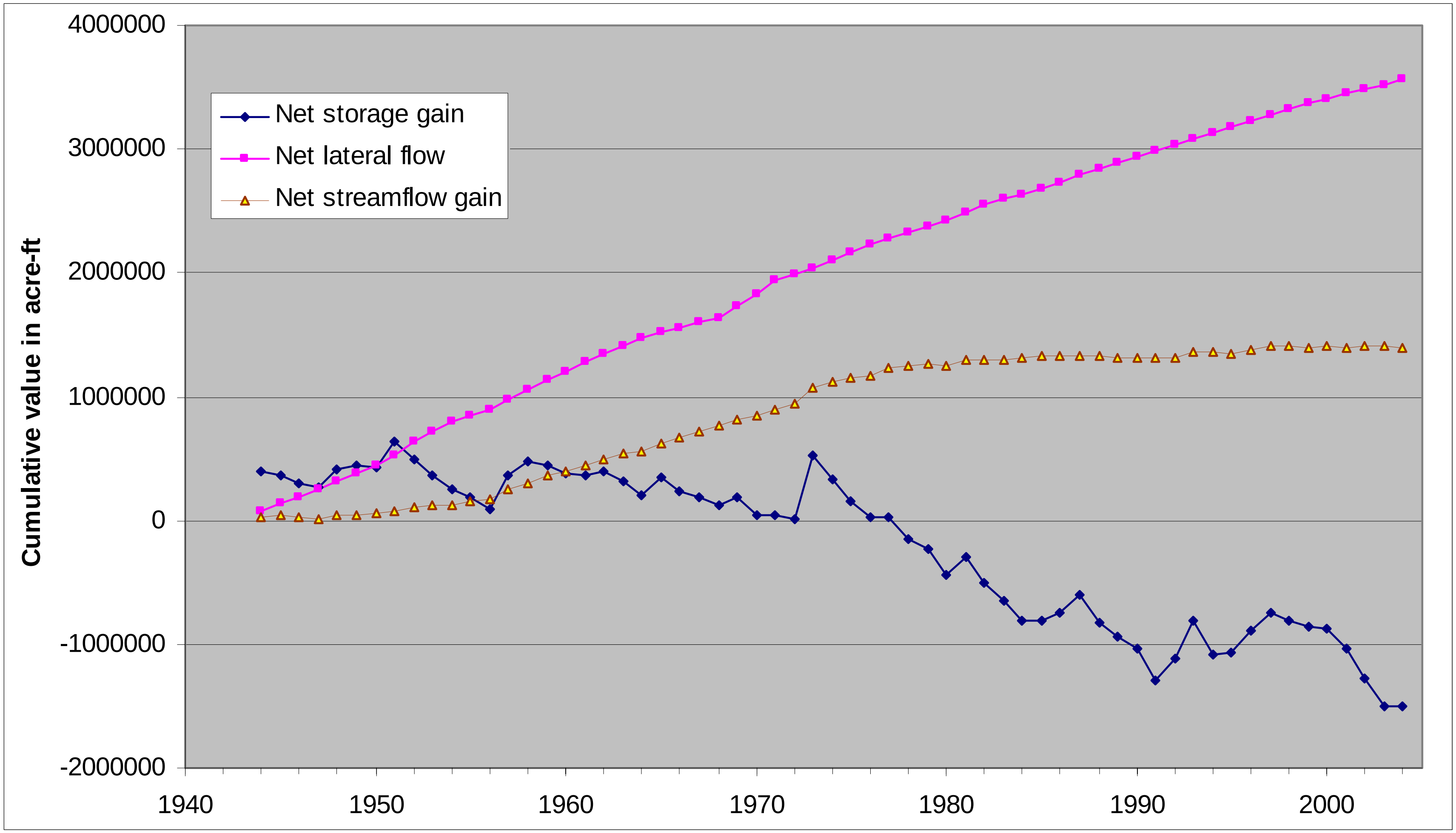

Figure 37. Cumulative net aquifer storage, streamflow gain, and lateral flow simulated by the transient model.

lateral outflow lines begin to decrease, indicating decreases in streamflow gain and ground-water flow out of the model area. During the last two decades, the line for cumulative net streamflow gain flattened, indicating an approximate balance of ground-water discharge to and recharge from the streams in the active model area.

The long-term averages for the water-budget components during the entire 61-year simulation period are listed in Table 5. Based on the total model area of 993,440 acres, the long-term recharge rate from areal precipitation for this period is 1.81 in/yr. This value is within the range of estimates for areal recharge for the region of the Middle Arkansas subbasin calculated using many different approaches (Sophocleous, 2004). In addition, it is essentially the same as the 1.8 in/yr recharge value obtained by Sophocleous et al. (1993) from a numerical modeling investigation of the Kinsley to Great Bend reach of the Arkansas River corridor for the period 1955-1990. The recharge value is slightly less than the 1.9 in/yr estimate obtained by Sophocleous and Perkins (1993) and Sophocleous et al. (1997) from a numerical modeling study of the Rattlesnake Creek subbasin for 1955-1990. The slightly lower value in this case would be expected because the Middle Arkansas subbasin is in an area of lower precipitation just to the west of the Rattlesnake Creek subbasin.

Table 5. Average annual simulated components of the model water balance for different periods. All values are in acre-ft/yr except the last column.

Period	Net pumping	Net storage gain	Net lateral flow	Net streamflow gain	Evapotrans-piration	Recharge	Recharge in/yr
1944 - 2004	85,690	-24,710	58,410	22,890	6,930	149,690	1.81
1944 - 1973	14,060	17,350	68,080	35,530	11,690	147,770	1.78
1980 - 2004	166,160	-50,770	47,300	5,550	2,210	170,420	2.06
1988 - 2000	168,360	-20,610	47,630	6,010	2,520	203,950	2.46
1990 - 2004	177,080	-37,960	44,790	5,140	2,310	191,370	2.31

During the first 30 years (1944-1973) of the simulation, the mean annual rate of areal recharge was about the same as the long-term 61-year average (Table 5). However, the average pumpage during this period was much smaller than that for the last 25 years of the modeling period (1980-2004). The net aquifer storage gain was a small positive value during 1944-1973 and the rate of net streamflow gain was greater than 35,000 acre-ft/yr, even though the simulated evapotranspiration loss was over 10,000 acre-ft/yr. The latter three periods listed in Table 5 represent the last 25 years of the modeling period (1980-2004), the period (1988-2000) considered in the Middle Arkansas River subbasin study by the DWR (SWRMP, 2004), and the last 15 years of the simulation (1990-2004), respectively. Even though the recharge for these periods was greater than the long-term 1944-2004 average, the substantially greater pumpage resulted in appreciable net storage losses, lower net lateral outflow of ground water from the subbasin, and much smaller net streamflow gains. The smaller simulated evapotranspiration for the latter periods compared to the first 30 years of the simulation primarily resulted from the lower water tables in the vicinity of the Arkansas River valley.

The model results show the substantial role of consumptive pumping in reducing baseflow to streams, as reflected in the decrease in net streamflow gain. The net streamflow gain (baseflow minus stream leakage) in the subbasin decreased from an annual average of 35,530 acre-ft/yr during 1944-1973 to 5,140 acre-ft/yr during 1990-2004 (Table 5). The average annual stream inflows to the subbasin also decreased from the first to the second period. If the average stream inflows had been similar during 1990-2004 as during 1944-1973, the average stream-water levels would have been higher, leading to greater leakage of streamflow to the aquifer and a resultant net streamflow gain smaller than 5,140 acre-ft/yr. If that were the case, the decline in net streamflow gain would have been greater than 30,390 acre-ft/yr (the difference between 35,530 acre-ft/yr and 5,140 acre-ft/yr for the two periods).

The changes in selected major components of the model water budget from the first 30 to the last 15 years of the simulation period are listed in Table 6. The changes in selected components relative to the change in pumpage indicate what percent of the increased pumpage came from storage, lateral outflow, streamflow, and evapotranspiration. The total decrease in net storage, net lateral outflow, net streamflow gain, and evapotranspiration equals 118,160 acre-ft/year, which is 72.5 % of the pumpage increase. The other 27.5 % of the pumping increase came primarily from greater than average recharge during 1990-2004 (2.31 in/yr) compared to 1944-1973 (1.78 in/yr).

Table 6. Change in average simulated annual components of the water budget from the first 30 years to the last 15 years of the modeling period. Values are in acre-ft/yr.

Period or change	Net pumping	Net storage gain	Net lateral flow	Net streamflow gain	Evapotrans-piration
1944 - 1973	14,060	17,350	68,080	35,530	11,690
1990 - 2004	177,080	-37,960	44,790	5,140	2,310
Change	163,020	-55,310	-23,290	-30,390	-9,170
Change/pumping change, as %		-33.9	-14.3	-18.6	-5.6

Management Scenario Simulations

The DWR and KWO provided five different scenarios to be simulated with the model. One scenario involved running the model for 1944-2004 using different streamflow inputs during 1980-2004. The other four scenarios involved simulations of future conditions (50-year period 2005-2054) using different pumping strategies. Table 7 is a matrix summarizing the scenarios considered in these management simulations.

Table 7. Summary of scenario conditions.

Scen-ario	Management scenario description	Type of scenario	Ground-water boundary conditions	Streamflow input at boundaries	Dundee diversion	Precipitation (recharge)	Past pumping	Future pumping	Irrigation return recharge
A	Effect of greater upper Arkansas River inflow for 1980-2004 (35% and 60% cases)	Effect of change in streamflow input at boundaries for 1980-2004	Same as for 1944-2004	Same for 1944-1979, substitute 35% and 60% of 1947-1971 inflows (ordered by precipitation) for 1980-2004	Use 1944-2004 values	Use 1944-2004 values	Use 1944-2004 values	N/A	Use 1944-2004 values
B	Effect of extending current pumping for 50 years	Future prediction for 50 years, two cycles of portions of 1980-2004 conditions	Heads at time-varying specified head boundaries change with time according to changes during 1980-2004	Two sets of 1980-2004 values for future	Two sets of 1980-2004 values for future	Two sets of 1980-2004 values for future	N/A	Two 25-year cycles of pumping based on DWR/KWO modification of 1980-2004 irrigation values	Keep constant at 2004 values
C	Effect of turning off all pumping for 50 years	Future prediction for 50 years, two cycles of portions of 1980-2004 conditions	Head at time-varying specified head boundaries held constant at 2004 values	Two sets of 1980-2004 values for future	Two sets of 1980-2004 values for future	Two sets of 1980-2004 values for future	N/A	All pumping off	N/A
D	Effect of 24% reduction in irrigation pumping in CREP area for 50 years	Future prediction for 50 years, two cycles of portions of 1980-2004 conditions	Same as for scenario B	Two sets of 1980-2004 values for future	Two sets of 1980-2004 values for future	Two sets of 1980-2004 values for future	N/A	Same as scenario B except 24% reduction in irrigation pumping in CREP area of model	Keep constant at 2004 values
E	Effect of retiring Circle K Ranch water rights during 2010-2014	Future prediction for 50 years, two cycles of portions of 1980-2004 conditions	Same as for scenario B	Two sets of 1980-2004 values for future	Two sets of 1980-2004 values for future	Two sets of 1980-2004 values for future	N/A	Same as scenario B except retire pumping for individual water rights in different years according to KWO list	Keep constant at 2004 values

Sensitivity to Increased Stream Inflows

The flow of the Arkansas River entering the model area has decreased over the last three decades. This scenario was designed to determine the effect of increased stream inflows during 1980-2004 on the model results. The KWO provided a table of years during 1947-1971 to use to substitute inflows for 1980-2004. The substitute years and flows are listed in Table 8. There are two cases for this scenario, one in which the substituted inflows are 35% of the 1947-1971 inflows and another in which the substituted inflows are 60% of the 1947-1971 inflows. The sequence of the substituted inflows was based on an ordering of annual precipitation in the model area for the 1947-1971 and 1980-2004 periods. The average of the substituted inflows for the Arkansas and Pawnee rivers in the 35% case is greater than the average of the actual 1980-2004 inflows for these rivers, and the substituted average for Walnut Creek is a little smaller than the actual average for the period. The average of the substituted inflows for each of the three streams in the 60% case is appreciably greater than the average of actual 1980-2004 inflows for each stream. The average annual inflow rates for the 35% and 60% cases are 8.56 ft^3/sec (6,201 acre-ft/yr) and 104.74 ft^3/sec (75,880 acre-ft/yr), respectively, greater than the average annual inflow rate of 126.09 ft^3/sec (91,348 acre-ft/yr) for the base case. These are inflow increases of 6.8% and 83.1% for the 35% and 60% cases, respectively, relative to the 1980-2004 inflows. In both cases, the model was run for the period 1944-2004 using the substitute inflows for the 1980-2004 period.

The most noticeable changes in the water budget for the two substituted inflow cases compared to the base case are in the net streamflow gain (Tables 9 and 10). The average annual streamflow gains for 1980-2004 in the base case (5,551 acre-ft/yr) change to losses for the substituted inflow cases (negative gains of 209 acre-ft/yr and 3,896 acre-ft/yr for the 35% and 60% cases, respectively). Losses to the aquifer are greater for the higher streamflows of this scenario than for the base case during 1980-2004 because declines in aquifer water levels had begun to impact streamflow. The cumulative net storage losses are somewhat smaller and the net lateral flows are somewhat greater for the substituted inflow scenario, especially the 60% case, than for the base case. The most visible change in the cumulative graphs (Figures 38 and 39) from that for the base case (Figure 37) is the somewhat smaller amount of streamflow gains during 1980-2004, particularly for the 60% case. In general, comparison of Figures 38 and 39 with Figure 37 indicates that the scenario did not substantially decrease the cumulative storage losses in the aquifer that started in the late 1970s. The cumulative storage losses as of 2004 are only 5.8% and 9.4% smaller for the 35% and 60% cases, respectively, than for the base case. The average annual rate of net aquifer storage loss for 1980-2004 is reduced by 3,510 AF/yr (6.9%) for the 35% case and 5,657 AF/yr (11.1%) for the 60% case. These reductions in the average annual rates of storage loss amount to about 57% and 7.5% of the average annual increased inflows for the 35% and 60% cases, respectively, for 1980-2004. This indicates that much of a small inflow increase recharges the aquifer, but most of a large inflow increase passes through the subbasin.

Tables 11 and 12 list the simulated streamflow and change in streamflow at the different gaging stations along the Arkansas River in the model area. The river flow at the Larned gaging station is greater in the scenario than the base case due to both increased Arkansas and Pawnee river flows. However, between Larned and Great Bend, there is little change in the actual or

Table 8. Actual model annual inflows (ft^3/sec) for 1980-2004 and substitute inflows used in scenario A for that period.

Actual year	Actual inflow Arkansas River	Actual inflow Pawnee River	Actual inflow Walnut Creek	Substitute year	35% substitute inflow Arkansas River	35% substitute inflow Pawnee River	35% substitute inflow Walnut Creek	60% substitute inflow Arkansas River	60% substitute inflow Pawnee River	60% substitute inflow Walnut Creek
1980	8.32	30.30	12.80	1964	20.80	4.83	3.23	35.66	8.28	5.54
1981	1.85	43.10	21.20	1951	192.15	173.25	110.36	329.41	297.00	189.19
1982	1.53	39.20	5.75	1952	45.49	14.39	14.57	77.98	24.66	24.98
1983	2.79	12.50	0.09	1947	152.84	20.93	19.77	262.02	35.88	33.90
1984	2.48	3.08	2.99	1960	54.11	27.55	39.55	92.76	47.22	67.80
1985	0.54	1.20	2.15	1948	57.64	58.45	45.60	98.81	100.20	78.16
1986	3.92	19.40	9.68	1971	30.05	19.11	12.11	51.52	32.76	20.76
1987	344.91	74.00	111.00	1959	59.33	23.66	60.90	101.70	40.56	104.40
1988	31.68	3.00	1.16	1954	21.68	3.75	4.88	37.16	6.42	8.36
1989	0.71	25.20	8.16	1955	46.39	24.78	22.68	79.53	42.48	38.89
1990	4.51	25.20	19.40	1963	18.80	11.73	17.61	32.22	20.10	30.18
1991	0.24	0.00	1.57	1956	16.09	4.59	5.75	27.58	7.86	9.86
1992	0.07	33.70	37.30	1967	49.10	45.50	46.90	84.18	78.00	80.40
1993	2.07	147.00	204.00	1965	269.52	16.42	12.85	462.04	28.14	22.02
1994	0.16	3.98	30.50	1966	70.01	1.17	1.16	120.01	2.00	1.98
1995	41.98	17.90	28.90	1970	34.95	10.12	12.60	59.91	17.34	21.60
1996	66.74	115.00	107.00	1957	50.63	45.50	37.19	86.79	78.00	63.76
1997	125.52	59.40	43.60	1950	90.91	125.65	84.98	155.84	215.40	145.68
1998	260.80	29.30	55.40	1961	28.96	17.33	47.60	49.64	29.70	81.60
1999	417.46	15.00	84.90	1969	57.35	11.69	15.37	98.32	20.04	26.34
2000	79.49	11.50	41.20	1958	79.73	103.95	72.84	136.68	178.20	124.86
2001	16.53	25.00	108.00	1949	137.64	59.15	46.04	235.95	101.40	78.93
2002	0.10	3.51	9.44	1968	29.56	9.28	8.30	50.68	15.90	14.22
2003	0.86	7.22	4.02	1953	21.52	19.64	18.77	36.88	33.66	32.18
2004	0.01	20.13	22.10	1962	44.16	46.55	26.32	75.71	79.80	45.12

Table 9. Water budgets for base run and scenarios. Values are in acre-ft/yr except where noted.

Scenario		A - 35%	A - 60%	B	C	D	E
Scenario description	Base run	Substitute inflows	Substitute inflows	Continued pumping	No pumping	CREP pumping	Circle K retirement
Net pumpage							
1944-1979	29,809	29,809	29,809	29,809	29,809	29,809	29,809
1980-2004	166,158	166,158	166,158	166,158	166,158	166,158	166,158
2005-2029	n/a	n/a	n/a	177,286	0	151,999	170,796
2030-2054	n/a	n/a	n/a	177,286	0	151,999	169,130
2005-2054	n/a	n/a	n/a	177,286	0	151,999	169,963
Recharge							
1944-1979	135,297	135,297	135,297	135,297	135,297	135,297	135,297
1980-2004, and 2005-2054	170,417	170,417	170,417	170,417	170,417	170,417	170,417
Recharge, in/yr							
1944-1979	1.63	1.63	1.63	1.63	1.63	1.63	1.63
1980-2004 and 2005-2054	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Net streamflow gain							
1944-1979	34,931	34,931	34,931	34,931	34,931	34,931	34,931
1980-2004	5,551	-209	-3,896	5,551	5,551	5,551	5,551
2005-2029	n/a	n/a	n/a	-12,854	36,945	-6,425	-11,089
2030-2054	n/a	n/a	n/a	-19,812	58,352	-10,173	-16,984
2005-2054	n/a	n/a	n/a	-16,333	47,648	-8,299	-14,037
Net storage gain							
1944-1979	-6,612	-6,612	-6,612	-6,612	-6,612	-6,612	-6,612
1980-2004	-50,771	-47,262	-45,114	-50,771	-50,771	-50,771	-50,771
2005-2029	n/a	n/a	n/a	-36,693	51,452	-21,394	-34,118
2030-2054	n/a	n/a	n/a	-23,664	12,657	-14,876	-22,016
2005-2054	n/a	n/a	n/a	-30,178	32,054	-18,135	-28,067
Net lateral flow							
1944-1979	66,134	66,134	66,134	66,134	66,134	66,134	66,134
1980-2004	47,297	49,401	50,602	47,297	47,297	47,297	47,297
2005-2029	n/a	n/a	n/a	41,202	79,043	44,657	43,341
2030-2054	n/a	n/a	n/a	35,373	95,776	42,099	39,033
2005-2054	n/a	n/a	n/a	38,287	87,409	43,378	41,187
Evapotranspiration							
1944-1979	10,214	10,214	10,214	10,214	10,214	10,214	10,214
1980-2004	2,206	2,404	2,756	2,206	2,206	2,206	2,206
2005-2029	n/a	n/a	n/a	1,559	2,649	1,670	1,570
2030-2054	n/a	n/a	n/a	1,330	3,139	1,462	1,348
2005-2054	n/a	n/a	n/a	1,444	2,894	1,566	1,459
Drains							
1944-1979	983	983	983	983	983	983	983
1980-2004	0	7	16	0	0	0	0
2005-2029	n/a	n/a	n/a	0	368	0	0
2030-2054	n/a	n/a	n/a	0	551	0	0
2005-2054	n/a	n/a	n/a	0	460	0	0

Table 10. Change in components of water budgets for scenarios. Values are in acre-ft/yr.

Scenario no.	A - 35%	A - 60%	B	C	D	E
Scenario change description	Substitute inflows, change from base run	Substitute inflows, change from base run	Continued pumping, values	No pumping, change from scenario B	CREP pumping, change from scenario B	Circle K retirement, change from scenario B
Net pumpage						
1944-1979			29,809			
1980-2004	0	0	166,158	0	0	0
2005-2029	n/a	n/a	177,286	-177,286	-25,287	-6,490
2030-2054	n/a	n/a	177,286	-177,286	-25,287	-8,156
2005-2054	n/a	n/a	177,286	-177,286	-25,287	-7,323
Recharge in model area						
1944-1979			135,297			
1980-2004 and 2005-2054	0	0	170,417	0	0	0
Net streamflow gain						
1944-1979			34,931			
1980-2004	-5,760	-9,447	5,551	0	0	0
2005-2029	n/a	n/a	-12,854	49,800	6,430	1,765
2030-2054	n/a	n/a	-19,812	78,164	9,640	2,828
2005-2054	n/a	n/a	-16,333	63,982	8,035	2,297
Net storage gain						
1944-1979			-6,612			
1980-2004	3,510	5,657	-50,771	0	0	0
2005-2029	n/a	n/a	-36,693	88,145	15,299	2,575
2030-2054	n/a	n/a	-23,664	36,320	8,788	1,647
2005-2054	n/a	n/a	-30,178	62,233	12,044	2,111
Net lateral flow						
1944-1979			66,134			
1980-2004	2,104	3,306	47,297	0	0	0
2005-2029	n/a	n/a	41,202	37,841	3,455	2,139
2030-2054	n/a	n/a	35,373	60,403	6,726	3,660
2005-2054	n/a	n/a	38,287	49,122	5,091	2,900
Evapotranspiration						
1944-1979			10,214			
1980-2004	198	551	2,206	0	0	0
2005-2029	n/a	n/a	1,559	1,089	111	11
2030-2054	n/a	n/a	1,330	1,809	132	18
2005-2054	n/a	n/a	1,444	1,449	121	15
Drains						
1944-1979			983			
1980-2004	7	16	0	0	0	0
2005-2029	n/a	n/a	0	368	0	0
2030-2054	n/a	n/a	0	551	0	0
2005-2054	n/a	n/a	0	460	0	0

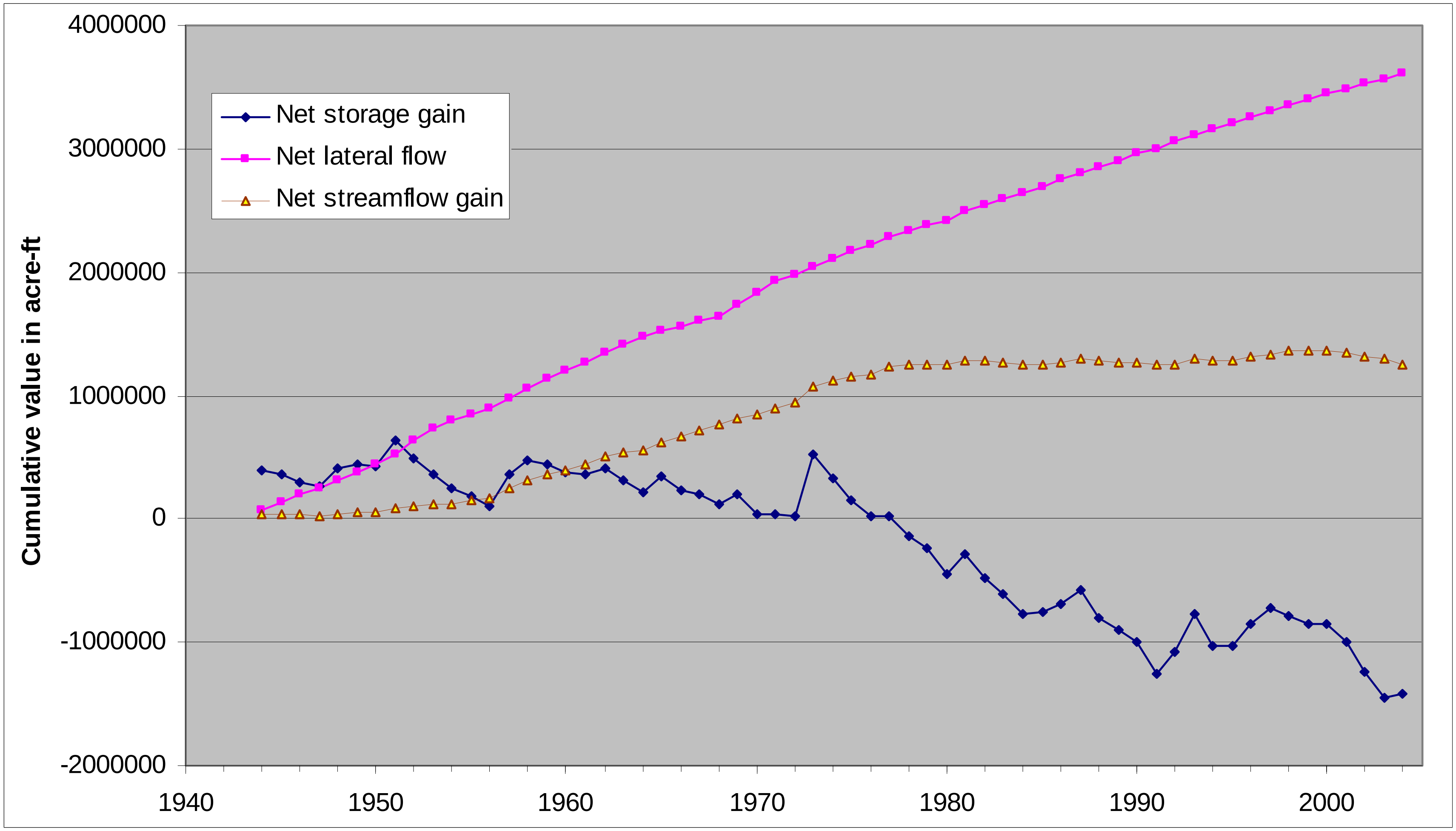

Figure 38. Cumulative net aquifer storage, streamflow gains, and lateral flow simulated for the 35% substituted inflows case of scenario A.

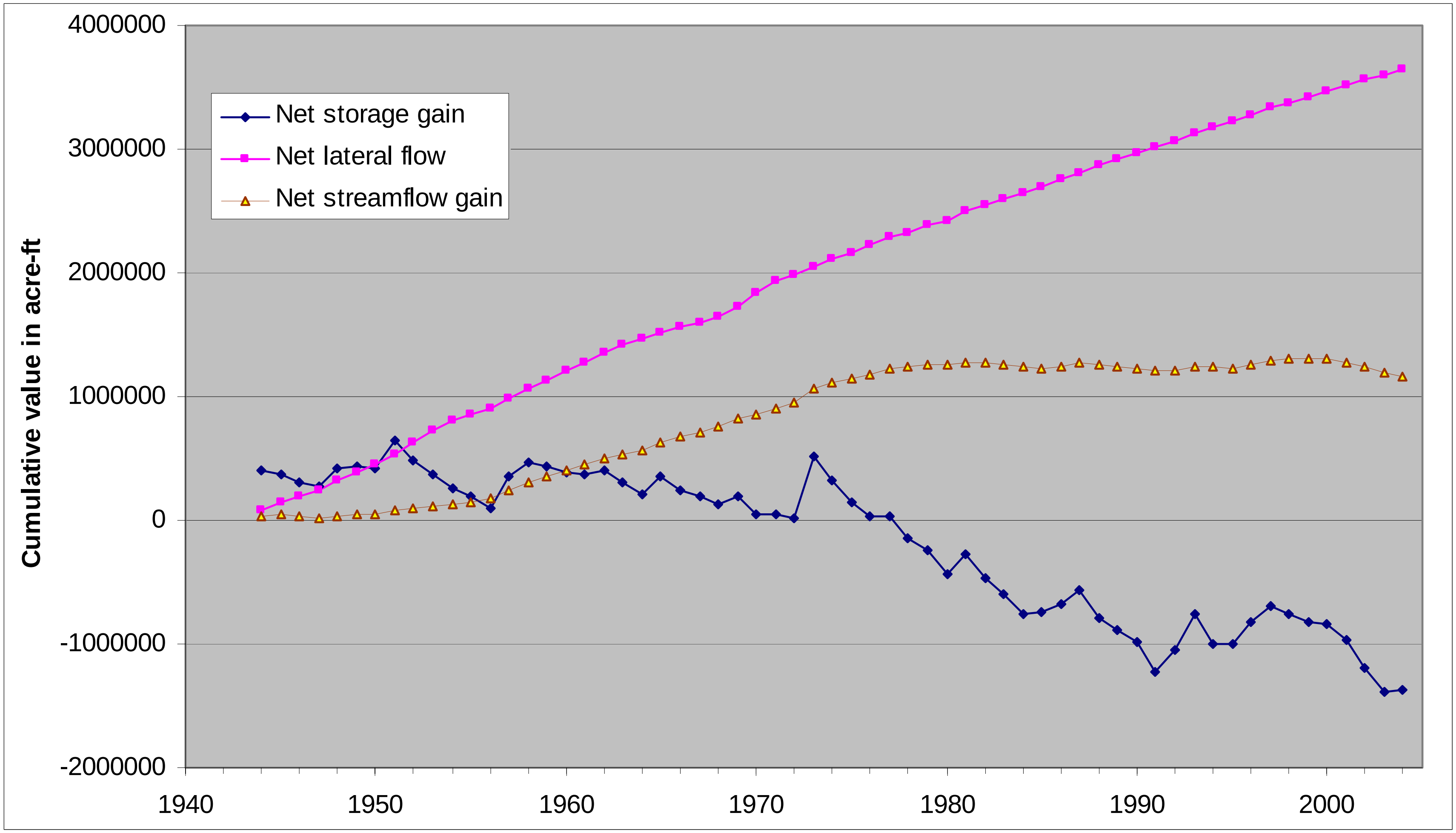

Figure 39. Cumulative net aquifer storage, streamflow gains, and lateral flow simulated for the 60% substituted inflows case of scenario A.

Table 11. Summary of streamflow (ft^3/sec) for base run and scenarios.

Scenario no.		A - 35%	A - 60%	B	C	D	E
Scenario description	Base run	Substitute inflows	Substitute inflows	Continued pumping	No pumping	CREP pumping	Circle K retirement
Total stream inflow							
1944-1979	327.2	327.2	327.2	327.2	327.2	327.2	327.2
1980-2004 and 2005-2054	126.1	134.6	230.8	126.1	126.1	126.1	126.1
Arkansas River inflow							
1944-1979	160.5	160.5	160.5	160.5	160.5	160.5	160.5
1980-2004 and 2005-2054	56.6	67.2	115.2	56.6	56.6	56.6	56.6
Simulated Arkansas River flow, Kinsley							
1944-1979	153.1	153.1	153.1	153.1	153.1	153.1	153.1
1980-2004	51.9	59.3	106.1	51.9	51.9	51.9	51.9
2005-2029	n/a	n/a	n/a	43.1	56.5	44.7	44.8
2030-2054	n/a	n/a	n/a	38.4	60.2	40.6	41.2
2005-2054	n/a	n/a	n/a	40.7	58.4	42.7	43.0
Simulated Arkansas River flow, Larned							
1944-1979	247.6	247.6	247.6	247.6	247.6	247.6	247.6
1980-2004	73.7	84.5	153.9	73.7	73.7	73.7	73.7
2005-2029	n/a	n/a	n/a	58.1	92.8	63.6	60.5
2030-2054	n/a	n/a	n/a	52.1	109.4	60.3	56.0
2005-2054	n/a	n/a	n/a	55.1	101.1	62.0	58.3
Simulated Arkansas River flow, Great Bend							
1944-1979	246.5	246.5	246.5	246.5	246.5	246.5	246.5
1980-2004	74.5	83.3	151.8	74.0	74.0	74.0	74.0
2005-2029	n/a	n/a	n/a	53.0	107.7	60.4	55.4
2030-2054	n/a	n/a	n/a	44.9	132.7	56.1	48.8
2005-2054	n/a	n/a	n/a	48.9	120.2	58.3	52.1

simulated streamflows. There is a small loss in the simulated streamflows due to the higher stream stage in the simulations, whereas there is a very small gain in the base case.

Figures 40-45 display the water-level surface simulated for the substituted inflow cases compared to the surface observed in January 2005, the saturated thickness of the High Plains aquifer simulated for the substituted inflow cases, and the difference between the water level observed in January 2005 and that simulated in the cases. There are little differences between the results of the base case and those of the two cases of scenario A on the scale of the ranges used in the water-level and saturated thickness figures.

Table 12. Summary of streamflow change (ft^3/sec) for scenarios.

Scenario	A - 35%	A - 60%	B	C	D	E
Scenario change description	Substitute inflows, change from base run	Substitute inflows, change from base run	Continued pumping, values (not change)	No pumping, change from scenario B	CREP pumping, change from scenario B	Circle K retirement, change from scenario B
Total stream inflow						
1944-1979			327.2			
1980-2004 and 2005-2054	8.6	104.7	126.1	0.0	0.0	0.0
Arkansas River inflow						
1944-1979			160.5			
1980-2004 and 2005-2054	10.6	58.5	56.6	0.0	0.0	0.0
Simulated Arkansas River flow, Kinsley						
1944-1979			153.1			
1980-2004	7.4	54.2	51.9	0.0	0.0	0.0
2005-2029	n/a	n/a	43.1	13.5	1.6	1.7
2030-2054	n/a	n/a	38.4	21.8	2.2	2.8
2005-2054	n/a	n/a	40.7	17.6	1.9	2.3
Simulated Arkansas River flow, Larned						
1944-1979			247.6			
1980-2004	10.7	80.2	73.7	0.0	0.0	0.0
2005-2029	n/a	n/a	58.1	34.7	5.5	2.4
2030-2054	n/a	n/a	52.1	57.3	8.3	3.9
2005-2054	n/a	n/a	55.1	46.0	6.9	3.2
Simulated Arkansas River flow, Great Bend						
1944-1979			246.5			
1980-2004	9.3	77.8	74.0	0.0	0.0	0.0
2005-2029	n/a	n/a	53.0	54.7	7.5	2.4
2030-2054	n/a	n/a	44.9	87.8	11.2	3.9
2005-2054	n/a	n/a	48.9	71.3	9.4	3.2

Ground-Water Pumpage Scenarios

The simulation period for all of the pumping scenarios was 50 years: 2005 to 2054. Most of the conditions used during these 50 years were based on cycling through the conditions for the 25 years from 1980 to 2004 twice (for 2005-2029 and then again for 2030-2054). Table 7 summarizes these scenarios and further details are provided in this section. The net pumpage values in Tables 9 and 10 reflect the total ground-water pumped minus the recharge due to irrigation return flow and leakage from the Dundee canal. The average recharge for the 1980-2004 conditions is equivalent to 2.06 in/yr for the model area (Table 9), which is somewhat above the long-term average of 1.81 in/yr for 1944-2004 and considerably more than the 1.63 in/yr for the period before 1980 (1944-1979).

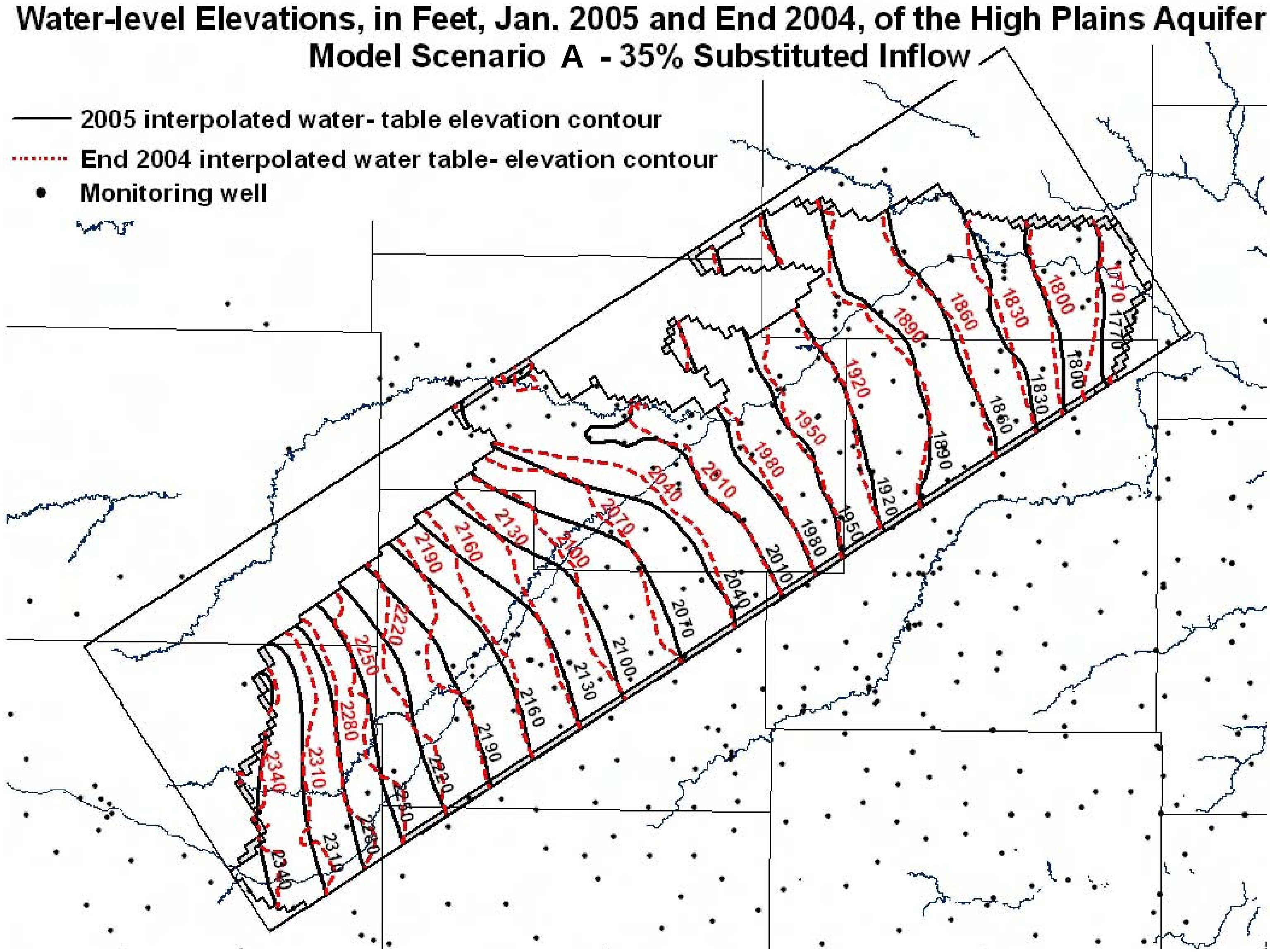

Figure 40. Comparison of observed (2005) water-level contours with contours simulated (end of 2004) for the 35% substituted inflows case of scenario A.

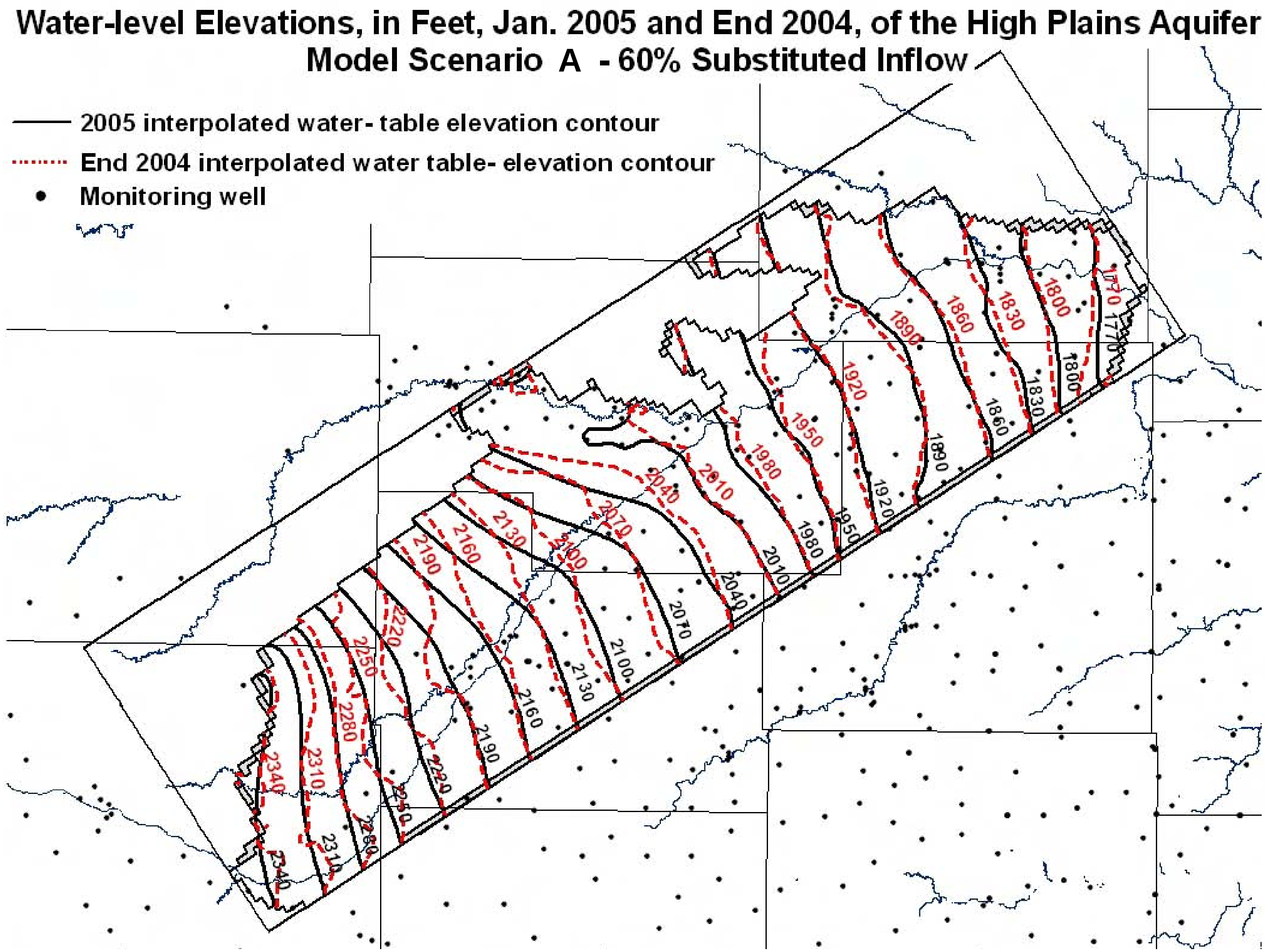

Figure 41. Comparison of observed (2005) water-level contours with contours simulated (end of 2004) for the 60% substituted inflows case of scenario A.

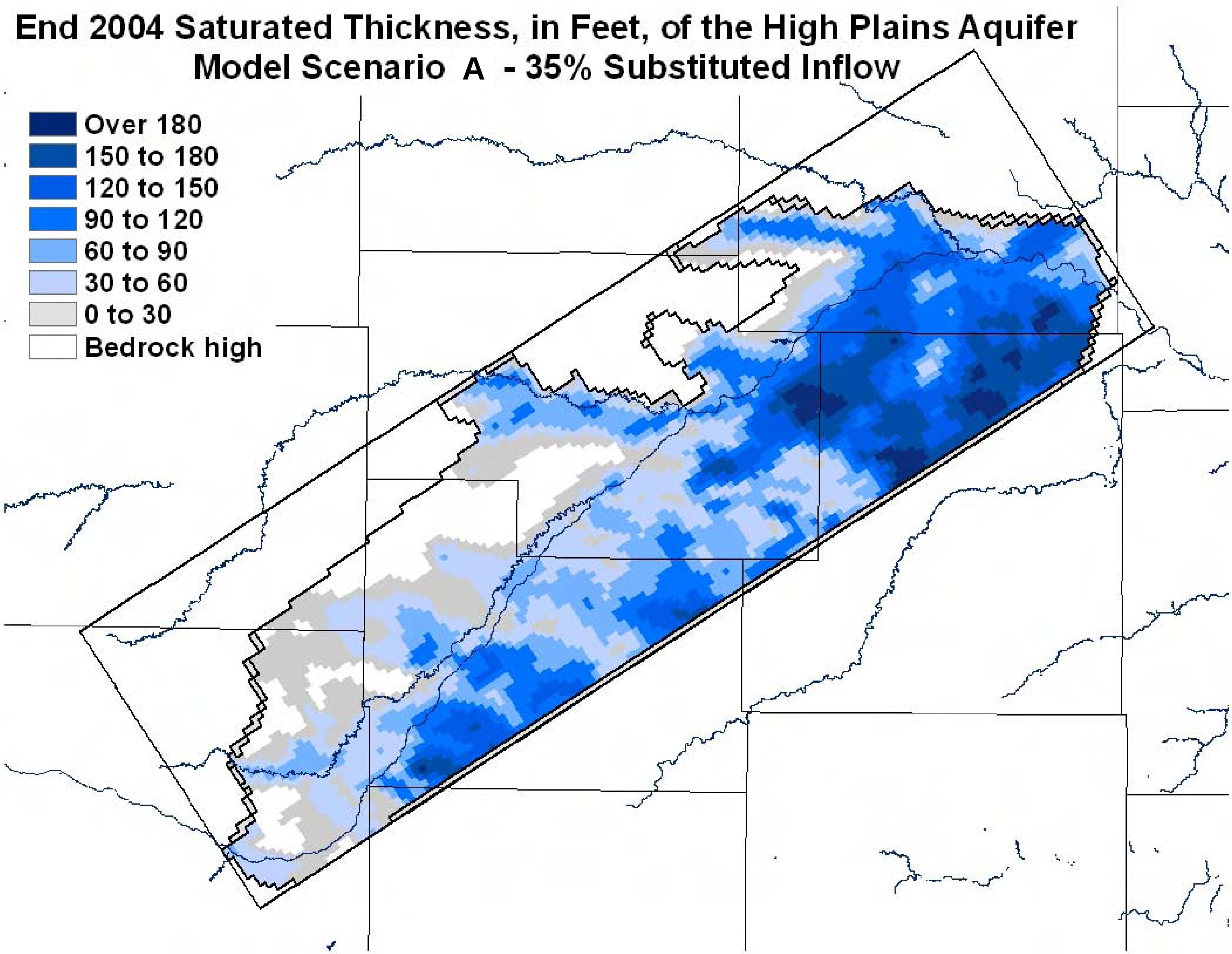

Figure 42. Saturated thickness of the High Plains aquifer simulated for the 35% substituted inflows case of scenario A.

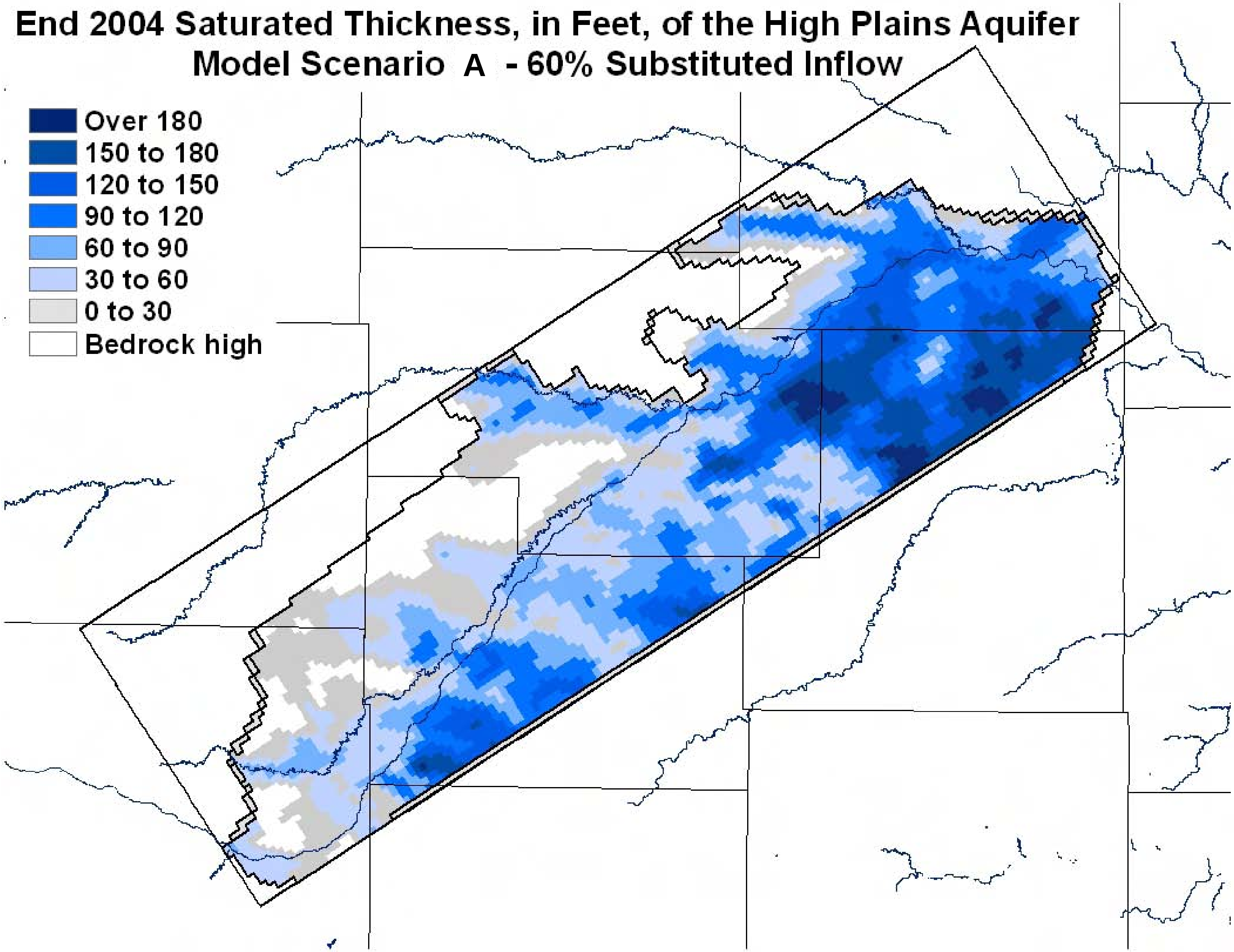

Figure 43. Saturated thickness of the High Plains aquifer simulated for the 60% substituted inflows case of scenario A.

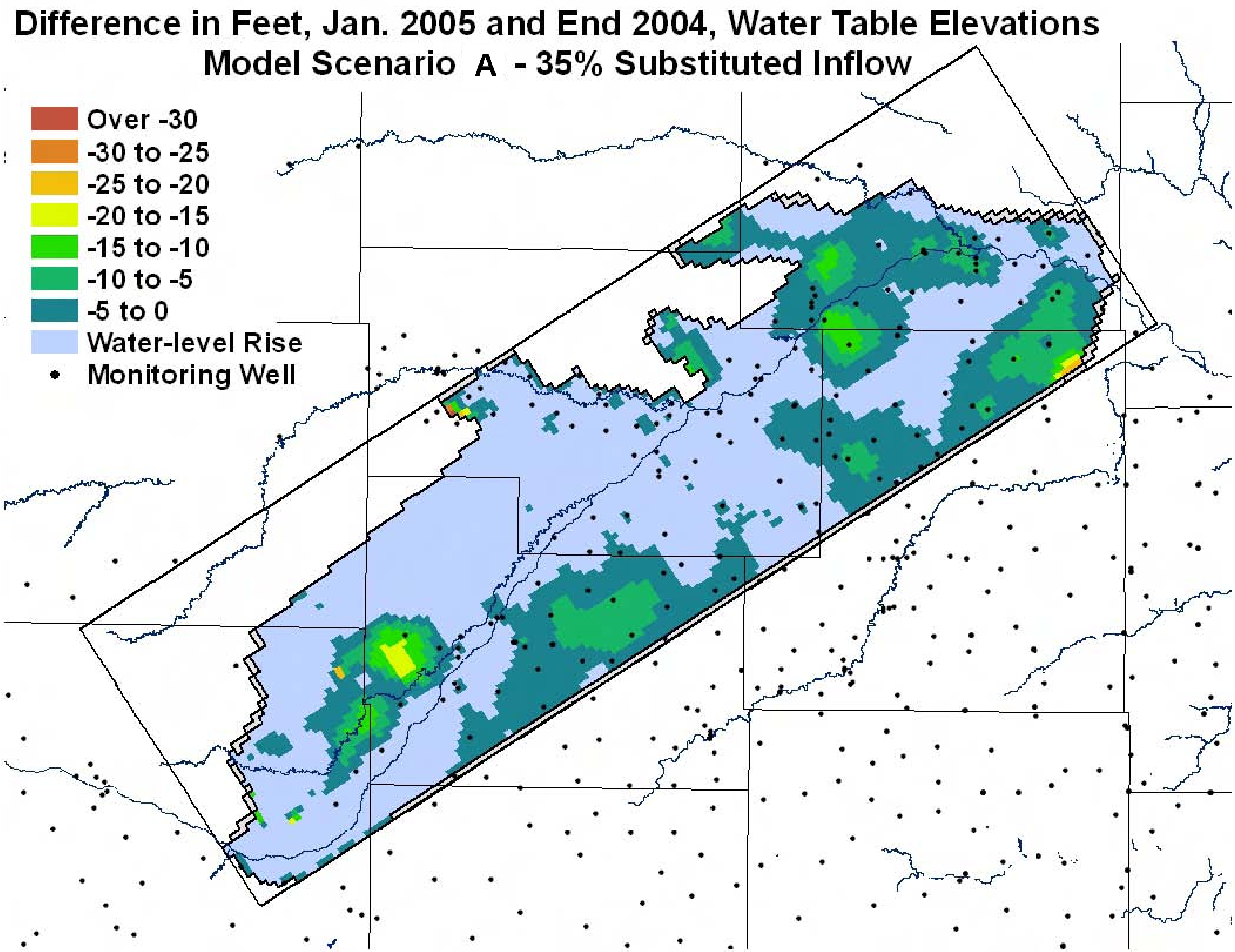

Figure 44. Difference between observed water table and that simulated for the 35% substituted inflows case of scenario A.

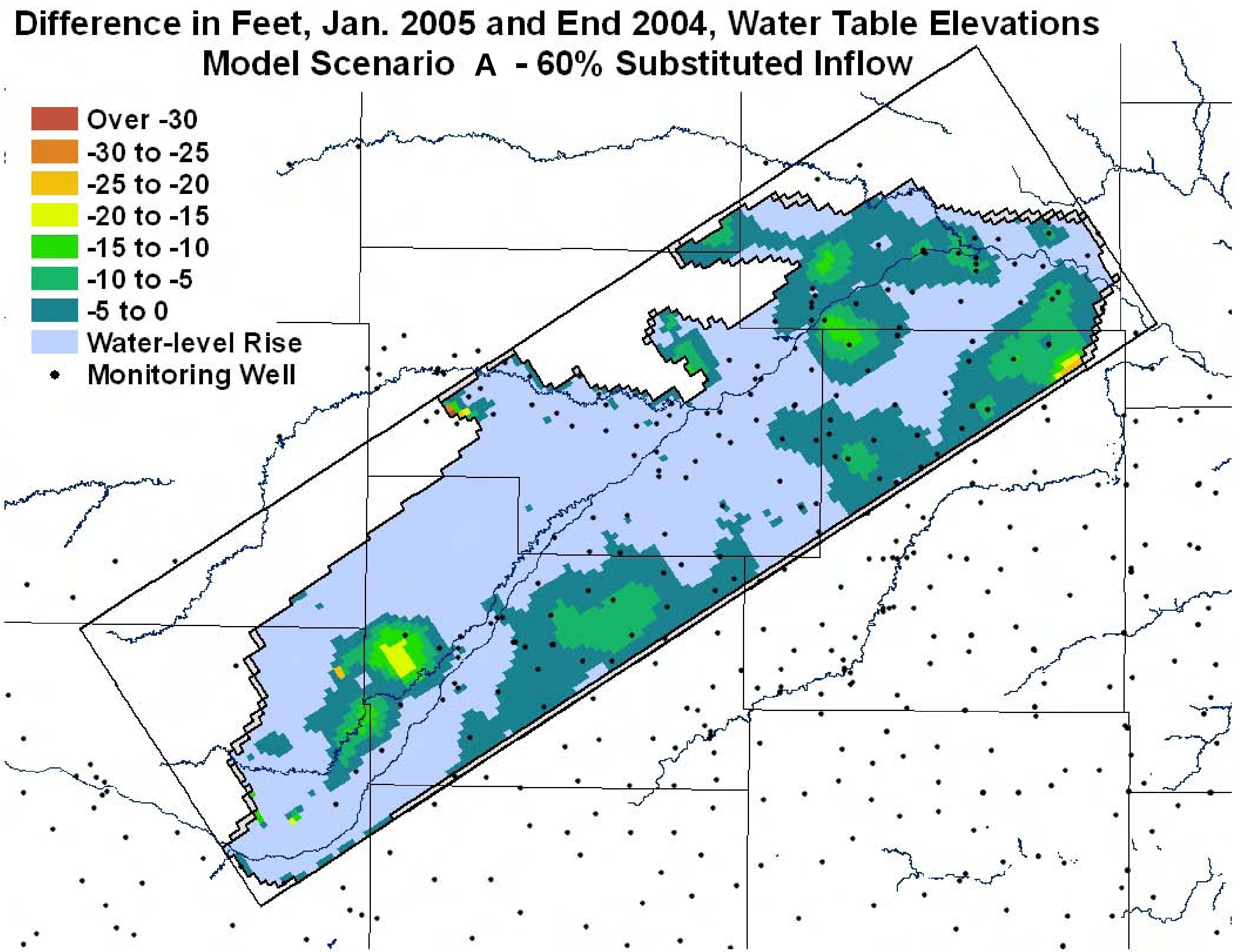

Figure 45. Difference between observed water table and that simulated for the 60% substituted inflows case of scenario A.

Pumpage at Current Levels

Many of the well hydrographs for the High Plains aquifer in the vicinity of the southern model boundary show long-term declines during 1980-2004. The year-to-year changes in the time-varying specified head boundaries for 1980-2004 were used to adjust the boundaries each year from 2005 to 2029 and then again from 2030 to 2054 for the continued pumping at current levels (henceforth, continued pumping) scenario. This adjustment to the time-varying specified head boundaries was found to be better than using constant head or constant flow based on an examination of hydrographs simulated using the various boundary conditions.

The pumpage during 1980-2004 was adjusted as recommended by the DWR and KWO for use in future projections. Two adjustments were made: 1) a factor to adjust the 1980-2004 pumping to the 2004 level of authorized use, and 2) a factor to adjust the 1980-2004 net pumping to the current irrigation efficiency. These adjustments removed the small increasing trend with time observed in the pumping data for 1980-2004 (Figure 36). The resulting series was used as the net pumping for 2005-2029 and then again for 2030-2054. Thus, the projected pumping had no long-term trend but did reflect the inverse relationship with annual precipitation (and recharge) during 1980-2004. The adjustment factors by which the 1980-2004 pumpage was multiplied to obtain the 25-year data set for use in the continued pumping scenario are listed in Table 13.

Figure 46 illustrates the year-to-year changes in the components of the water budget from 1944 to the end of 2054 for the continued pumping scenario. The three general cycles of model conditions are apparent for the 1980-2004, 2005-2029, and 2030-2054 periods. However, a general downward trend in net streamflow gain and net lateral flow is also apparent. The shift from streamflow gain to loss is indicated in Table 9, which shows that, whereas there was an average gain simulated for 1980-2004, there is an average loss of increasing magnitude during 2005-2054. There is a substantial net storage loss during 2005-2054 but the loss becomes smaller with time. The decrease in average annual net lateral flow is similar between the 2005-2029 and 2030-2054 subperiods. Evapotranspiration loss decreases during 2005-2054 because the ground-water levels generally decline.

The decline in the cumulative net aquifer storage that began during the late 1970s persisted during 2005-2054 in the continued pumping scenario (Figure 47). However, the long-term trend is not linear but has a small concave upward curvature that reflects the slow decrease in net lateral flow from the aquifer with time and also the greater amount of streamflow loss to the aquifer during periods of substantial inflows in the Arkansas River. The cumulative loss in aquifer storage sums to about 3,000,000 acre-ft by 2054. The cumulative net streamflow gain (Figure 47) shows the change from a nearly level line, indicating no substantial gain or loss, to a downward trend signifying substantial streamflow loss (recharge of the aquifer). Although the small concave downward curvature in the cumulative plot for net lateral flow during 1960-2004 decreases during 2005-2054, there is still a small continued decline in net lateral flow.

Hydrographs for wells in the main aquifer in recharge zones 1 and 3 generally show long-term declines during 2005-2054, with declines generally smaller in zone 1 (for example, Figure 48A and B) than in zone 3 (Figure 48C and D). In general, wells close to the Arkansas River

Table 13. Factors by which the pumpage during 1980-2004 was multiplied to give pumpage values without a trend for use in the continued pumping scenario.

Year	Factor
1980	1.2323
1981	1.1916
1982	1.1709
1983	1.1513
1984	1.1240
1985	1.1202
1986	1.1174
1987	1.1014
1988	1.0902
1989	1.0680
1990	1.0515
1991	1.0484
1992	1.0438
1993	1.0435
1994	1.0429
1995	1.0409
1996	1.0361
1997	1.0290
1998	1.0237
1999	1.0217
2000	1.0189
2001	1.0123
2002	1.0060
2003	1.0047
2004	1.0000

have water-level declines that are less than those at a distance from the river. Hydrographs for many of the wells near the river, especially in Edwards and Pawnee counties, in both the base run and continued pumping scenarios show fluctuations reflecting the variations from low to high inflows in the Arkansas River and variations in areal recharge from very dry to wet years (for example, Figure 49A). The continued pumping scenario shows that the hydrograph variations for near-river wells generally increase in amplitude with time during 2005-2054, which reflects the progressively greater decline in ground-water levels during dry periods alternating with years of high recharge or Arkansas River inflows. The most predominant peaks in the variations for 2005-2054 are produced by the cycling of the conditions for the 1987 and 1996-2000 high inflows in the Arkansas River. These peaks appear at the start of 2013 and 2022-2026 in the first 25 years of the scenarios, and at the start of 2038 and 2047-2051 in the second 25 years. In some cases, the water level for the first year of the 2022-2026 and 2047-2051 sequences is relatively low and the water level for the year following the sequence is relatively high. This lower water level at the beginning of the period is explained by the large recharge loss of river water to the aquifer after a dry period. The higher water level at the end of the period is related to the additional time required for the recharged water to either discharge to

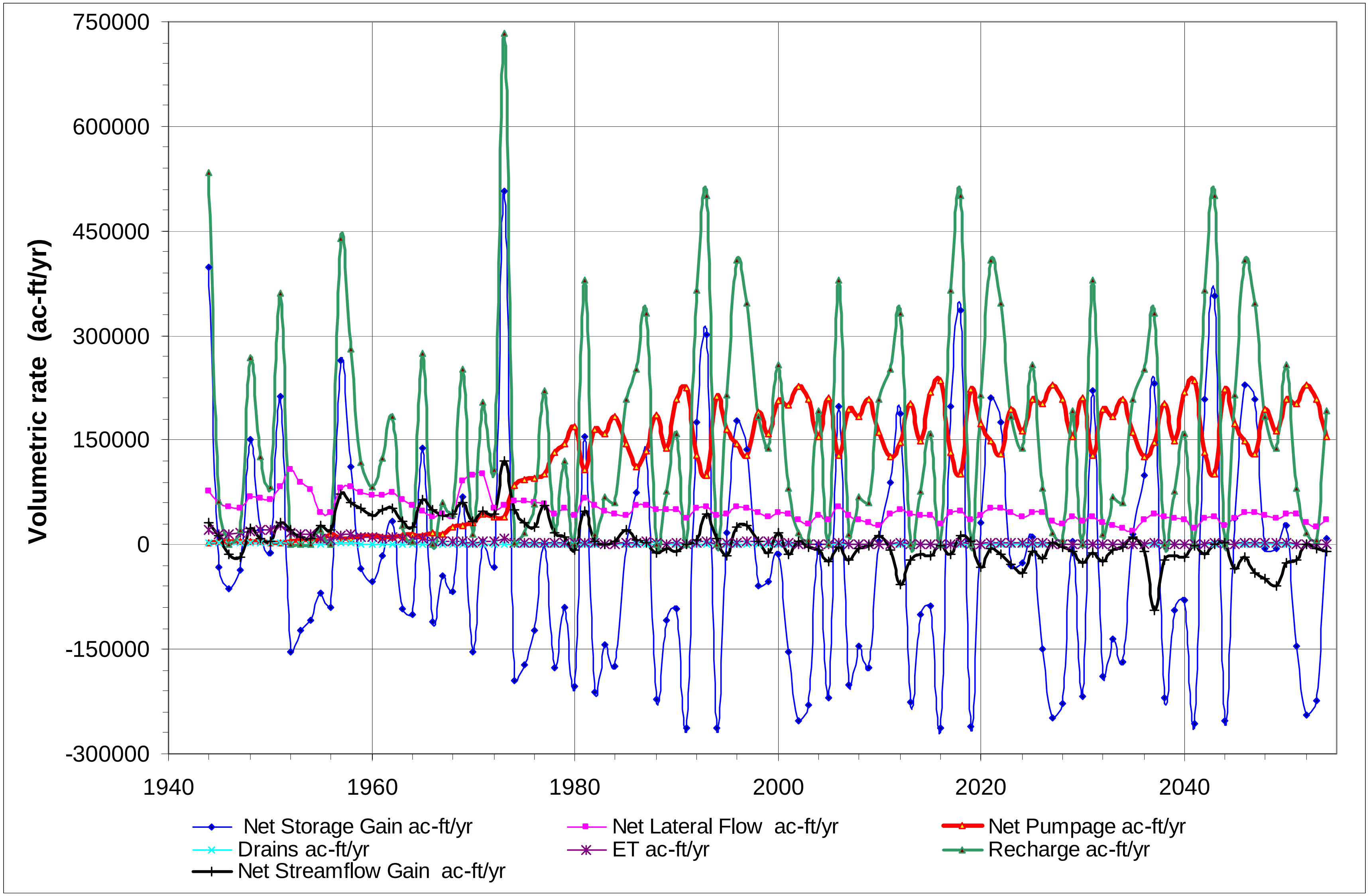

Figure 46. Water budget components simulated for the scenario of continued pumping.

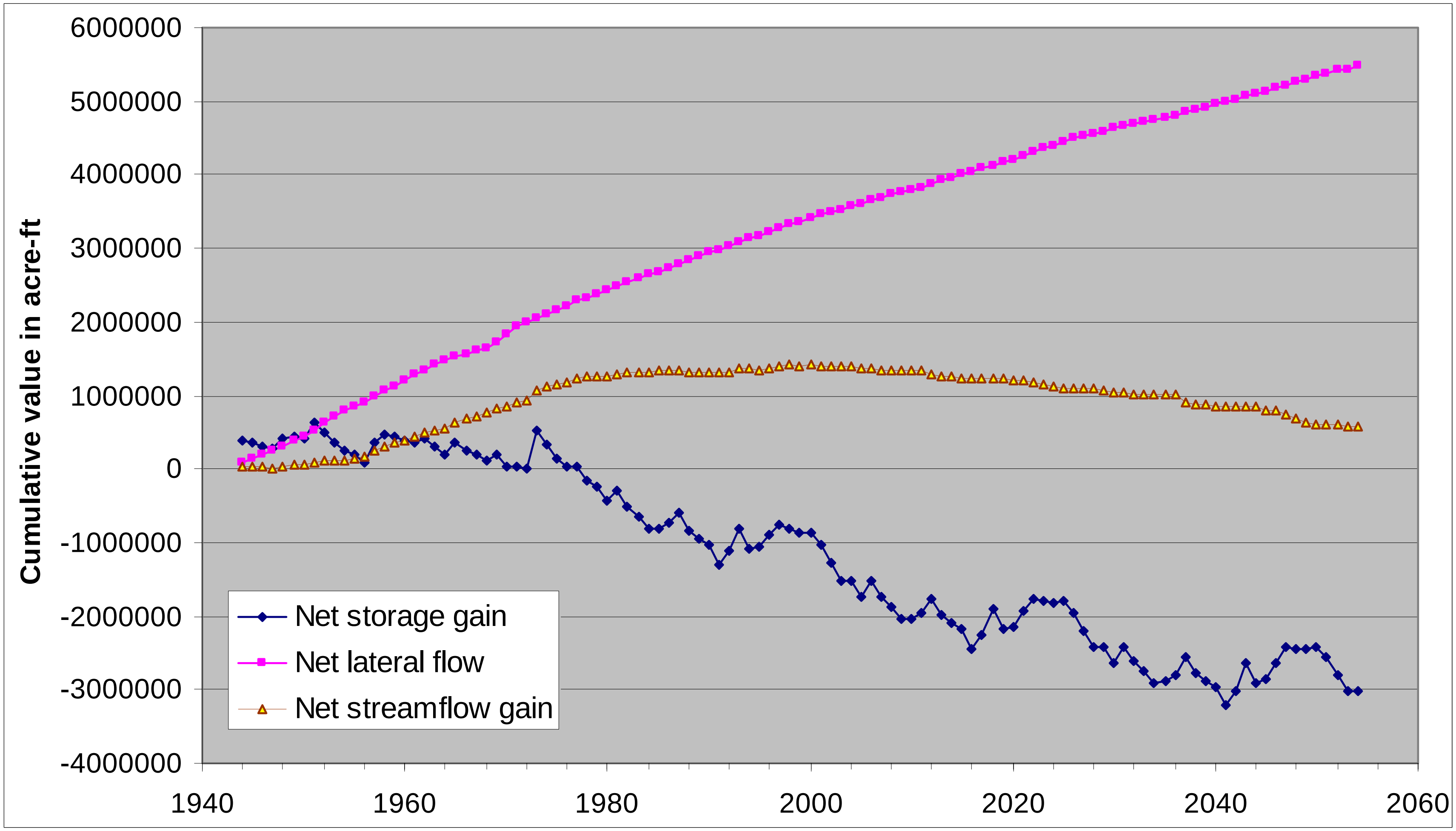

Figure 47. Cumulative net aquifer storage, streamflow gains, and lateral flow simulated for the continued pumping scenario.

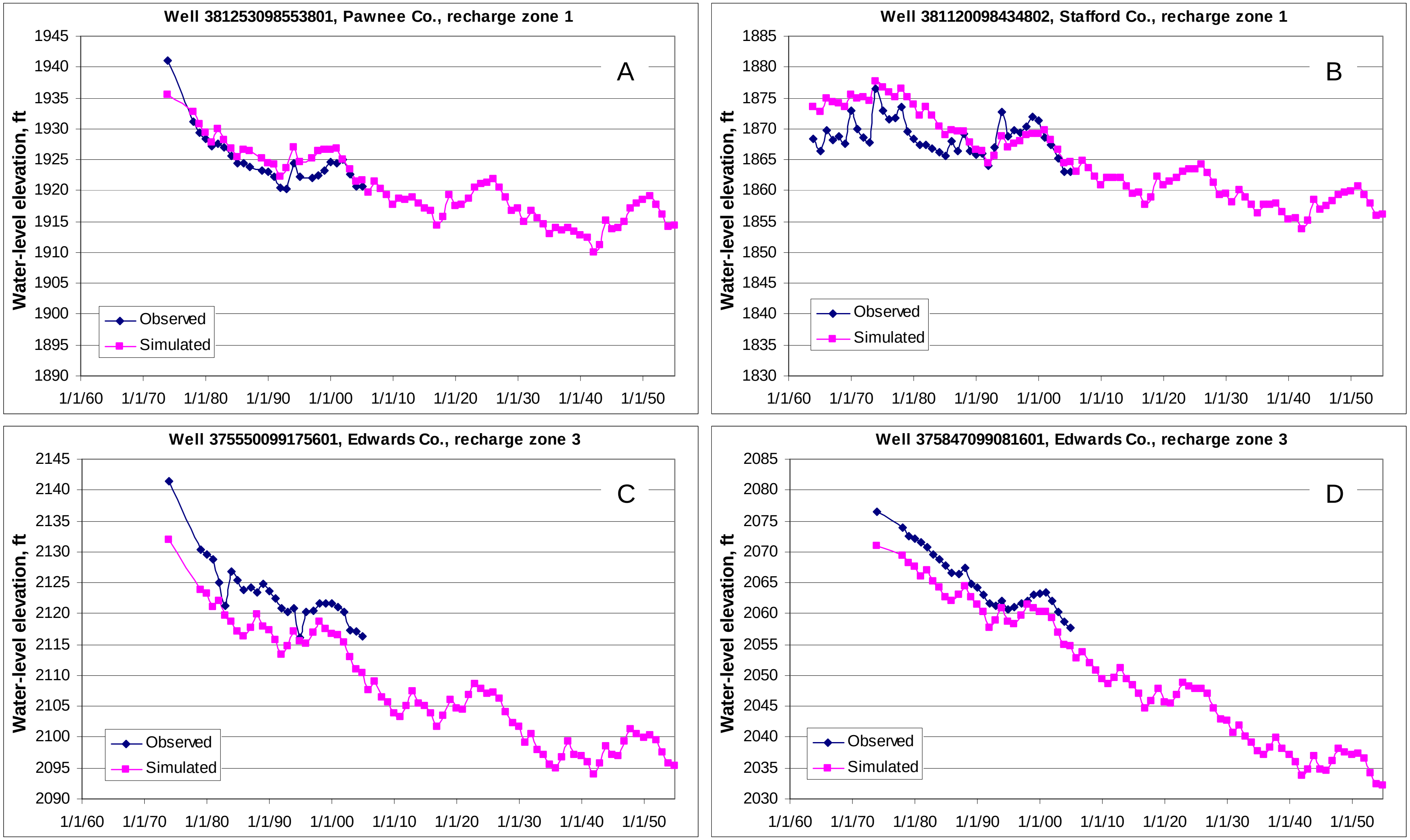

Figure 48. Examples of hydrographs for wells in the hydraulic conductivity zone for the main aquifer and in recharge zones 1 and 3 for the continued pumping scenario. Hydrographs A and C are for wells near the hydraulic conductivity zone that includes the alluvial aquifer, and hydrographs B and D are for wells near the middle of recharge zones 1 and 3 and at a greater distance from the hydraulic conductivity zone that includes the alluvial. See Figure 2 for well locations.

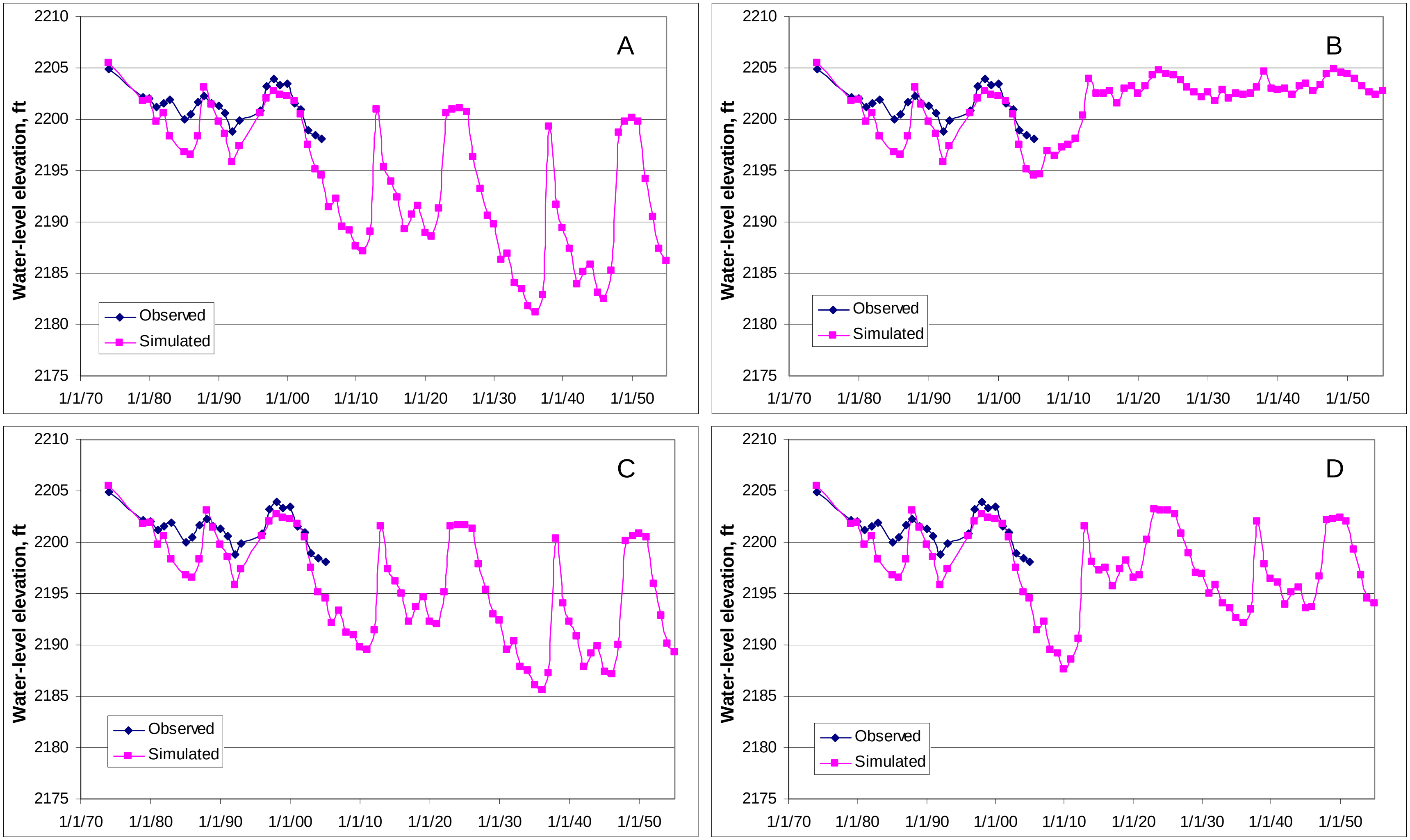

Figure 49. Hydrographs for the pumping scenarios for well 374954099270701 in southwest Edwards County, located in the hydraulic conductivity zone for the alluvial aquifer and underlying High Plains aquifer and in recharge zone 2. Hydrograph A is for the continued pumping scenario, B for the no pumping scenario, C for the CREP pumping scenario, and D for the Circle K Ranch scenario. See Figure 2 for well location.

the river or flow laterally out of the immediate area, as well as the fact that there was still reasonably substantial inflow in the year (2001) on which the conditions for 2027 and 2052 are based.

A peak also is present in the hydrographs for many of the wells near the Arkansas River that represents the 1993 high precipitation recharge (water-level response appearing at the start of 2019 and 2044) and sometimes for the high precipitation of 1982 (response at the start of 2008 and 2033). The relative sizes of the peaks depend on the specific geographic location of the well and the amount of recharge for the particular zone in which the well is located. Substantial troughs occur in the hydrographs of many of the near-river wells that reflect the end of years of dry to normal precipitation just before high flow in the Arkansas River. Particularly dry years with low recharge that do not occur during or immediately after high river flow, such as 1980 and 1991, also produce troughs in some hydrographs. Overall, water levels in the wells near the river do not show substantial long-term trends.

Streamflow graphs for the Arkansas River for the continued pumping scenario show the effect of repeated high inflows from 1987 and 1996-2000 (Figures 50 and 51). The peaks related to these flows have the dates 2012 and 2021-2025 for the first 25 years of the scenarios, and 2037 and 2046-2050 for the second 25 years. Flow peaks also appear in 2018 and 2043 in the Arkansas River at Larned and Great Bend, which reflect the large precipitation recharge of 1993 in the eastern part of the basin. The low streamflows in the Arkansas River generally become even lower with time after 2004. The only years during the scenario that indicate a substantial flow gain in the Arkansas River flow from Kinsley to Great Bend are for the conditions of high precipitation recharge for 1993 (2018 and 2043 in the future), 1996 (2021 and 2046), and 1997 (2022 and 2047). The Arkansas River loses flow between Kinsley and Great Bend in the simulation for the periods 2023-2025 and 2048-2050, which represent the repeated conditions of high inflow during 1998-2000, in contrast to a very small average gain simulated for 1998-2000. Table 11 indicates the simulated amount of decrease in flow in the Arkansas River at the Kinsley, Larned, and Great Bend gaging stations from 1980-2004 to 2005-2029 and to 2030-2054. The amount of decrease between the last two 25-year periods is considerably smaller than between the first two periods.

The contours for the water-level surface simulated for the end of 2054 (Figure 52) are shifted in an upgradient direction relative to the contours for the water-level surface observed in January 2005 in recharge zones 1 and 3 south of the Arkansas River. The simulated contours are also somewhat rotated in a clockwise direction within the main aquifer area indicating a shift to a more easterly flow direction.

There are substantial decreases in the saturated thickness simulated for the continued pumping scenario (Figure 53) compared to the saturated thickness in 2005 (Figure 17) in the main aquifer area. Based on Hecox et al. (2002), the well yield for a saturated thickness of 30 ft with a hydraulic conductivity of 120 ft/day (the main High Plains aquifer area in the model) is about 200 gpm. It is doubtful if irrigators could still operate economically at such a low pumping rate, so 30 ft is considered for this study as the minimum saturated thickness that can be used for practical irrigation. If the minimum economically feasible rate were 400 gpm, then the saturated thickness would need to be 40 ft for a hydraulic conductivity of 120 ft/day. However,

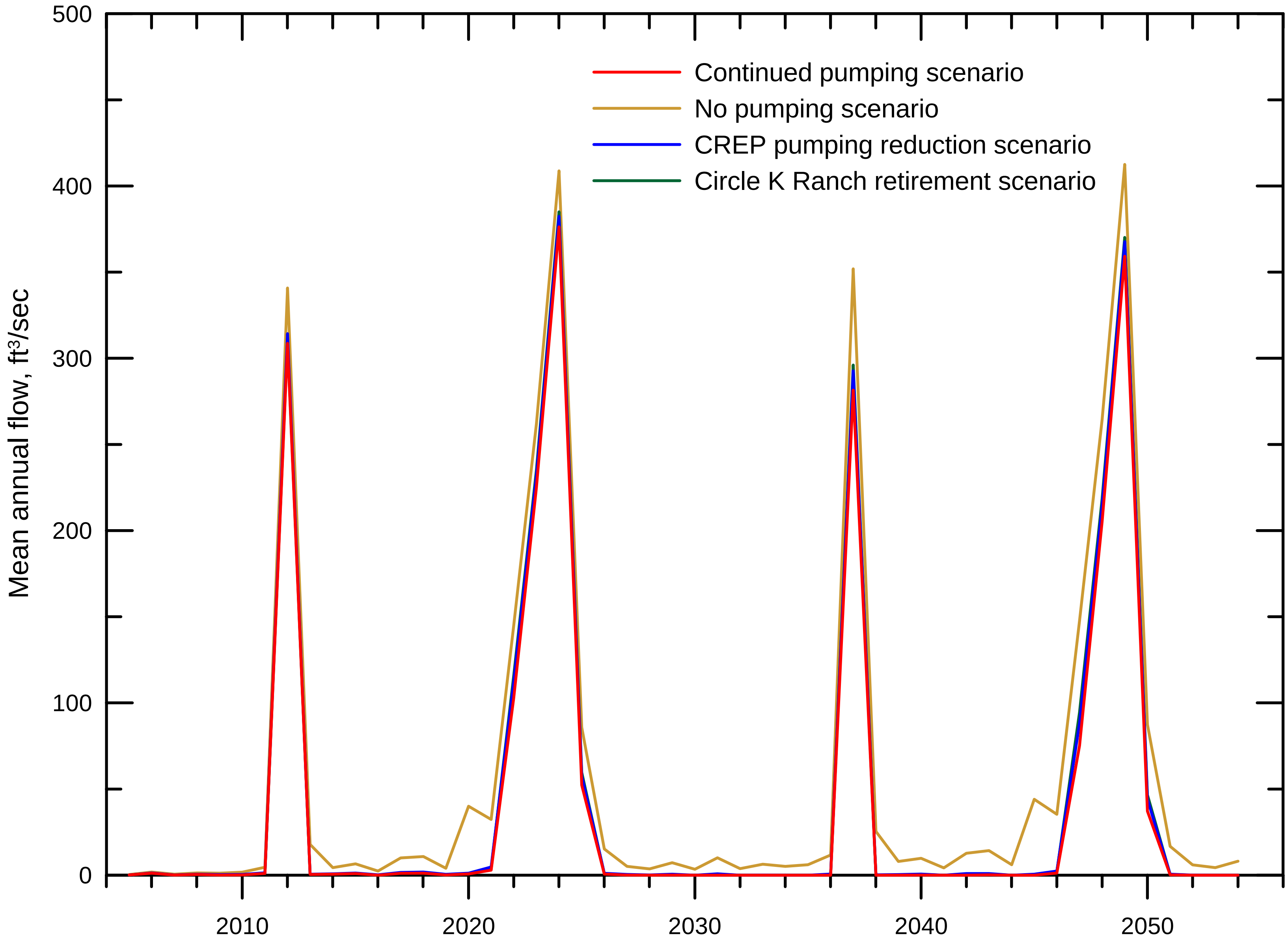

Figure 50. Arkansas River flow simulated at the Kinsley gage location for the pumping scenarios.

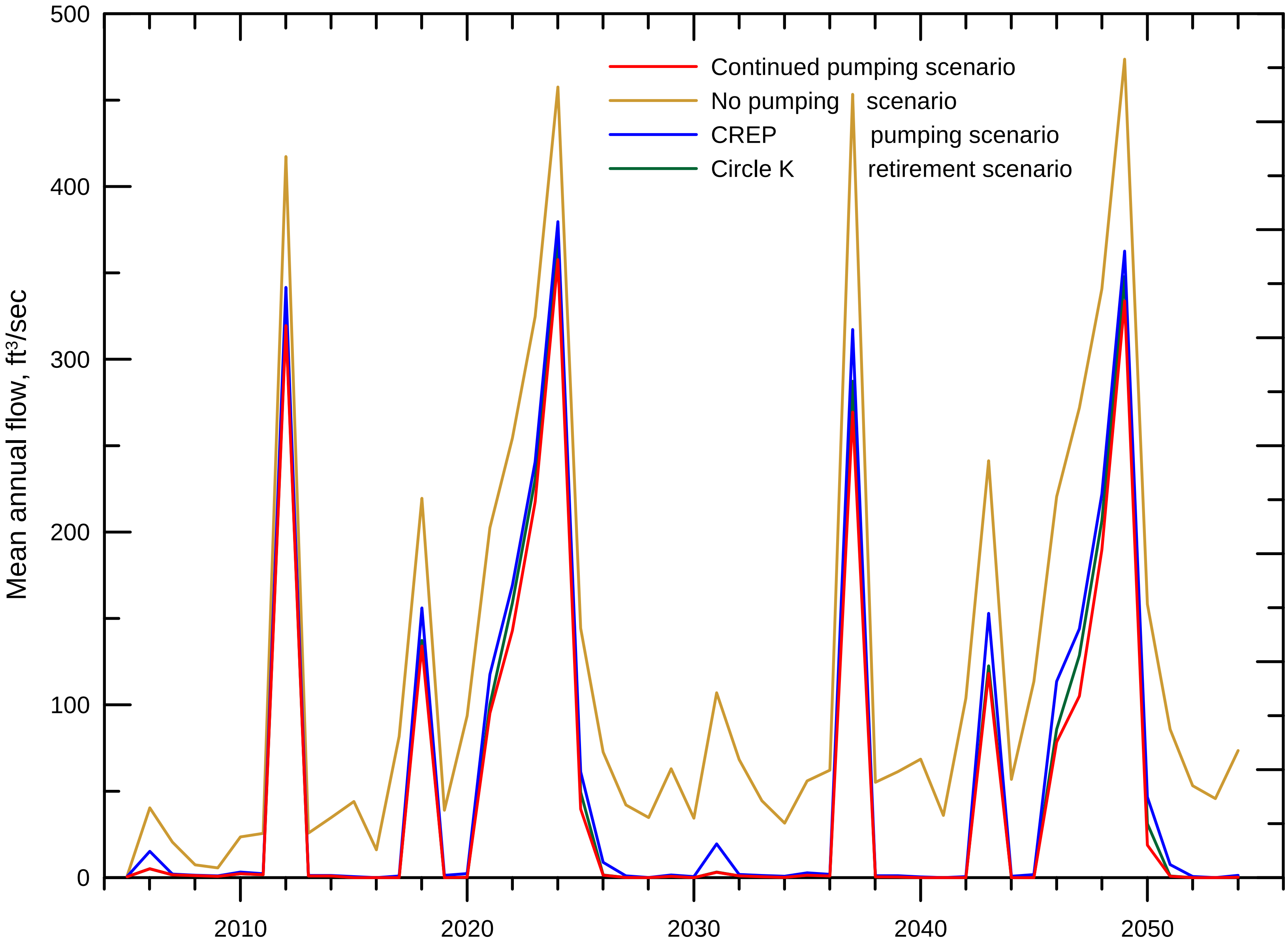

Figure 51. Arkansas River flow simulated at the Great Bend gage location for the pumping scenarios.

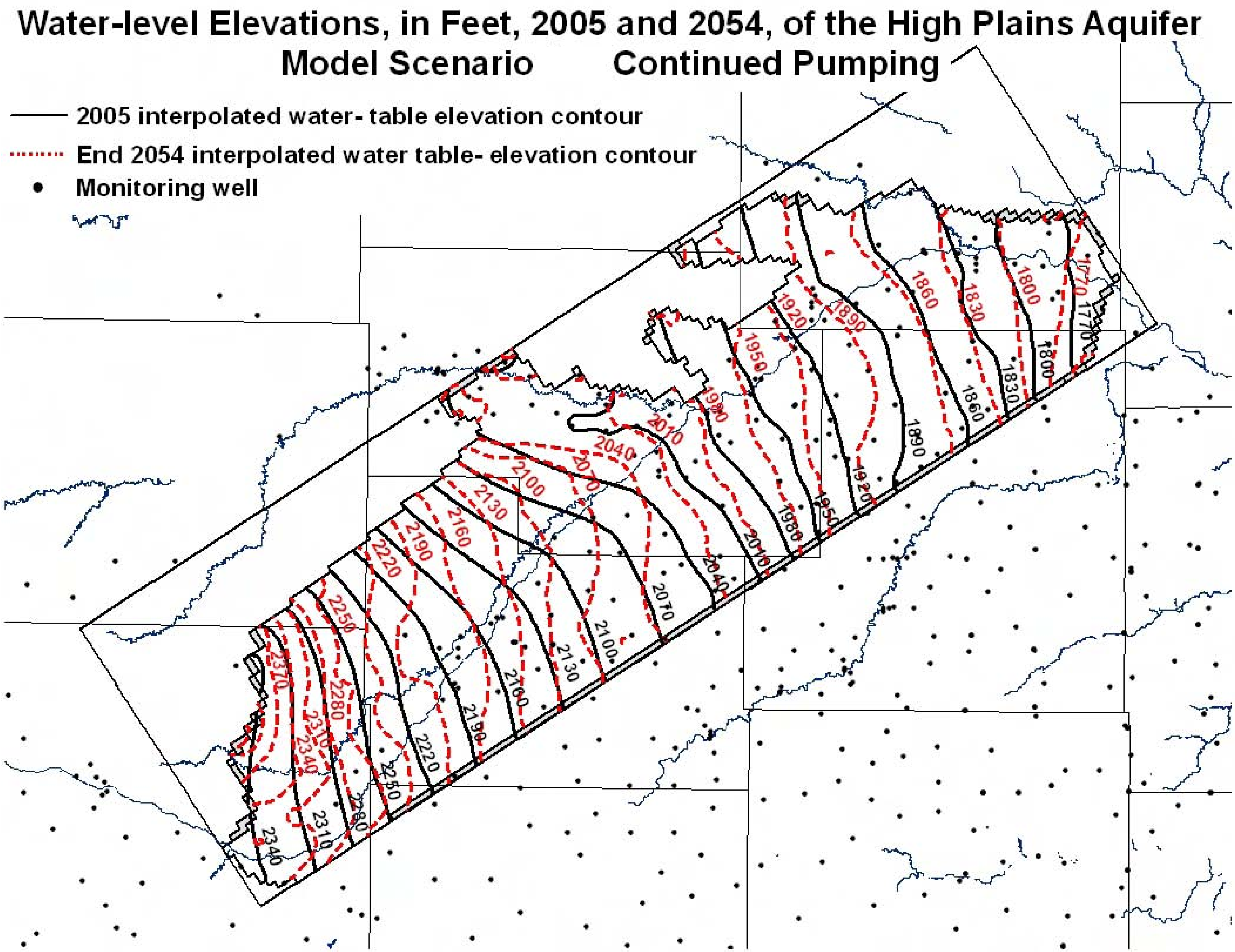

Figure 52. Comparison of observed water-level contours (2005) with contours simulated for the continued pumping scenario (2054).

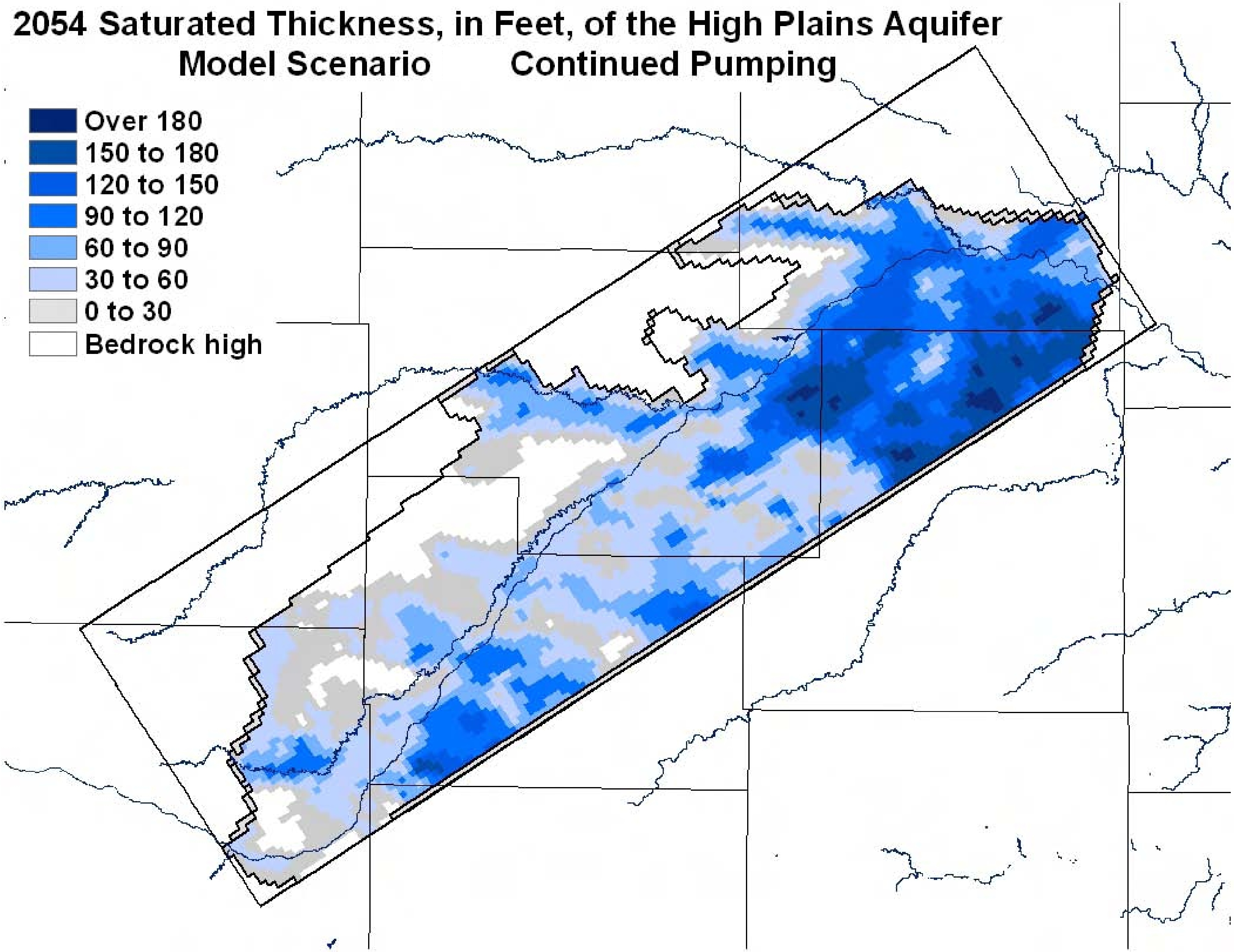

Figure 53. Saturated thickness of the High Plains aquifer simulated for the continued pumping scenario.

the hydraulic conductivity varies substantially across the aquifer, so the minimum saturated thickness practical for irrigation could range from about 20 to 40 ft. A comparison of Figures 17 and 53 shows that the areas of less than 30 ft of saturated thickness south of the Arkansas River (the light gray areas, as well as the two small white patches in central Edwards County that become bedrock highs, in Figure 53) greatly expand since 2005 and are largest in central Edwards, southeast Pawnee, and west-central Stafford counties.

The change in the water-level surface from that observed in January 2005 to that simulated in 2054 with the continued pumping scenario (Figure 54) shows that substantial declines would occur in the main aquifer south of the Arkansas River if pumping continued at the current levels. The declines are largest in central Edwards, southeast Pawnee, and west-central Stafford counties, the same locations of expansions of areas of saturated thickness less than 30 ft in the scenario. The large declines are generally in the same region as those that occurred from predevelopment to 2005 (Figure 18), although the location with the greatest decline to 2005 is along part of the north-south border of Pawnee and Stafford counties, and the area with the largest decline simulated from 2005 to 2054 is in central Edwards County.

In general, the continued pumping scenario indicates that, beginning in the late 1970s and extending into the future, the subbasin captures an increasingly greater percentage of precipitation recharge because of lower water tables, causing decreases in streamflow and lateral outflow of ground water. The variations in aquifer storage increase; the losses became greater during drier years but the amount of precipitation recharge capture increases. Although the extra capture of recharge helps, the long-term trend in aquifer storage is still a substantial decline. Greater variations with time also appear in the streamflow and to some extent in the year-to-year change in net streamflow gain during 2005-2054 (Figure 46). However, because the streamflow in low-flow years decreases and the duration of no-flow periods increases during 2005-2054, the overall changes in flow between Kinsley and Great Bend become smaller (zero flow minus zero flow, for example). The decrease in the net lateral flow decreases the ground-water flow into the Rattlesnake Creek subbasin.

No Pumpage

The time-varying specified head boundaries of the previous scenarios were treated as constant-head boundaries (2004 heads) for the 2005-2054 period in the no pumpage scenario. The rest of the conditions were the same as for the continued pumping scenario except that all pumping was turned off.

The results are clearly different from the continued pumping scenario. In the no pumping scenario, the budget plot (Figure 55) shows that the aquifer storage losses are smaller and net lateral flow and streamflow gains are greater for 2005-2054 than for 1980-2004. The storage losses are substantially smaller than for the continued pumping scenario for 2005-2054. The storage gains for the highest recharge years in the no pumping scenario are smaller than in the continued pumping scenario during 2005-2054 because there is more discharge to the stream and greater lateral outflow of ground water. The net streamflow gain, lateral flow, and evapotranspiration all successively increase during 2005-2054 (Table 9). The drains start flowing again during 2005-2029 and increase further during 2030-2054 as a result of higher

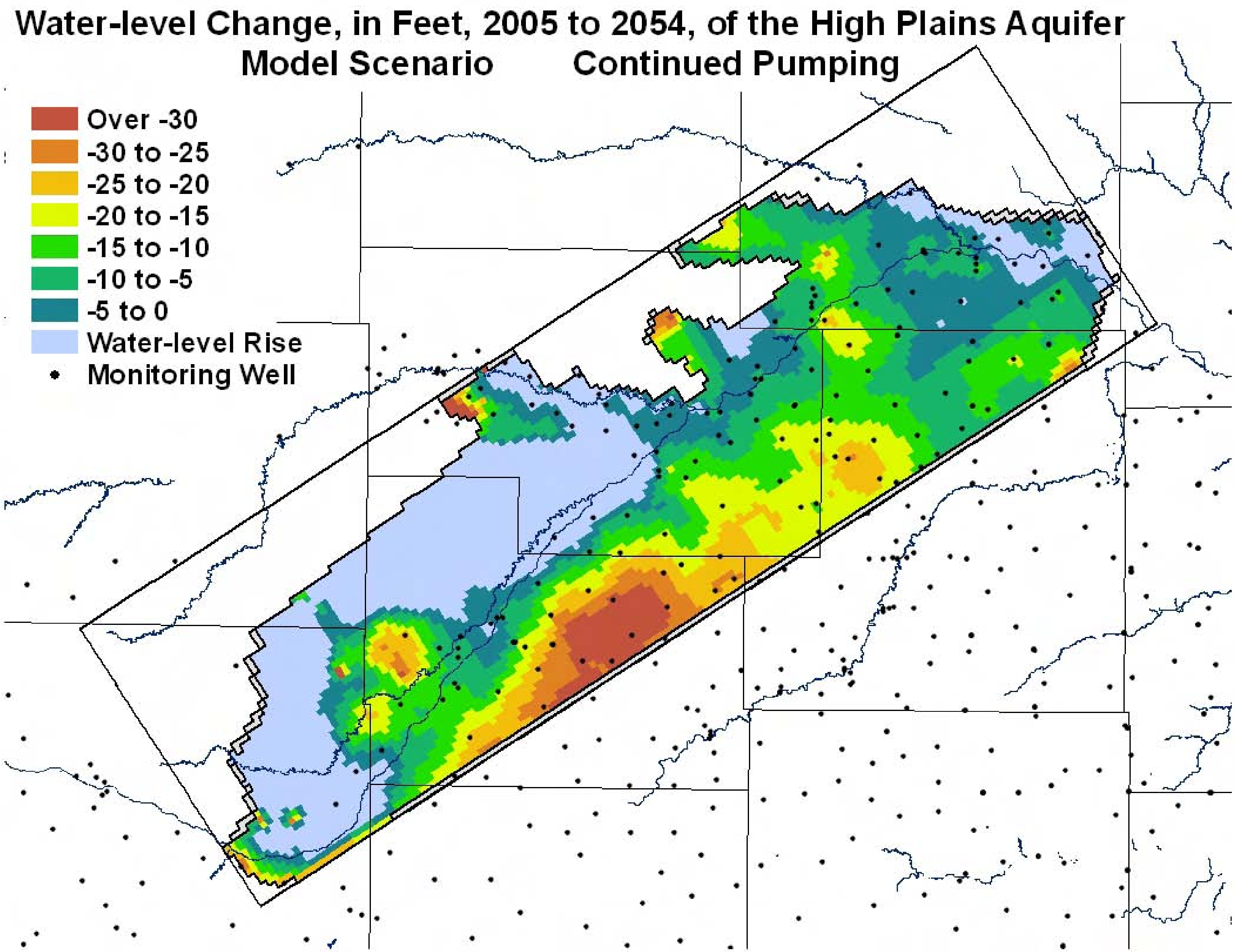

Figure 54. Difference between water table observed in 2005 and that simulated for the end of the continued pumping scenario.

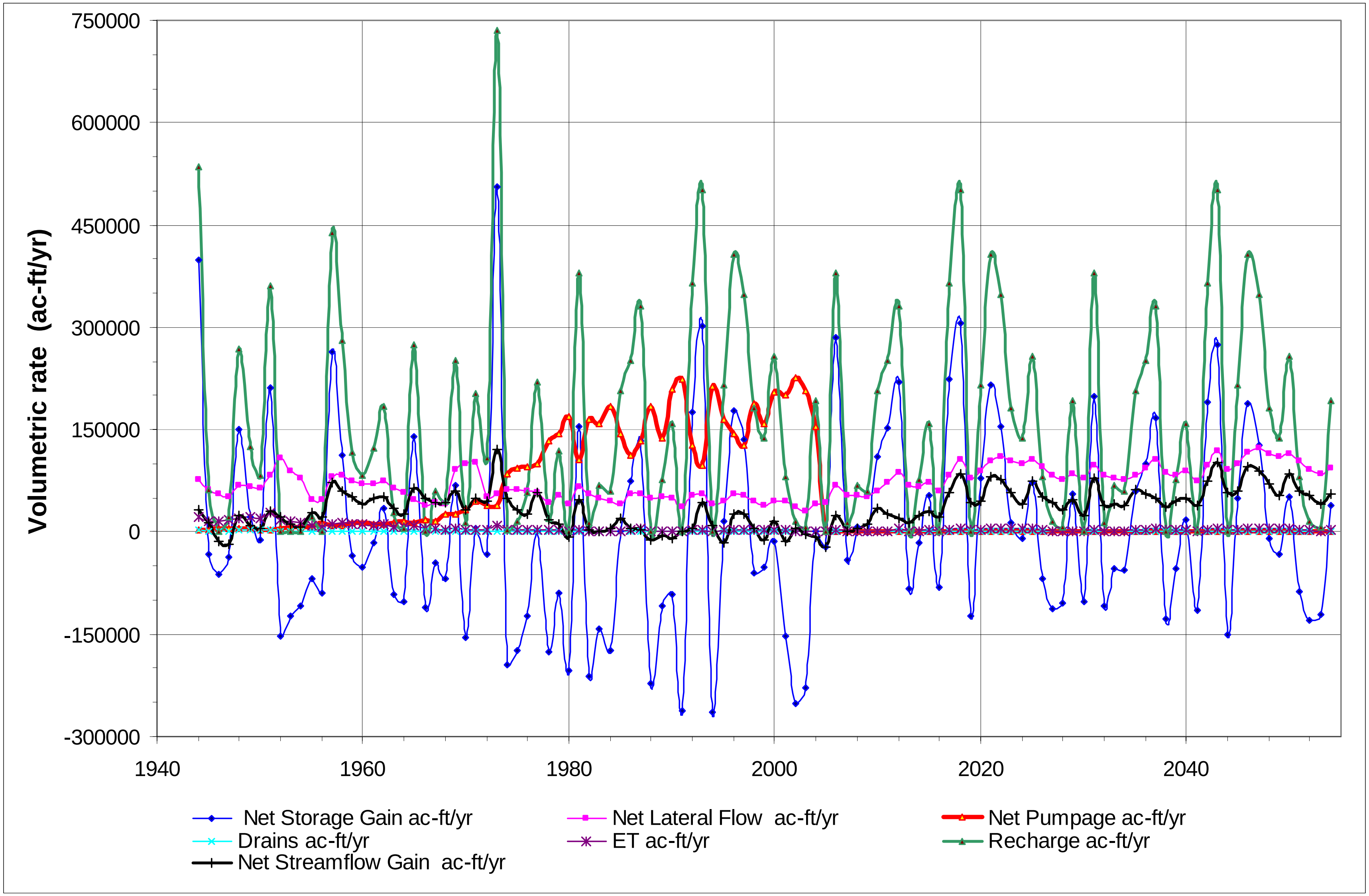

Figure 55. Water budget components simulated for the no pumping scenario.

ground-water levels. The variability in net aquifer storage for 2005-2054 is smaller than for 1980-2004 (Figure 55), and substantially smaller than for the continued pumping scenario for 2005-2054 (Figure 46). Table 10 shows the great difference in the water budget components between the continued pumping and no pumping scenarios.

The decline in the cumulative net storage loss in the aquifer for 1980-2004 reverses and becomes a cumulative gain after 2004 in the no pumping scenario (Figure 56). The storage generally increases steadily until the mid-2020s and then increases at a slower rate. This change in slope is related to the increases in lateral outflow, streamflow gain, evapotranspiration, and drain flow. By the mid 2040s, the aquifer storage has recovered to the range prior to the late 1970s. The cumulative net lateral flow begins to curve upward after 2004 (Figure 56). The net streamflow gain takes somewhat longer to respond; the slow rise begins around 2010. The additional time is required for the water tables to rise sufficiently in the vicinity of the rivers such that baseflow can start to increase.

Hydrographs for the no pumping scenario generally show an increase in water level starting at the end of 2005 (for example, Figure 57). The rises for the wells near the Arkansas1970s. The cumulative net lateral flow begins to curve upward after 2004 (Figure 56). The net streamflow gain takes somewhat longer to respond; the slow rise begins around 2010. The additional time is required for the water tables to rise sufficiently in the vicinity of the rivers such that baseflow can start to increase.

Hydrographs for the no pumping scenario generally show an increase in water level starting at the end of 2005 (for example, Figure 57). The rises for the wells near the Arkansas River are relatively small in comparison with those for wells at a distance from the river during the 50-year period and mainly occur within a few to several years after the end of 2005 (for example, compare Figure 49B with Figure 57). The variability in the water levels for wells near the river generally becomes much smaller in the no pumping than in the continued pumping scenario once baseflow is reestablished (for example, compare Figures 49A and B). The water levels in the no pumping scenario increase substantially for the wells in the main aquifer away from the river until the mid-2020s and then rise at a slower rate (Figure 57) primarily because there is more lateral outflow and discharge to the river during the later period.

The flow simulated for the Arkansas River in the no pumping scenario increases at all three gaging stations for 2005-2054 (Table 11). The simulated flow in the Arkansas River generally increases at Kinsley, Larned, and Great Bend after 2005 and continues to 2054. However, the lower flow years for the Arkansas River near Kinsley are still substantially lower for 2030-2054 than for the period prior to the mid-1970s. If the difference between the Arkansas River inflow for 1944-1979 and 1980-2004, which is about 104 ft^3/sec, is added to the flow simulated for 2030-2054 (Table 11), the simulated streamflows at Kinsley and Great Bend are close to those measured during 1944-1979. Table 12 illustrates the large difference in streamflows between the continued and no pumping scenarios.

The contours for the water-level surface simulated for the end of 2054 (Figure 58) are generally shifted in a downgradient direction relative to the contours for the water-level surface observed in January 2005 in recharge zones 1 and 3 south of the Arkansas River. However, the

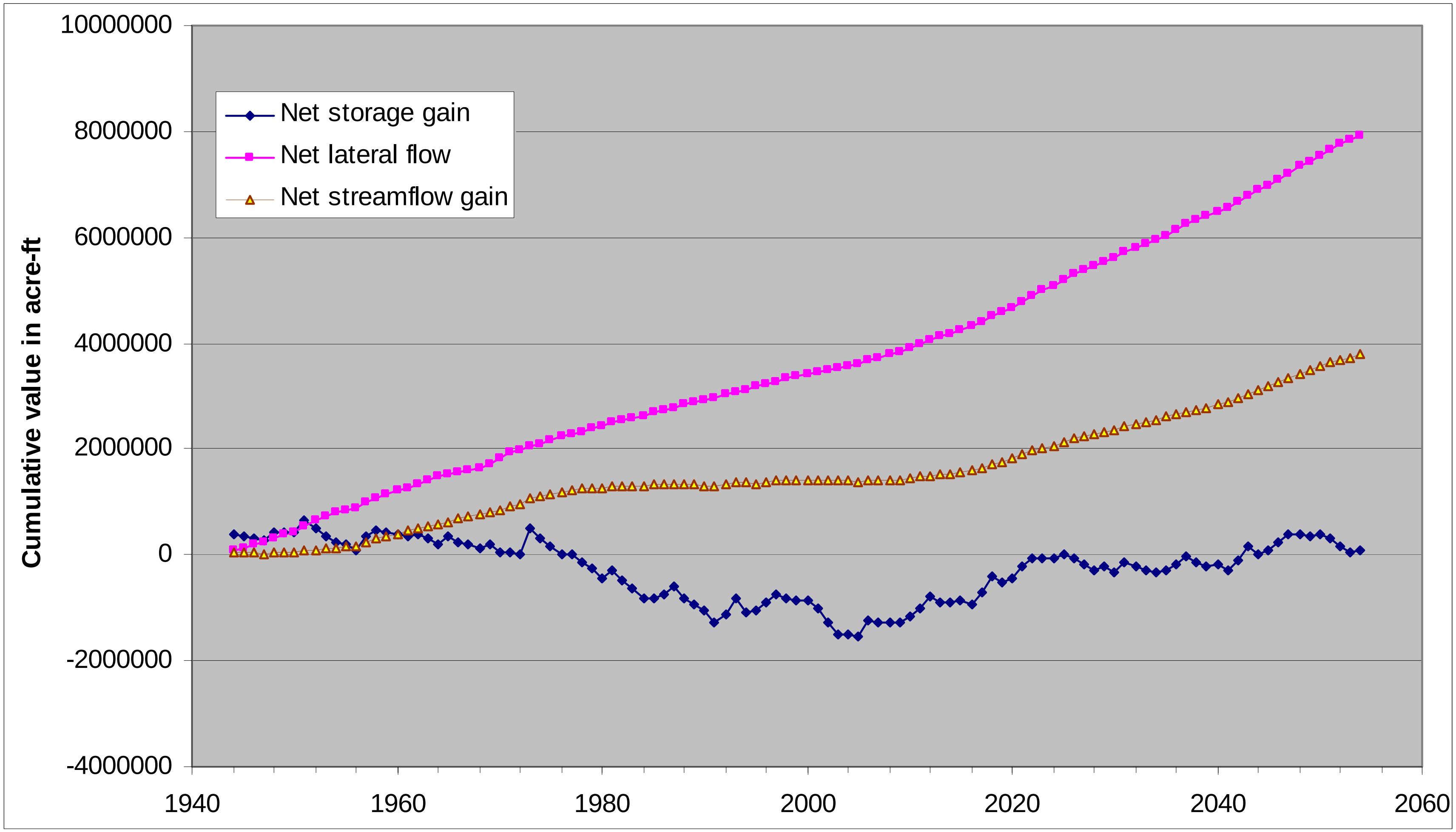

Figure 56. Cumulative net aquifer storage, streamflow gains, and lateral flow simulated for the no pumping scenario.

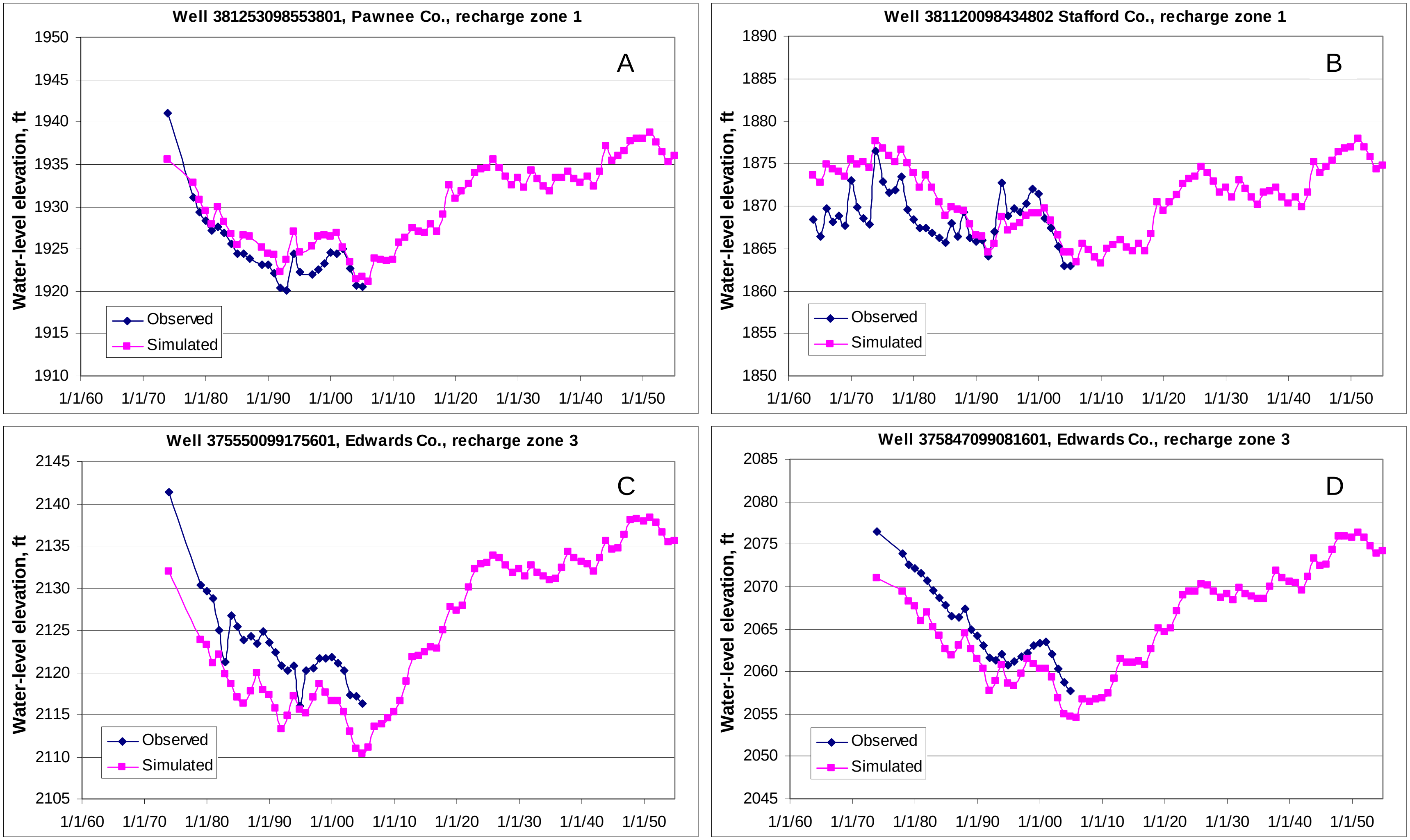

Figure 57. Examples of hydrographs for wells in the hydraulic conductivity zone for the main aquifer and in recharge zones 1 and 3 for the no pumping scenario. Hydrographs A and C are for wells near the hydraulic conductivity zone that includes the alluvial aquifer, and hydrographs B and D are for wells near the middle of recharge zones 1 and 3 and at a greater distance from the hydraulic conductivity zone that includes the alluvial aquifer. See Figure 2 for well locations.

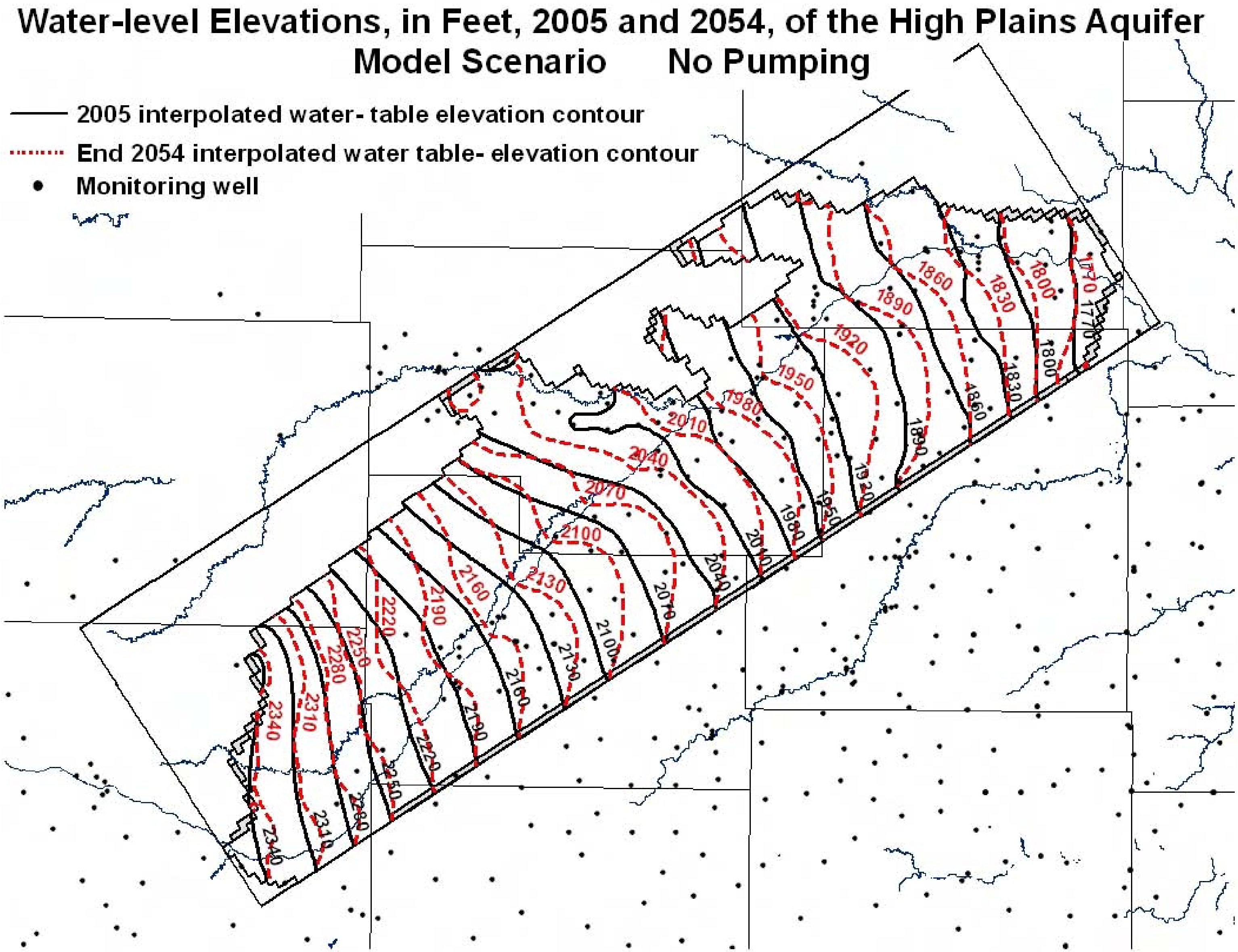

Figure 58. Comparison of observed water-level contours (2005) with contours simulated for the no pumping scenario (2054).

most easterly contour did not change substantially from the base simulation, indicating the smaller impact of pumping at the northeast end of the model area. Figure 58 suggests that if the water-levels had been allowed to rise along the constant head southern boundary, the contours might have rotated slightly in a counterclockwise direction, indicating a regional flow more closely related to the direction of the Arkansas River and Rattlesnake Creek valleys.

There are substantial increases in the saturated thickness simulated for the no pumping scenario (Figure 59) compared to the saturated thickness in 2005 (Figure 17) in the main aquifer area, and parts of the Pawnee River and side valleys. The expansion of the greater than 60-ft areas of saturated thickness is particularly notable.

The change in the water-level surface from that observed in January 2005 to that simulated in 2054 with the no pumping scenario (Figure 60) shows that substantial rises would occur in the main aquifer south of the Arkansas River and in part of the Pawnee River valley if all pumping ceased. The rises are greatest in a band extending from central Edwards through southeast Pawnee and west-central Stafford to south-central Barton counties, and in part of the Pawnee River valley south of the river. These rises are in areas where current ground-water pumping is substantial. The large water-level rises are generally in the same region as the declines that occurred from predevelopment to 2005 (Figure 18), although the location with the greatest decline to 2005 is along part of the north-south border of Pawnee and Stafford counties, and the area with the largest rise simulated from 2005 to 2054 is in south-east Pawnee County. Little significance should be attached to the large water-level rises in the area from southeast Hodgeman through northwest Edwards into southwest Pawnee counties because there are no monitoring wells in that area and thus little data. This is also an area where there is little to no saturated thickness in the surficial unconsolidated sediments.

In general, the no pumping scenario indicates that the long-term water-level declines in the main aquifer that began in the late 1970s start to reverse within a few years after the wells are shut off. The change from streamflow loss to increase takes a few years longer to occur due to the need to raise water levels enough to create substantial baseflow and reduce stream loss. The magnitude of the variations in aquifer storage, water levels near the river, and streamflow decrease. The increase in the net lateral flow increases the ground-water flow into the Rattlesnake Creek subbasin relative to the present condition.

Reduced Pumpage within Proposed CREP Area

The Conservation Reserve Enhancement Program (CREP) of the U.S. Department of Agriculture is a voluntary program for agricultural landowners that is a recent program within the Conservation Reserve Program (CRP). Under a state and federal partnership, landowners can receive annual rental payments and cost-share assistance to establish long-term, resource conserving covers on eligible land and to set aside that land for soil and water conservation. This includes not pumping ground water for irrigation from that land. The Kansas Water Plan Project Initiatives includes a proposed CREP project for the High Plains aquifer in the Arkansas River corridor from the state line with Colorado to Great Bend (Kansas Water Office web site, www.kwo.org/KWA/WPPI/Project_1.pdf). The DWR and KWO developed a scenario to be simulated with a 24% reduction in irrigation in the portion of the subbasin proposed for the

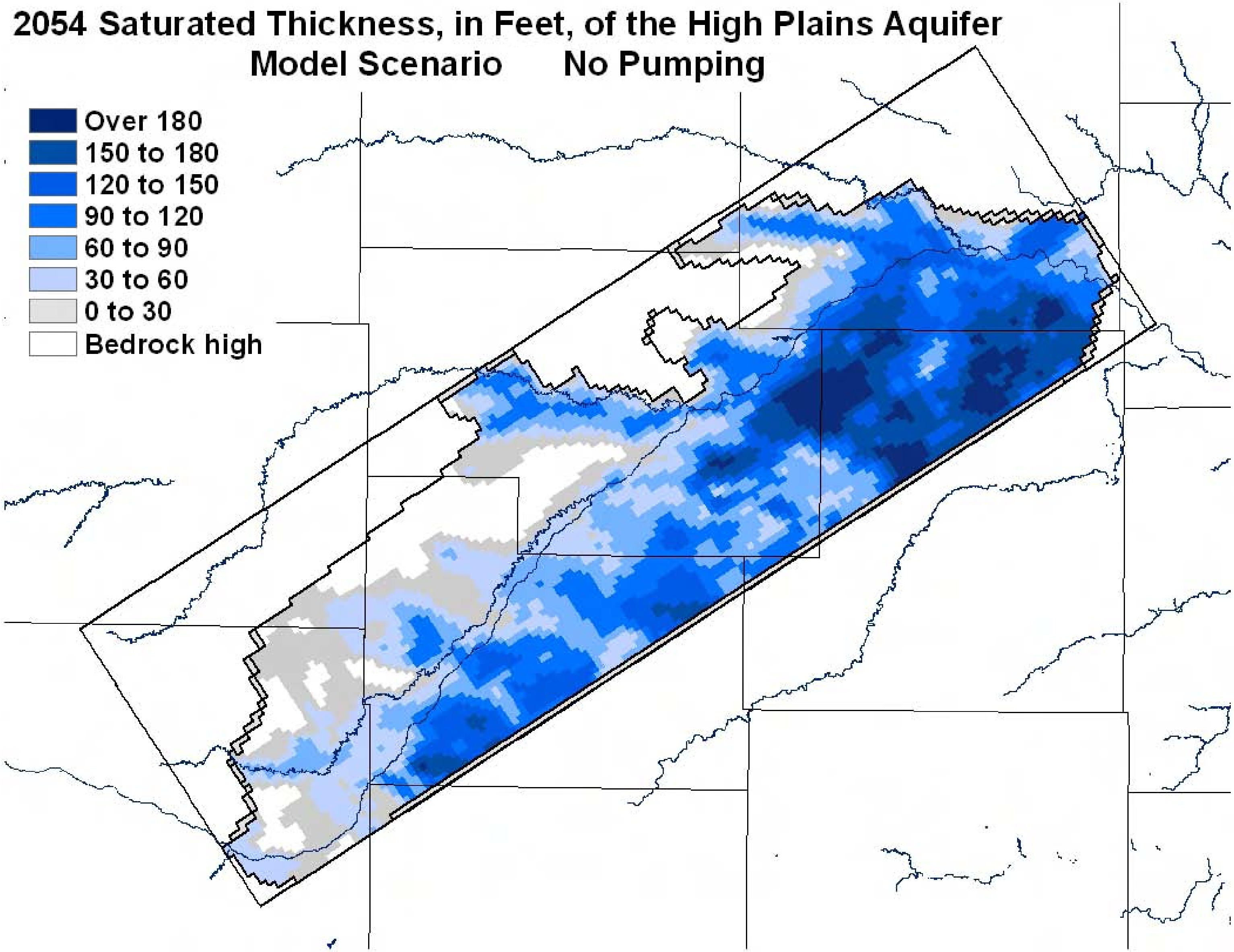

Figure 59. Saturated thickness of the High Plains aquifer simulated for the no pumping scenario.

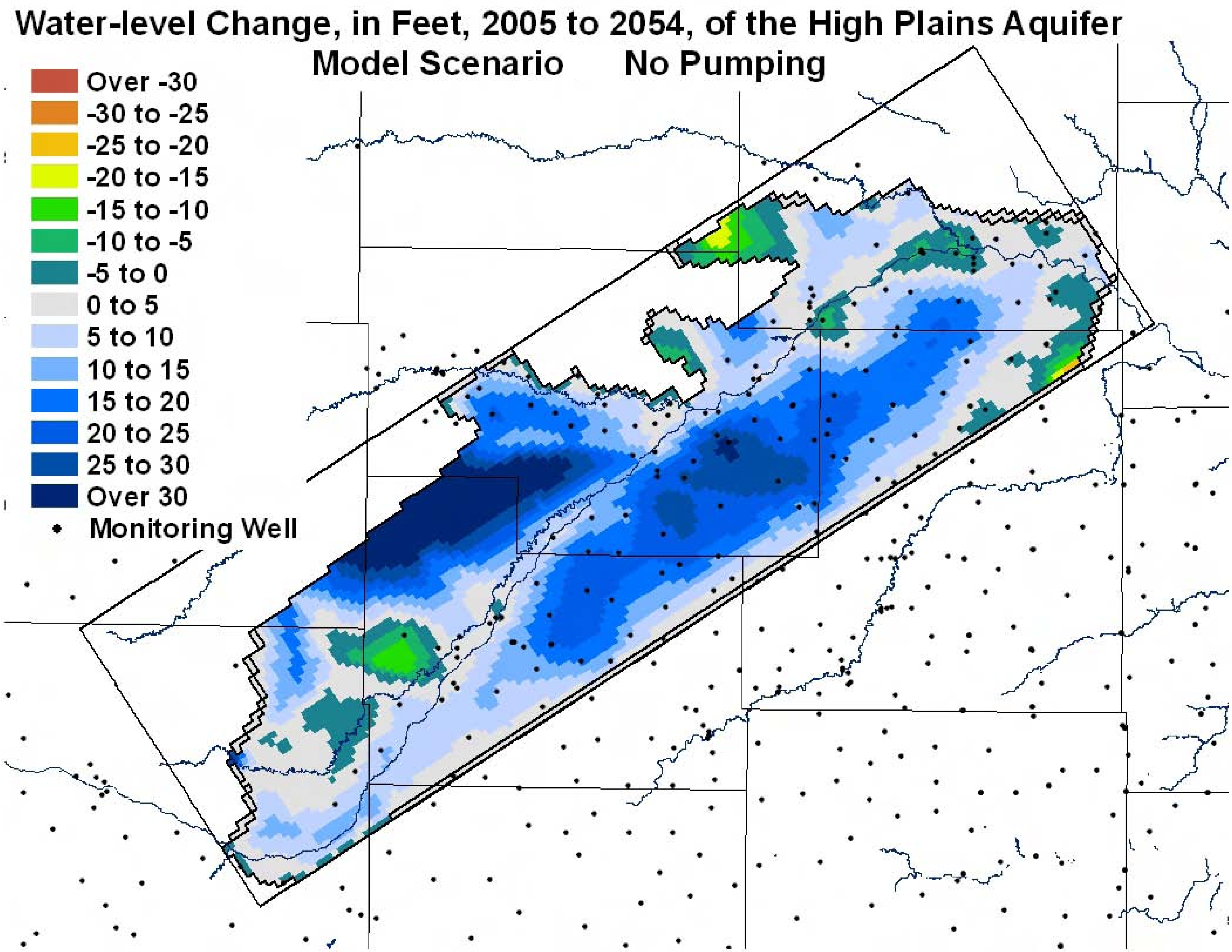

Figure 60. Difference between water table observed in 2005 and that simulated for the end of the no pumping scenario.

CREP. The CREP area within the Middle Arkansas subbasin only covers a portion of the active model area (Figure 61).

All of the conditions for the CREP scenario were the same as for the continued pumping scenario except for the reduction of 24% in the pumping in the CREP area for the 2004-2054 period. The 24% CREP condition amounts to a net pumping reduction of 25,287 acre-ft/yr compared to the continued pumping scenario (Table 10), which is equivalent to a reduction of 14.3% averaged over the active model area.

The results for the CREP scenario are noticeably different from those for the continued pumping scenario. The net streamflow is a loss during 2005-2054 for the CREP scenario but the rate is only about half as large as that for continued pumping (Table 9). The rate of aquifer storage loss for 2005-2054 in the CREP scenario is 18,135 acre-ft/yr, which is about 60% of that in the continued pumping scenario. The net lateral flow decreases at a much smaller rate in the CREP than in the continued pumping scenario. The budgets for the individual years indicate that the aquifer storage losses during years with losses are somewhat smaller for each successive 25-year scenario period than for 1980-2004, and storage gains during years with gains are greater. The differences in the net streamflow between the CREP and continued pumping scenarios increase from 2005-2029 to 2030-2054, as do the differences in the net lateral flow (Table 10). In contrast, the differences in the net aquifer storage between the two scenarios decrease between these two periods.

The cumulative net storage loss for the CREP scenario (Figure 62) is not as great a decline as for the continued pumping scenario. The cumulative storage loss by 2054 is about 2,500,000 acre-ft for the CREP scenario compared to approximately 3,000,000 acre-ft for the continued pumping scenario. The rate of storage loss is not as great during the latter part of the period as during the earlier part. The cumulative net lateral flow appears as nearly a straight line during 2005-2054, indicating that there is little decrease in the flow rate. The net streamflow gain decreases over 2005-2054, indicating the long-term loss of streamflow to the aquifer. However, the rate of loss is not as great as for the continued pumping scenario.

The rate of long-term water-level declines in hydrographs are not as great for the CREP scenario as for those in the continued pumping scenario (for example, compare Figure 63 with Figure 48). In addition, the rates of decline generally slow at a greater rate during the latter half of 2005-2054 for hydrographs in the CREP scenario than for those in the continued pumping scenario. The variations in the hydrographs of wells in the vicinity of the Arkansas River valley in the CREP scenario are generally smaller in amplitude than those in the continued pumping scenario, indicating that the water levels in the alluvial aquifer do not decline as much during dry years (for example, compare Figures 49A and C).

The decline in the water-level surface from that observed in January 2005 to that simulated in 2054 for the CREP scenario (Figure 64) is substantially less than that for the continued pumping scenario (Figure 54) in the High Plains aquifer south of the Arkansas River. The area of the >15 ft decline in the water-level surface is appreciably smaller, especially in central Edwards, southeast Pawnee, and west-central Stafford counties. The difference between

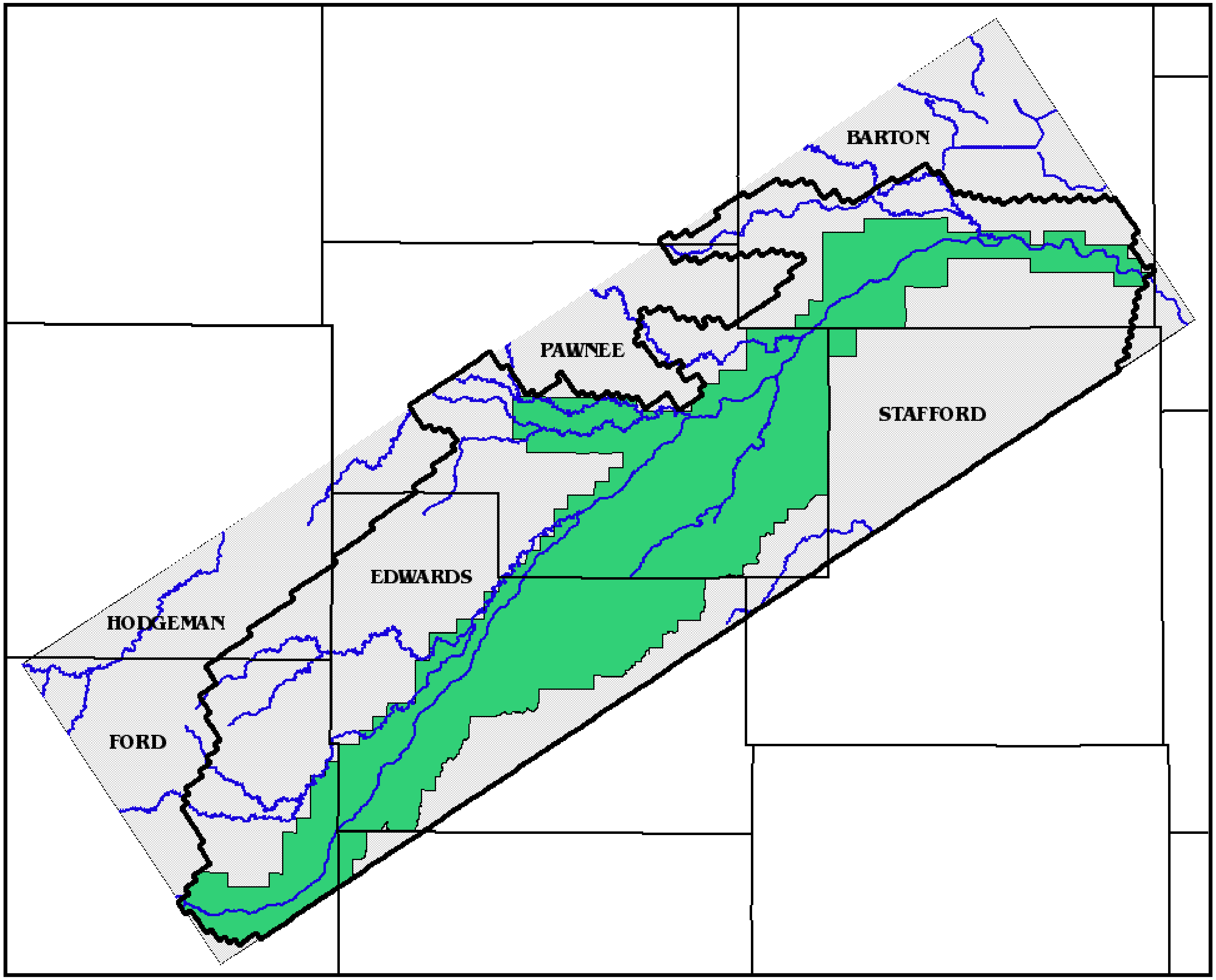

Figure 61. Location of proposed CREP area (shaded in green) in the Kansas Water Plan Projects Initiative.

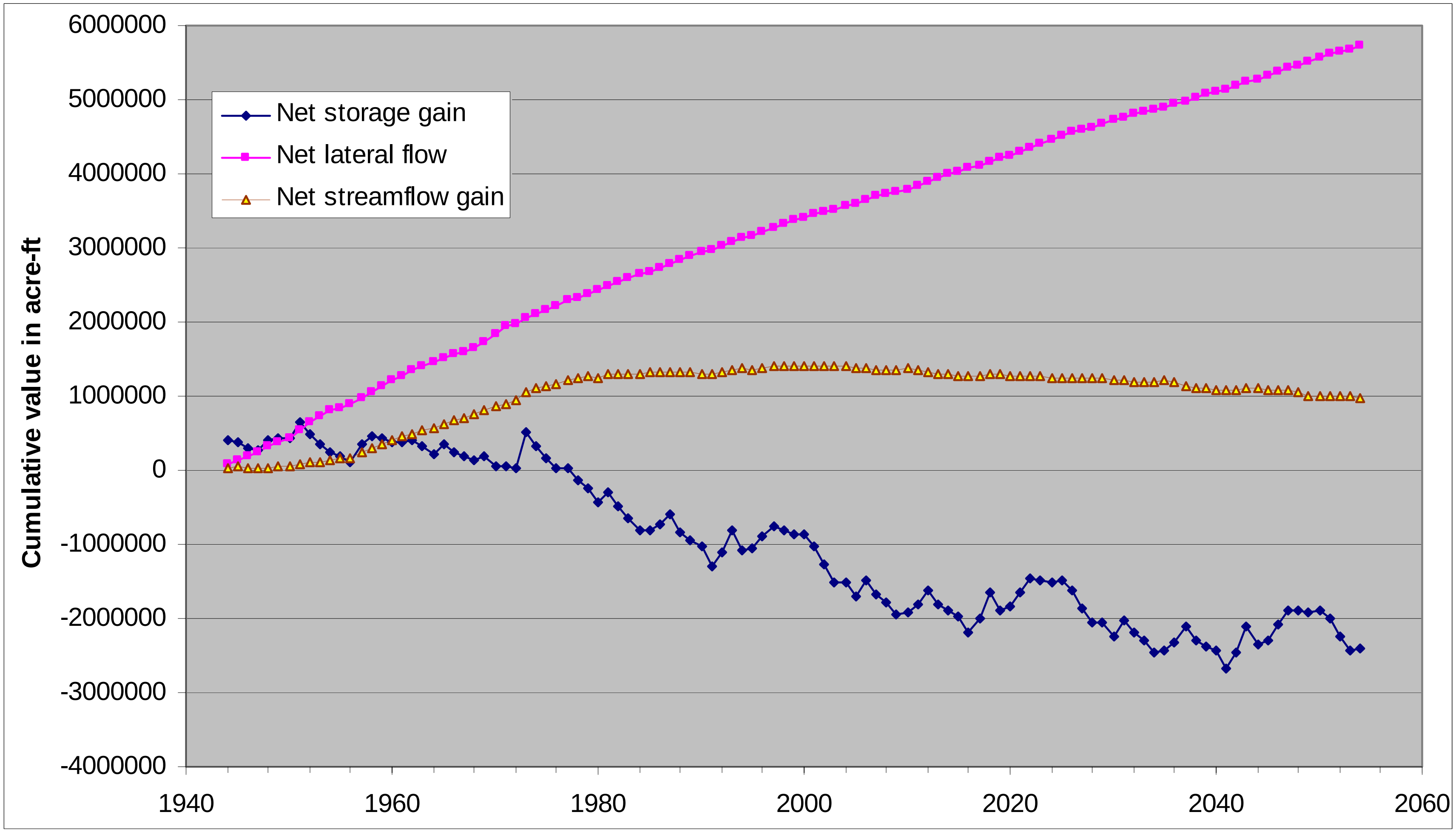

Figure 62. Cumulative net aquifer storage, streamflow gains, and lateral flow simulated for the CREP scenario.

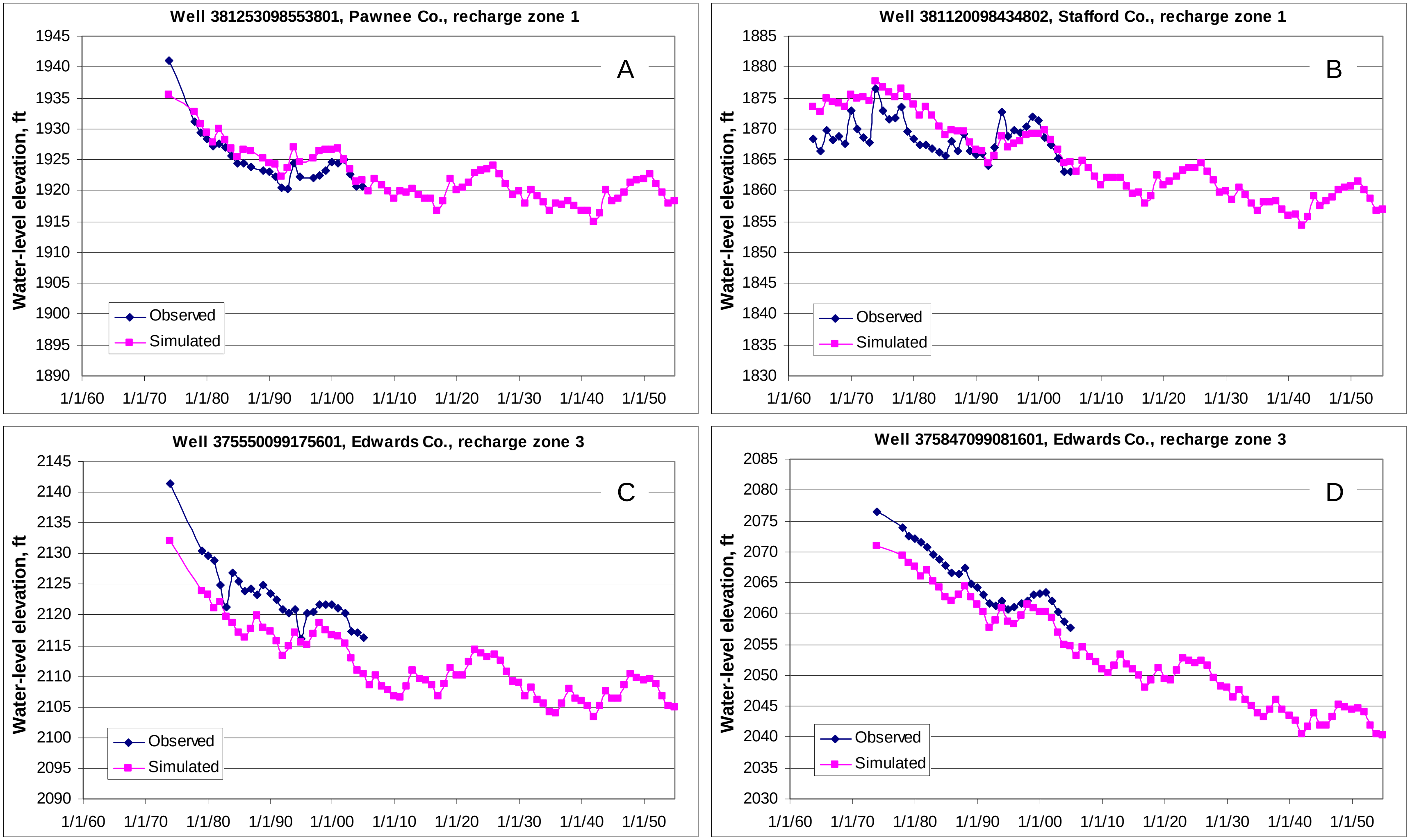

Figure 63. Examples of hydrographs for wells in the hydraulic conductivity zone for the main aquifer and in recharge zones 1 and 3 for the CREP pumping scenario. Hydrographs A and C are for wells near the hydraulic conductivity zone that includes the alluvial aquifer, and hydrographs B and D are for wells near the middle of recharge zones 1 and 3 and at a greater distance from the hydraulic conductivity zone that includes the alluvial aquifer. See Figure 2 for well locations.

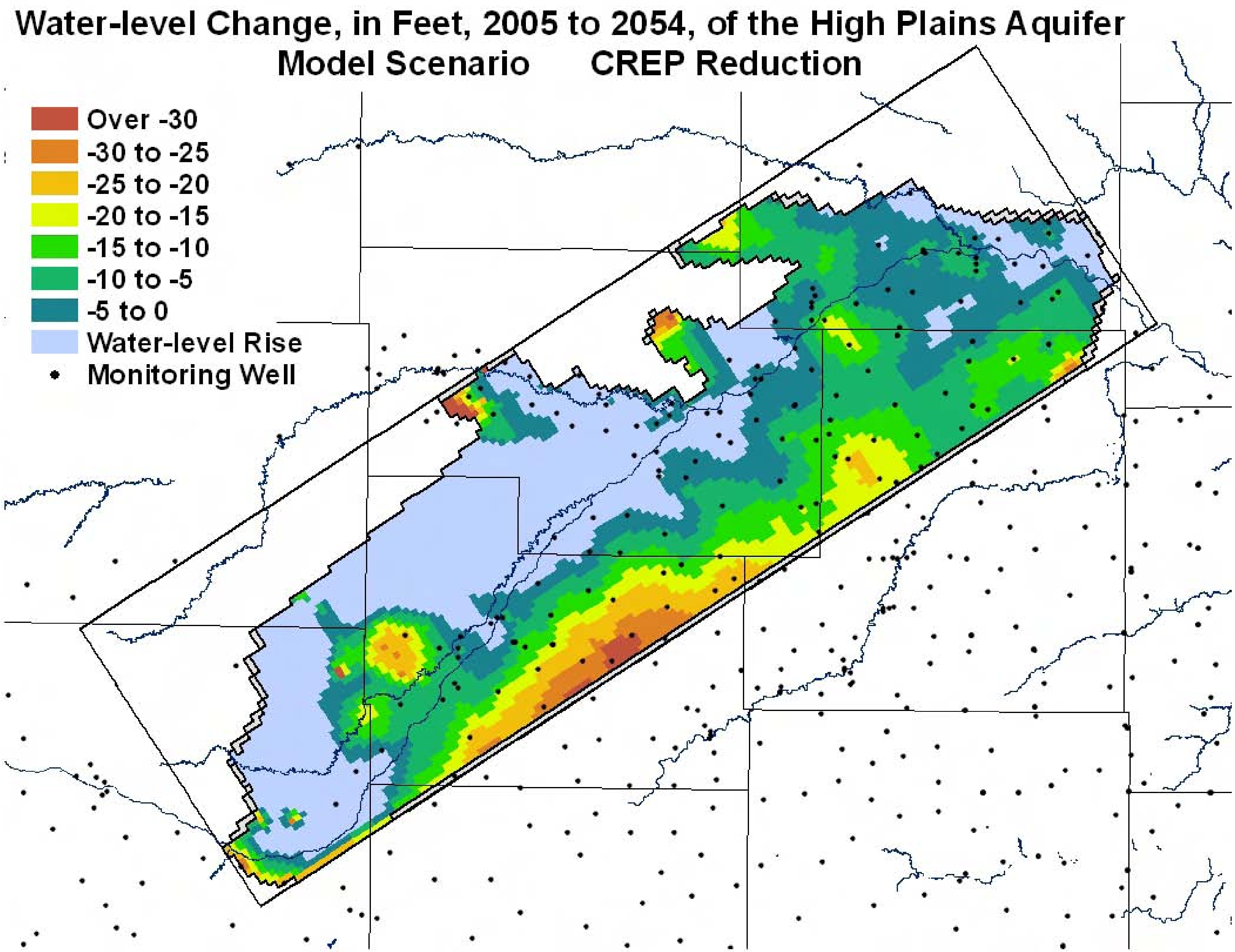

Figure 64. Difference between water table observed in 2005 and that simulated for the end of the CREP pumping scenario.

the CREP and continued pumping scenarios is smaller for the High Plains aquifer in the northeast part of the active model area.

The average Arkansas River flows in the CREP scenario decline during 2005-2054 but at a slower rate than in the continued pumping scenario (Table 11). The differences in the rates of decline between the two scenarios increase in a downstream direction (from the Kinsley to Larned to Great Bend gaging station locations, Tables 11 and 12). There are fewer years with essentially no flow at the Kinsley, Larned, and Great Bend gaging stations during 2005-2054 for the CREP than for the continued pumping scenario.

In general, the losses in net storage, streamflow, and lateral flow are not nearly as great in the CREP as in the continued pumping scenario but they continue during the 2005-2054 period. A substantially greater reduction in pumping would be needed to keep storage losses from declining and to restore perennial flow in the Arkansas River.

Retirement of Circle K Ranch Water Rights

One of the Basin Priority issues of the Upper Arkansas basin in the Kansas Water Plan is the Circle K Ranch Water Retirement, www.kwo.org/Kansas%20Water%20Plan/UARK_Basin_Section_081605.pdf. The Circle K Ranch was purchased by the cities of Hays and Russell to supplement their future water-supply needs. The cities have changed their plans and have offered to sell the ranch to the State. The ranch is located along the south side of the Arkansas River in southwestern Edwards County (Figure 65). There are 57 wells under 30 water rights with an appropriation of 8,039 acre-ft/yr for 5,366 acres. Forty-seven of the wells are located within 1.25 miles of the river. The average annual use during 1989-2000 was 6,643 acre-ft. There were 41 irrigation circles in 2004 (shown in Figure 65). The KWO and the DWR developed a scenario for assessing the effects of retiring the water rights of the Circle Ranch on ground-water levels and Arkansas River streamflow. Table 14 provides a listing of the water rights and the retirement year (year pumping stopped in the scenario).

The conditions for the Circle K Ranch scenario were the same as for the continued pumping scenario except for stopping the pumping of the ranch water rights according to the Table 14 schedule. The average difference in the net pumping rate between the Circle K scenario and the continued pumping scenario is 8,156 acre-ft/yr after water rights in the entire ranch area are retired (2030-2054 period, Table 10). This is a reduction of 4.6% in the net pumping for the active model area. The value of 8,156 acre-ft/yr is larger than the net pumping expected from full use of the 8,039 acre-ft/yr appropriation due to the adjustment in the pumpage to remove the trend for the continued pumping scenario.

The results for the Circle K scenario are not very different from those for the continued pumping scenario, except for the area within and surrounding the Circle K Ranch. The decrease in average net pumping of 7,323 acre-ft/yr between the continued pumping and the Circle K scenarios during 2005-2054 translates into decreases of 2,297 acre-ft/yr and 2,111 acre-ft/yr in streamflow losses and storage losses, respectively, and increases of 2,900 acre-ft/yr and 15 acre-ft/yr in net lateral flow and evapotranspiration, respectively (Tables 9 and 10). The most notable

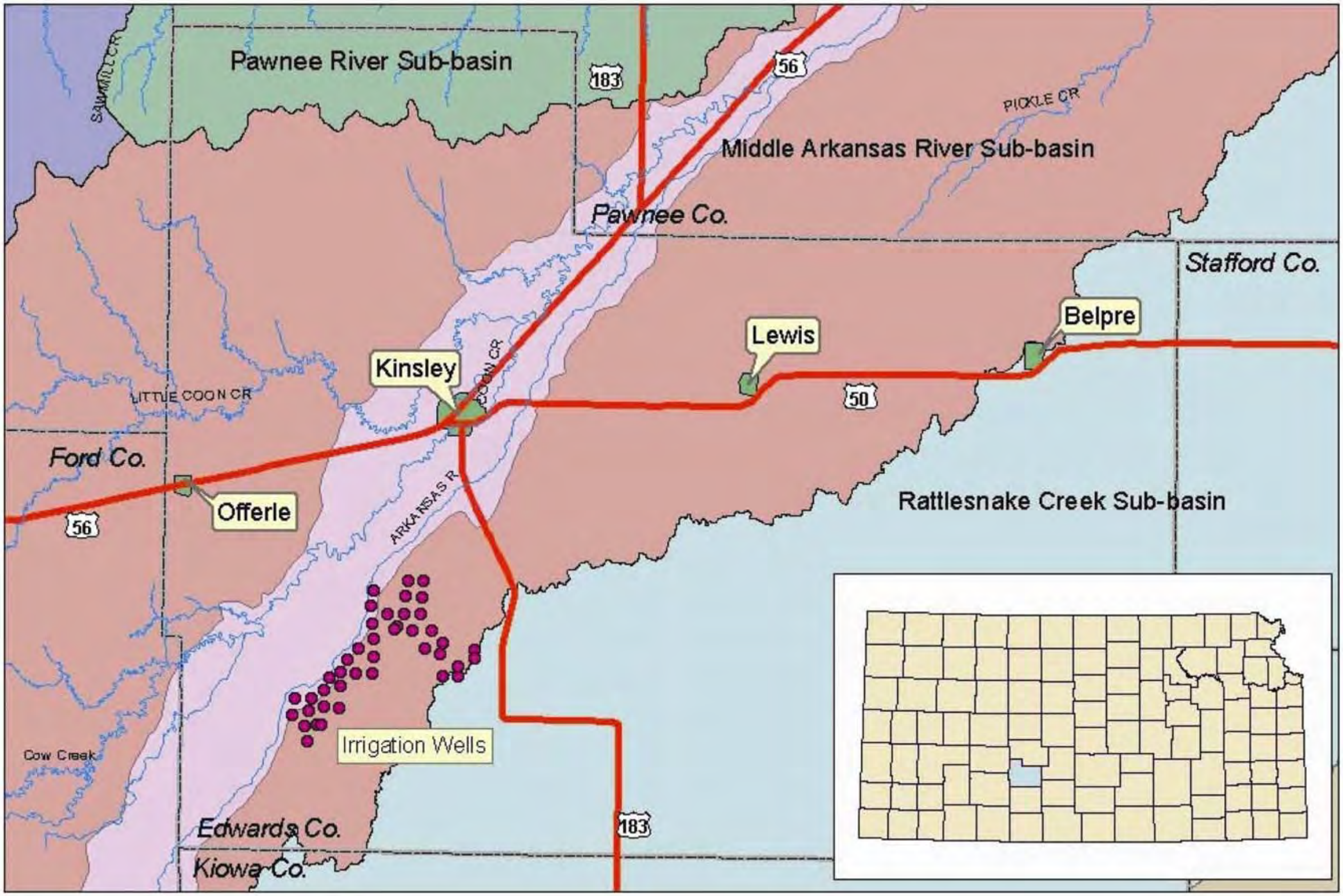

Figure 65. Location of the Circle K Ranch (red irrigation circles) in Edwards County (from the Upper Arkansas Basin Section of the Kansas Water Plan, www.kwo.org/Kansas%20Water%20Plan/UARK_Basin_Section_081605.pdf).

Table 14. Water right information and year of retirement for the Circle K Ranch scenario.

Water right number	Authorized quantity, acre-ft	Latitude	Longitude	Distance to stream, mi	Retirement year
21730	176	37.84678	99.45550	0.2462	2010
21731	800	37.84140	99.45507	0.2652	2010
22326	188	37.82121	99.46038	0.2367	2010
22332	188	37.81149	99.47256	0.2746	2010
22333	50	37.80927	99.47849	0.1136	2010
22338	162	37.80011	99.48846	0.2557	2010
22331	180	37.81594	99.46676	0.3788	2011
22335	198	37.80365	99.48147	0.3409	2011
22339	165	37.79960	99.49734	0.3220	2011
22341	188	37.79256	99.49851	0.3977	2011
22346	162	37.78200	99.49900	0.4735	2011
22325	186	37.82568	99.45326	0.6061	2012
22327	203	37.81841	99.45518	0.7481	2012
22329	108	37.81093	99.46420	0.7386	2012
22334	190	37.80572	99.47238	0.5019	2012
22340	162	37.79455	99.48981	0.7102	2012
27760	396	37.79632	99.47244	0.7386	2012
30084	147	37.81020	99.45991	0.9659	2012
21729	752	37.85122	99.42860	1.1837	2013
21732	593	37.83684	99.42993	1.6667	2013
22330	117	37.81104	99.45518	1.0606	2013
22342	75	37.78879	99.48490	1.1364	2013
22343	169	37.78796	99.49183	1.1553	2013
22345	159	37.78140	99.49022	1.6098	2013
30083	126	37.78904	99.48299	1.3068	2013
21733	189	37.82957	99.42335	2.0833	2014
21734	914	37.82458	99.41750	2.5758	2014
21841	195	37.82172	99.39996	3.4091	2014
21842	195	37.81054	99.40887	3.2197	2014
29816	188	37.81446	99.40903	3.5038	2014

difference between the water budgets for the Circle K and continued pumping scenarios is the smaller streamflow loss, which is a reduction of 14.1% in the loss rate for continued pumping. The reduction in the rates of aquifer storage loss and net lateral flow are only 7.0% and 7.6%, respectively, relative to the continued pumping scenario for 2005-2054. The appearance of the cumulative graphs for the Circle K and continued pumping scenarios is similar (Figures 66 and 47); net storage loss and net streamflow loss are only a little less and the net lateral flow only a little greater for the Circle K scenario by 2054. The difference in the cumulative storage loss between the Circle K and continued pumping scenarios by 2054 is 105,560 acre-ft, which is 3.5% less than the storage loss for the continued pumping scenario.

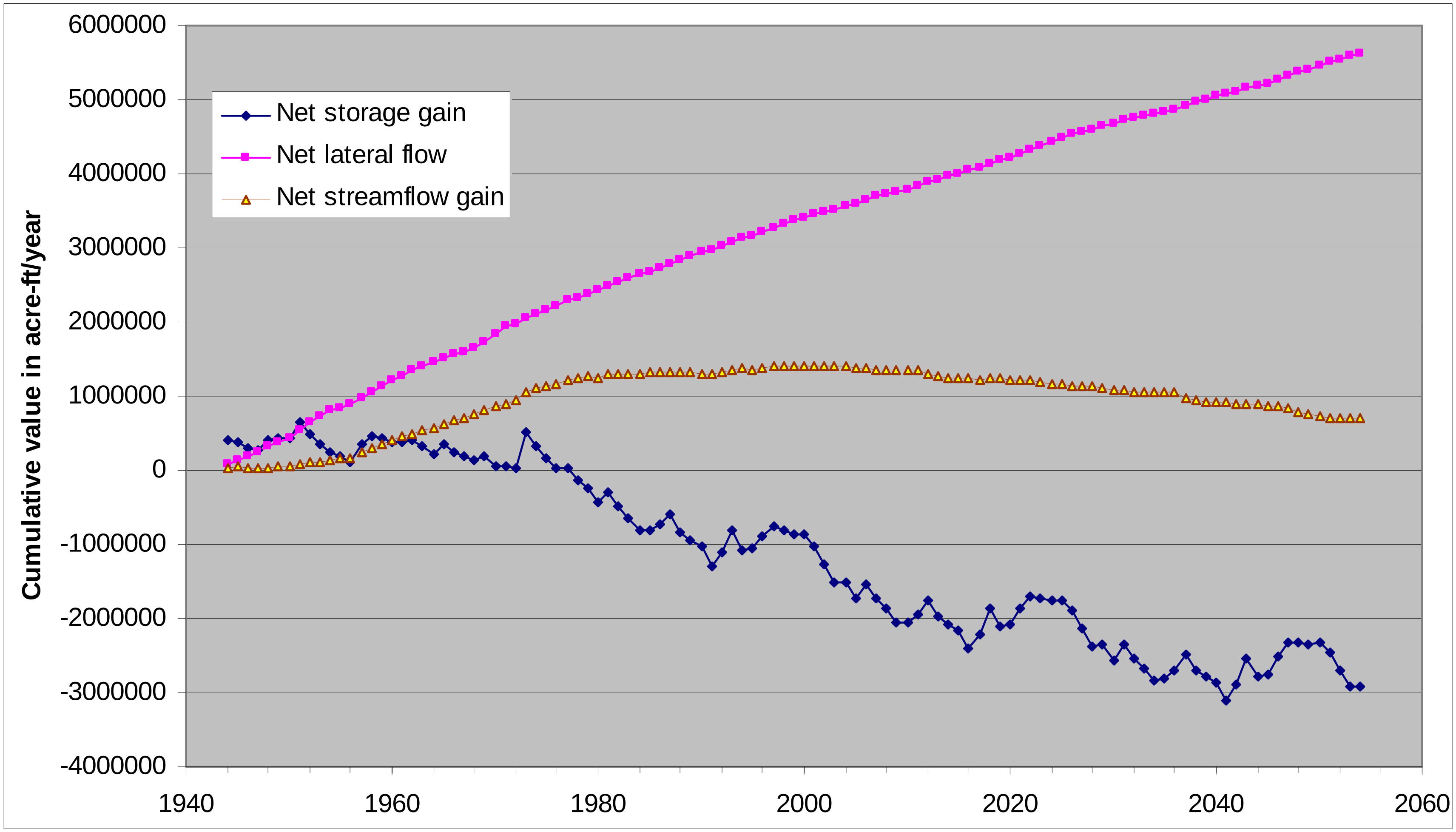

Figure 66. Cumulative net aquifer storage, streamflow gains, and lateral flow simulated for the Circle K Ranch water retirement scenario.

The hydrographs for the Circle K scenario are similar to those for the continued pumping scenario except for wells in the general area of the Circle K Ranch. For example, there is no significant long-term decline in the water levels in the hydrograph for target well 374954099270701 (Figure 2) located in the Circle K Ranch area for the Circle K scenario (Figure 49D), whereas there is a long-time decline for the hydrograph simulated for the continued pumping scenario (Figure 49A) during 2005-2054. The variations in the water levels are also smaller for this well in the Circle K retirement scenario compared to the continued pumping scenario. Once the Circle K Ranch wells are retired, the water levels do not drop as much at this well during dry to normal years without Arkansas River inflow, and recover faster during periods with substantial Arkansas River inflow in comparison to the continued pumping scenario. The water levels in target well 375513099231701 in Figure 2 in the Arkansas River valley farther downstream in Edwards county and in target well 375339099201601 in Figure 2 in the main aquifer to the northeast of the Circle K Ranch are only a very little higher in the Circle K scenario, indicating that the effect of the water-right retirement on water levels decreases appreciably with distance from the location of the retired water rights.

The decline in the water-level surface from that observed in January 2005 to that simulated in 2054 for the Circle K scenario (Figure 67) is essentially the same as that for the continued pumping scenario (Figure 54) except for the Arkansas River corridor in southwest Edwards County. The change is most noticeable in the vicinity of the Circle K Ranch, where an area of >10 ft decline in the water table for the continued pumping scenario changes to an area of <5 ft decline.

In the Circle K scenario, there are fewer years with essentially no flow in the Arkansas River near Kinsley for 2005-2054 than in the continued pumping scenario. The average river flows near Kinsley during both 2005-2029 and 2030-2054 are slightly greater in the Circle K scenario than in the CREP scenario, but the flows are smaller than in the CREP scenario at the gages farther downstream near Larned and Great Bend (Table 11). The differences in the average river flows between the Circle K and continued pumping scenarios are greater at the Larned and Great Bend gages than at the Kinsley gage (Table 12). However, these flow differences near Larned and at Great Bend are only about one-half and one-third, respectively, of the differences between the CREP and continued pumping scenarios.

The general outcome of retiring the Circle K Ranch water rights does increase streamflow and lateral ground-water flow and decrease the rate of aquifer storage loss compared to continuing pumping at current rates, but only to a limited extent. Substantial declines in net aquifer storage, net streamflow gain, and net lateral flow all continue during the Circle K scenario.

Comparison of Flow in the Arkansas River for Pumping Scenarios

Figures 50 and 68 show Arkansas River flow at the Kinsley gage location simulated for the pumping management scenarios during 2005-2054. Figure 68 enlarges the <10 ft^3/sec portion of Figure 50. The values for the Circle K Ranch retirement scenario (green line) are so similar to those for the continued pumping scenario (red line) that the green line is virtually indistinguishable from (lies underneath) the red line for most of the 2005-2054 period in Figure

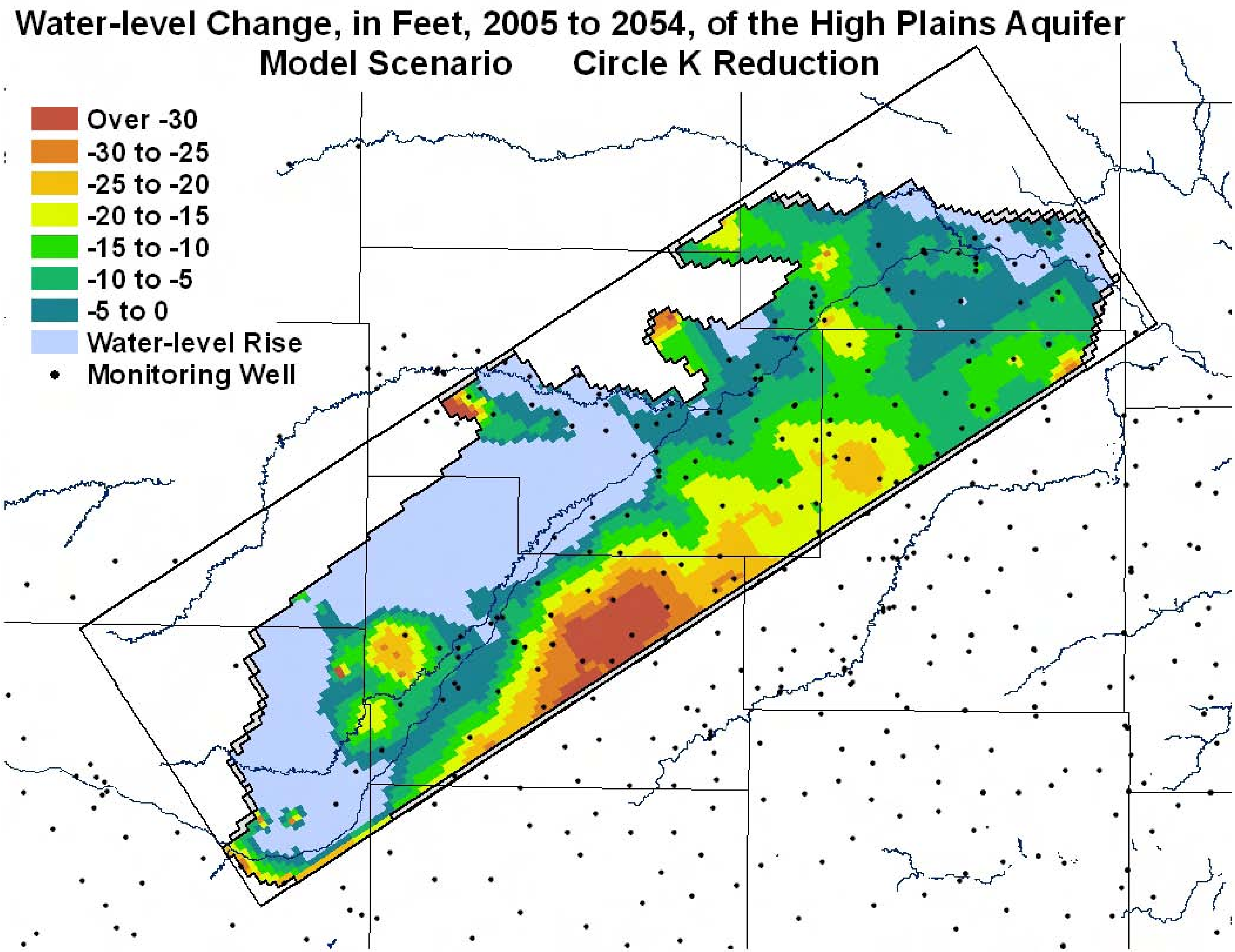

Figure 67. Difference between water table observed in 2005 and that simulated for the end of the Circle K Ranch scenario.

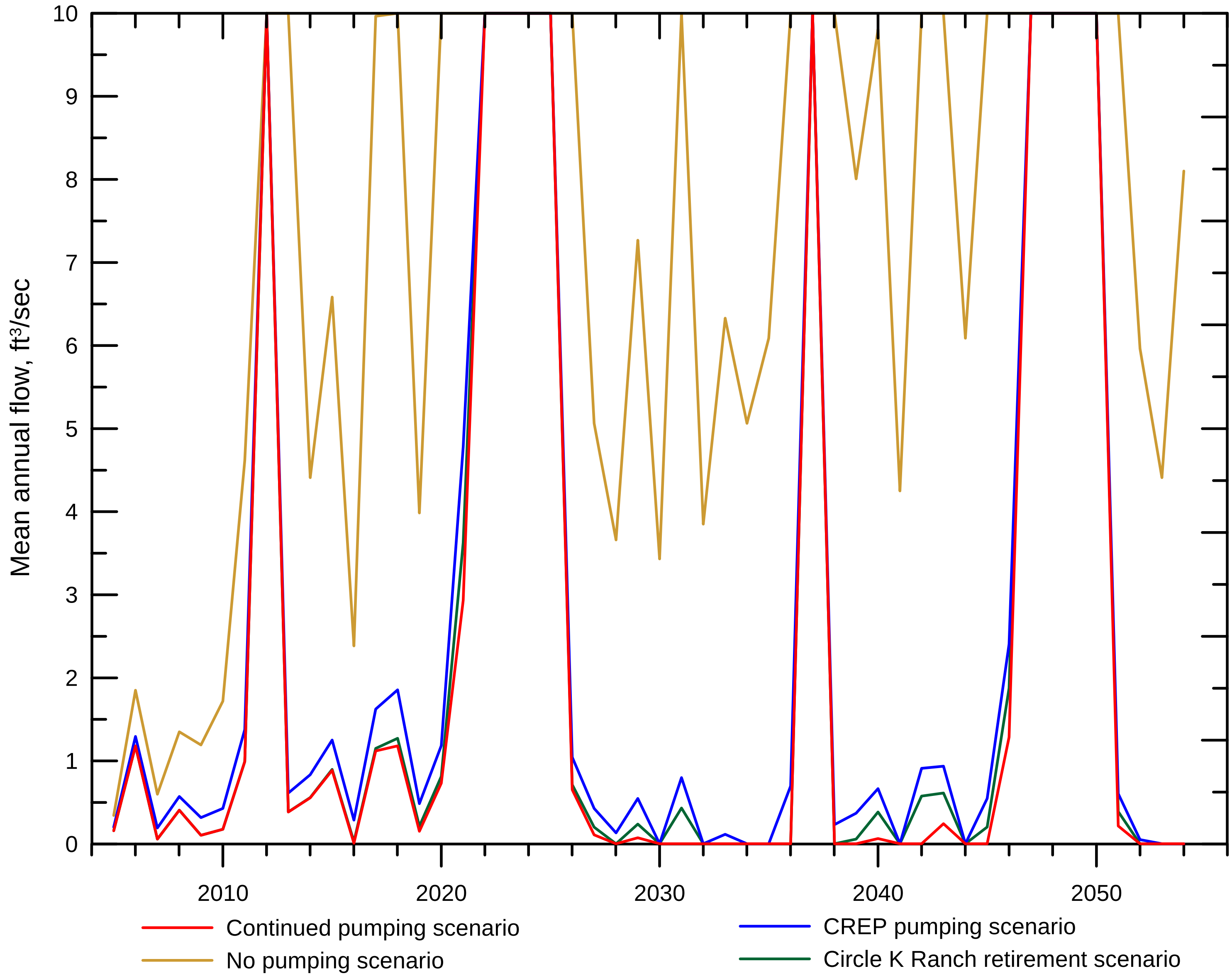

Figure 68. Comparison of Arkansas River flow <10 ft^3/sec simulated at the Kinsley gage location for the pumping scenarios.

50. Flows during low-flow years in the Circle K scenario are higher than those for the continued pumping scenario but lower than those for the CREP scenario (Figure 68). The lower flow for the Circle K than for the CREP scenario for flows <10 ft^3/sec is in contrast to the reverse situation for the average flow. The reason is that the high flows for the Circle K scenario are greater than those for the CREP scenario. The number of years with no flow in the Arkansas River increases with time for the continued pumping, CREP, and Circle K scenarios. There are fewer dry river years for the Circle K scenario than for the continued pumping scenario, and even fewer for the CREP scenario. There are no dry river years for the no pumping scenario and the average flow increases over the 2005-2054 period. This simulation indicates that a pumping reduction greater than that for the CREP scenario would be required to produce baseflows most of the time in the Arkansas River at the Kinsley gage given river inflows similar to those for 1980-2004. The model shows the importance of the upper Arkansas inflows for producing more than low flows near Kinsley.

Figures 51 and 69 display 2005-2054 Arkansas River flow at the Great Bend gage location for the pumping management scenarios. Figure 69 enlarges the <10 ft^3/sec portion of Figure 51. The flows for the Circle K scenario (green line) are so similar to those for the continued pumping scenario (red line) that the green line is virtually unobservable (lies underneath the red line) except for a few years in Figure 51 and the last year in Figure 69. The number of years with no flow in the Ark River increases with time for the continued pumping and Circle K scenarios, and remains about the same for the CREP scenario. These scenarios indicate that a pumping reduction greater than the CREP scenario would be needed to keep low flows in the Arkansas River at the Great Bend gage near the same level as observed in most dry years during the last couple decades. However, as Figure 70 shows for an example normal precipitation year (1990), the Arkansas River channel could be dry in some sections in the future (2015 and 2040), whereas it had flow throughout nearly all the channel in 1990.

The flow simulated along the Arkansas River channel for the example normal precipitation year of 1990 (Figure 70) indicates that there was flow along the entire river channel except along the stretch where the Circle K Ranch is located. For the continued pumping scenario, only a small amount of the river channel has flow during the scenario years 2015 and 2040, which have input conditions similar to those of 1990. The sections of dry channel increase from 2015 to 2040. The flows for the CREP scenario are lower than those for the base run for 1990 and higher than those in the continued pumping scenario for a particular scenario year. Lines for the Circle K scenario, if plotted, would fall nearly in the same position as for the continued pumping scenario.

Figures 71-73 show simulated flows along the Arkansas River channel for an example year with above normal precipitation and substantial Arkansas River inflow (2000). This was the last year of the 1995-2000 period when Kansas received relatively high flows from Colorado. The flows along the channel for the continued pumping and CREP scenarios in Figure 71 and for the continued pumping and Circle K scenarios in Figure 72 in the years 2025 and 2050 are less than for 2000, and decrease from 2025 to 2050. The flows for each pair of scenarios in 2025 and 2050 in both Figures 71 and 72 diverge starting at the beginning of the Circle K Ranch location. Figure 73 compares the flow along the channel for the CREP and Circle K scenarios with the base run for 2000. There is not much difference between the channel flows for the CREP and

Circle K scenarios for 2025 and 2050 from the southwest boundary of the model to the Pawnee River. After the Pawnee confluence, the channel flows diverge for each scenario.

The model scenarios show that, although both the CREP pumping reduction and Circle K Ranch retirement result in less decline in Arkansas River flow than the continued pumping scenario, the periods of dry river bed within much or most of the subbasin will increase and those periods with substantial Arkansas River inflow entering the subbasin will experience smaller flows than for equivalent inflows in the past. If future precipitation conditions are similar to those during the last 25 years, the Arkansas River from the southwest part of the Middle Arkansas subbasin to the confluence with Walnut Creek will generally be a dry channel during dry to normal years with no inflow from the upper Arkansas River if pumpage continues at near current levels.

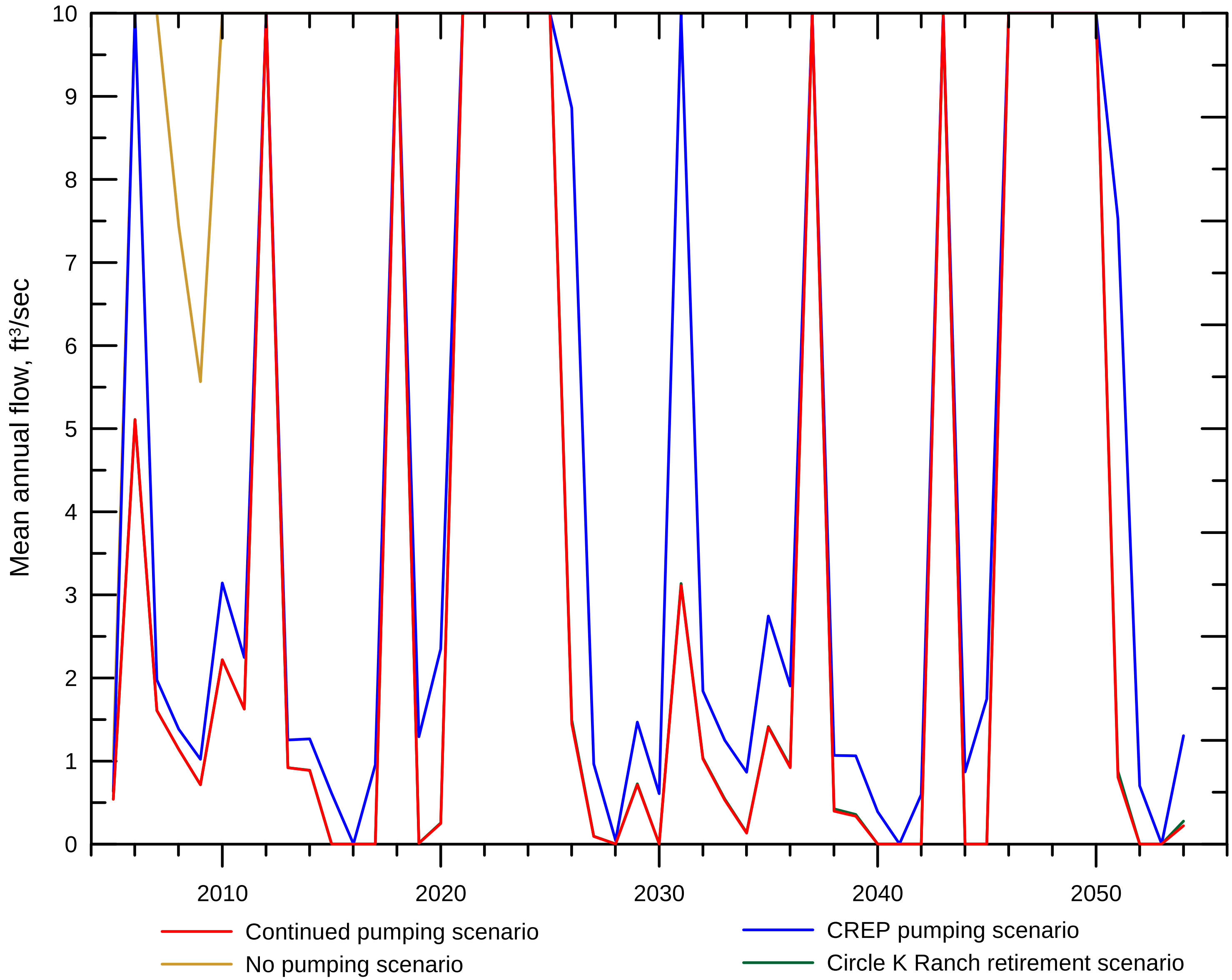

Figure 69. Comparison of Arkansas River flow <10 ft^3/sec simulated at the Great Bend gage location for the pumping scenarios.

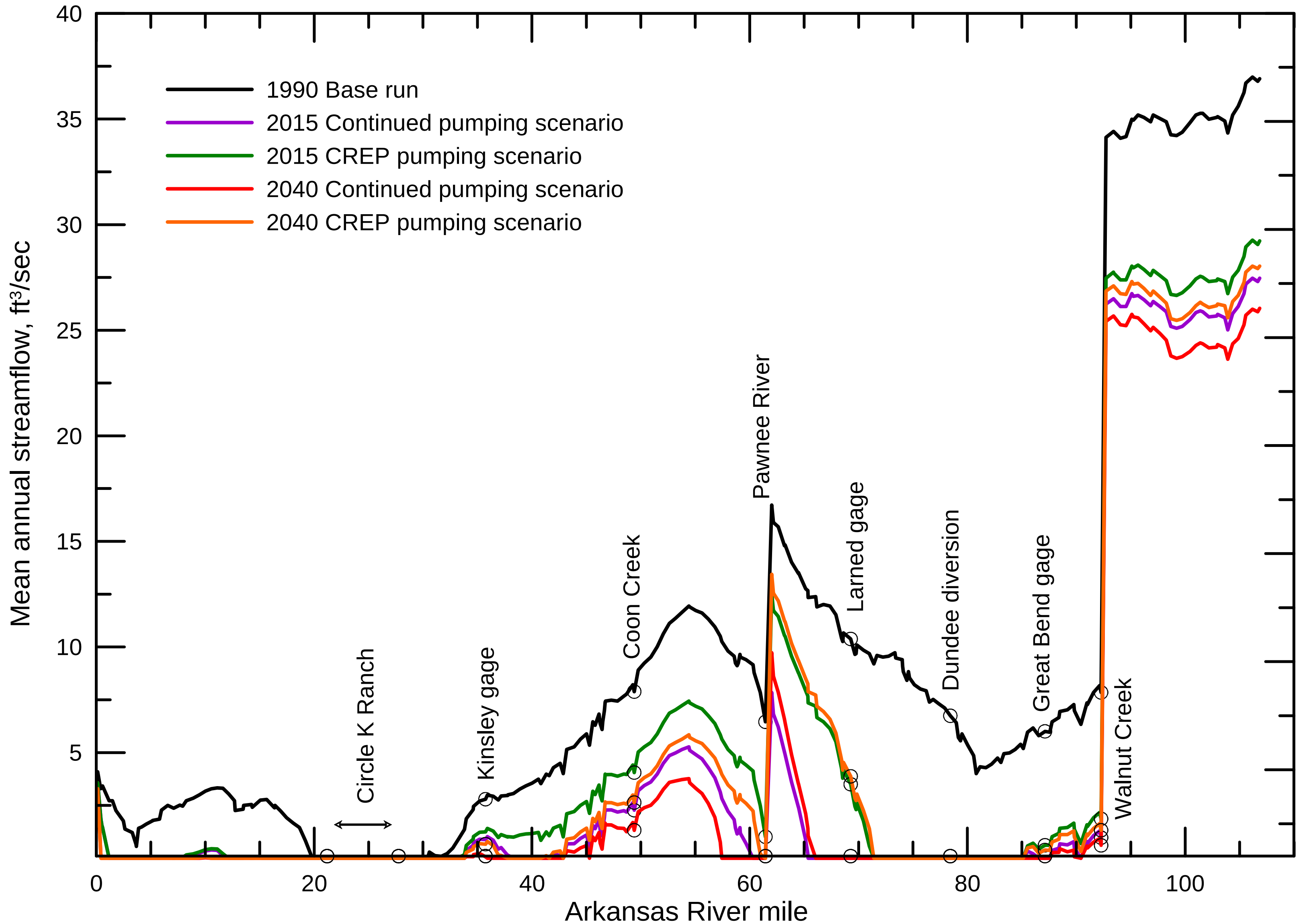

Figure 70. Flow simulated along the Arkansas River for the continued pumping and CREP scenarios for normal precipitation years 1990, 2015, and 2040. Circles show the start and end of the Circle K Ranch, and tributary confluence and gaging station locations.

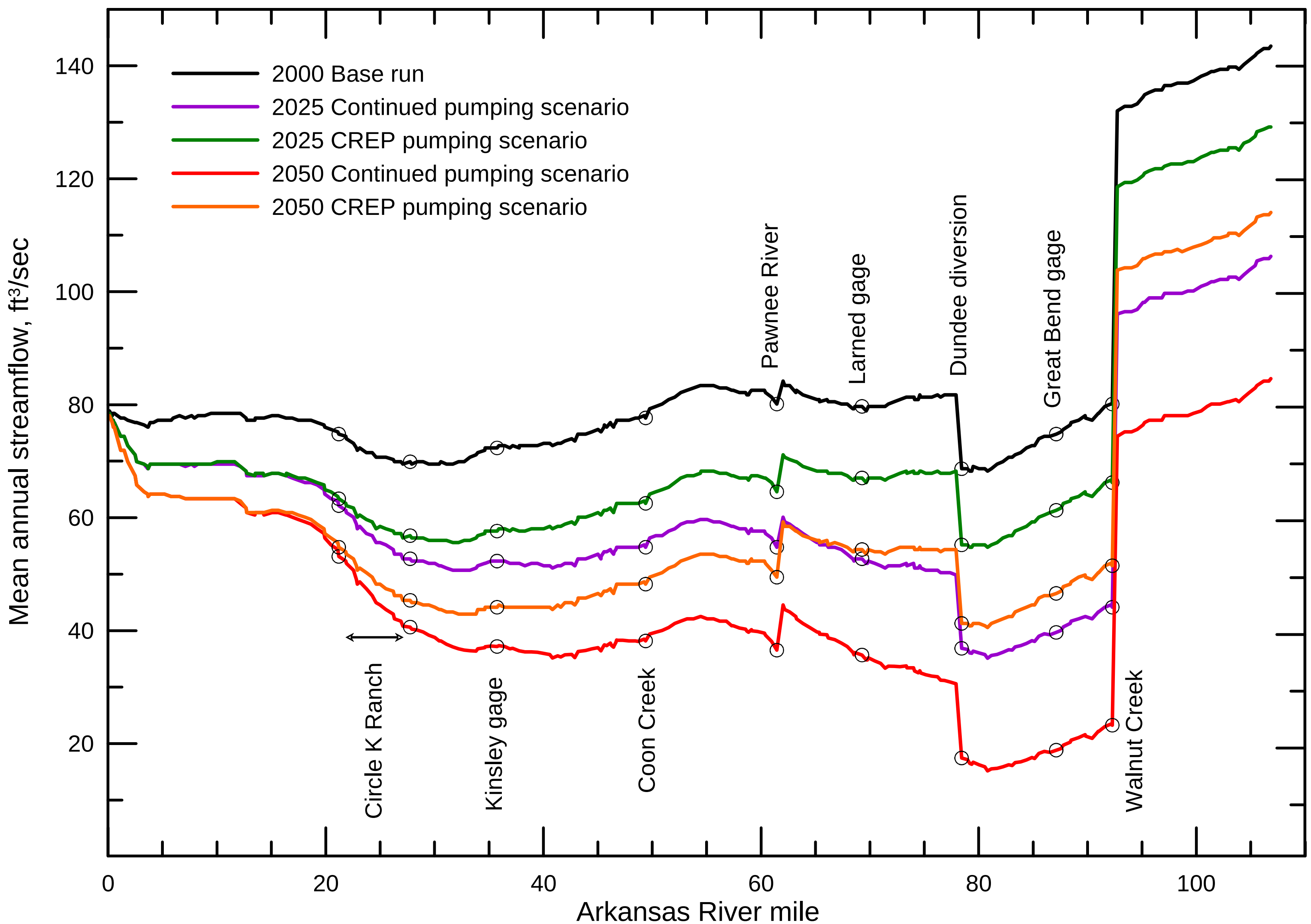

Figure 71. Flow simulated along the Arkansas River for the continued pumping and CREP scenarios for high inflow years 2000, 2025, and 2050. Circles show the start and end of the Circle K Ranch, and tributary confluence and gaging station locations.

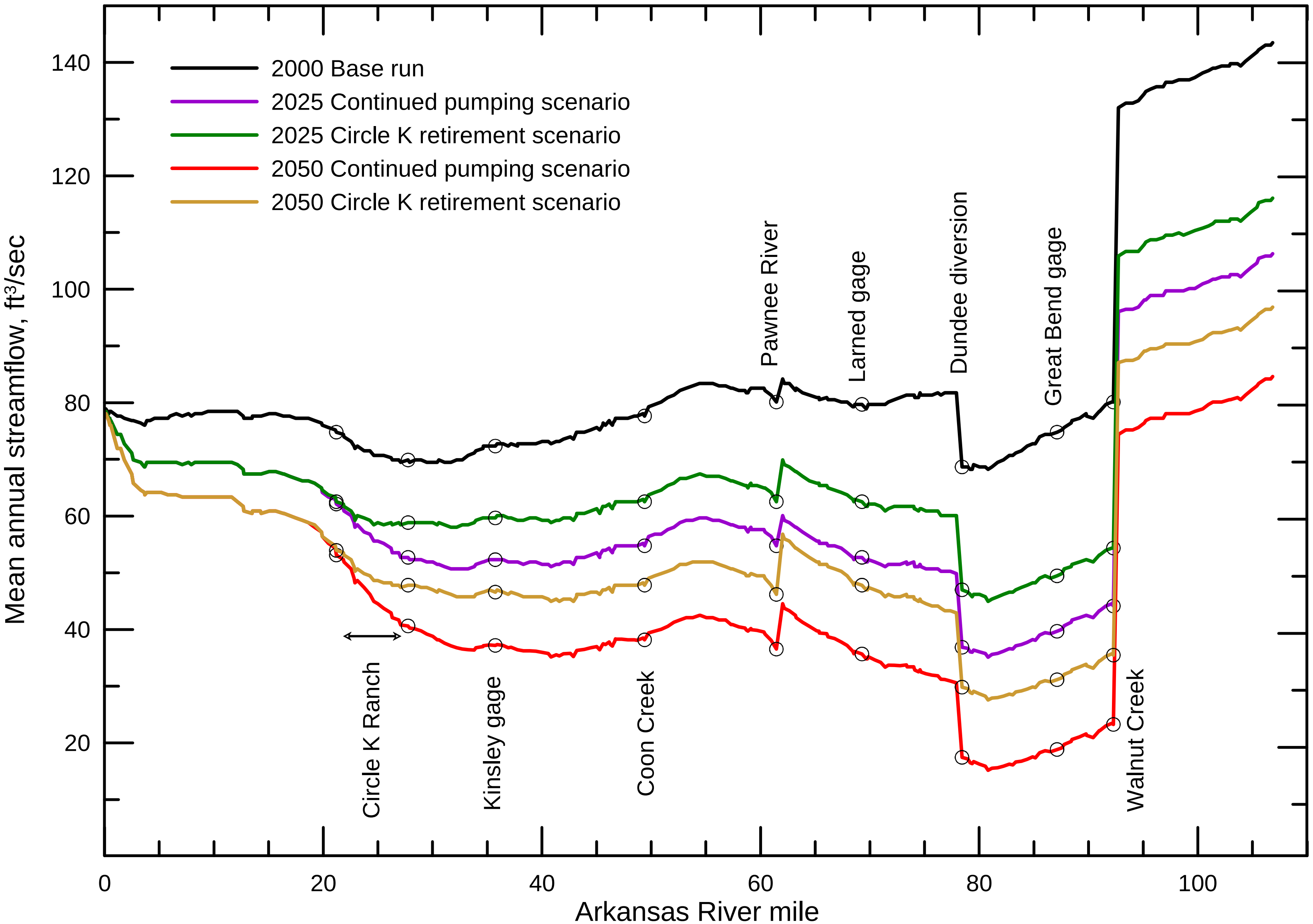

Figure 72. Flow simulated along the Arkansas River for the continued pumping and Circle K Ranch scenarios for high inflow years 2000, 2025, and 2050. Circles show the start and end of the Circle K Ranch, and tributary confluence and gaging station locations.

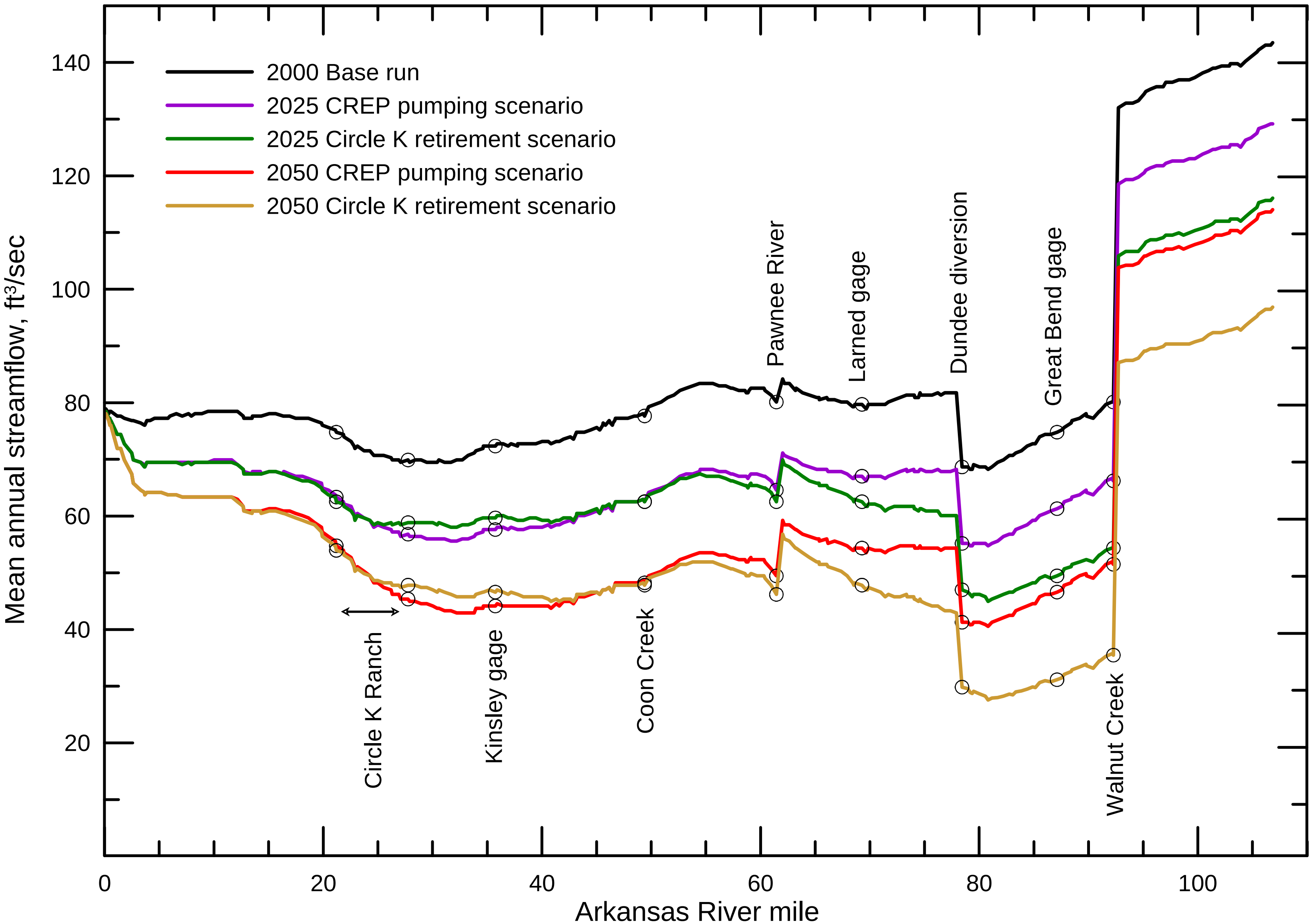

Figure 73. Flow simulated along the Arkansas River channel for the CREP and Circle K Ranch scenarios for 2000, 2025, and 2050. Circles show the start and end of the Circle K Ranch, and tributary confluence and gaging station locations.

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