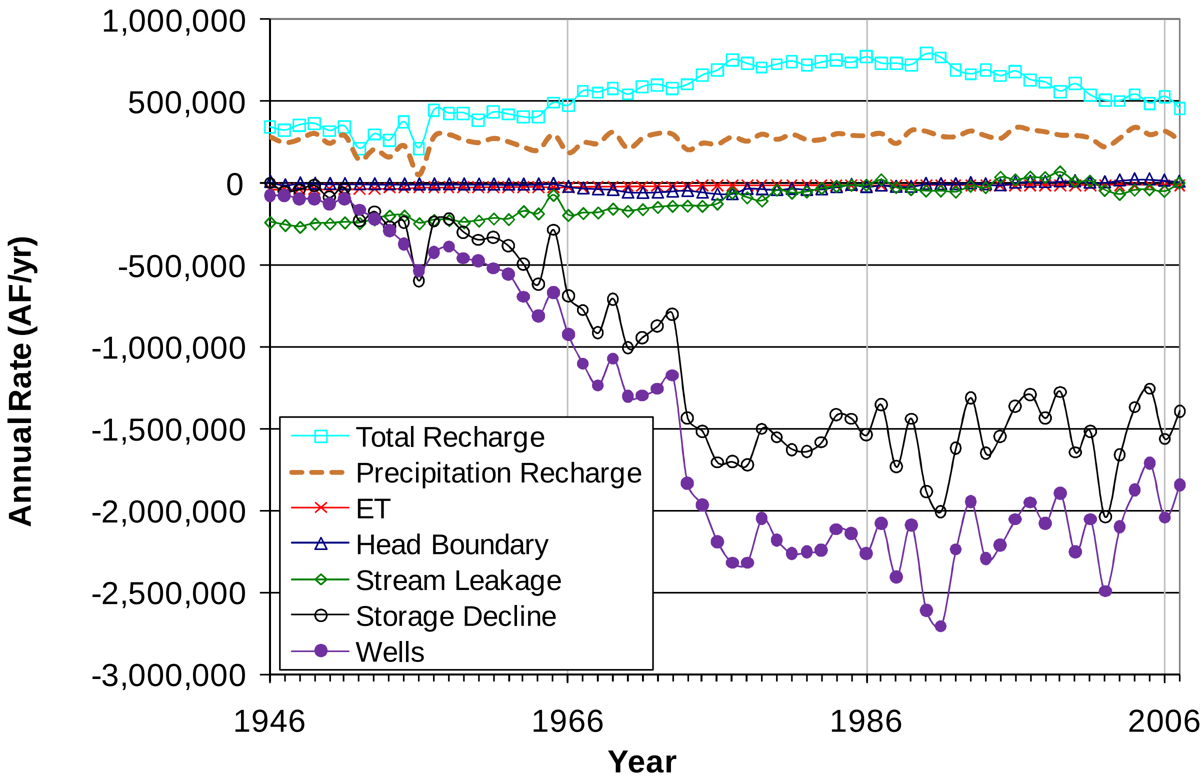
Ground-Water Model for Southwest Kansas Groundwater Management District No. 3

Kansas Water Office Contract 08-0110 (KAN49960)

**Funded by the
U.S. Bureau of Reclamation
and
Kansas Water Office (Kansas Water Plan)**



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Kansas Geological Survey Open File Report 2010-18

GEOHYDROLOGY

KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

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EXECUTIVE SUMMARY

Ground-water levels have been declining during the last few decades in the Ogallala-High Plains aquifer (HPA) in western Kansas, including within Southwest Kansas Groundwater Management District No. 3 (GMD3). The water-level declines have decreased ground-water discharge to the Arkansas and Cimarron rivers, thereby causing decreasing streamflow. One of the Kansas Water Plan (KWP) objectives is to "Reduce water-level declines rates within the Ogallala aquifer and implement enhanced water management in targeted areas." An associated goal of the KWP is to "Conserve and extend the life of the HPA." As a part of planning and management activities, the Kansas Water Office (under a cooperative agreement with the U.S. Bureau of Reclamation) and GMD3 contracted with the Kansas Geological Survey (KGS) to develop a computer model of the HPA in the GMD3 area to further characterize the hydrologic system and water availability. The model will provide more information on water in storage and allow projection of likely aquifer responses to possible future conditions and management scenarios (KWP, Upper Arkansas River Basin High Priority Issue, Management of the HPA).

The KGS constructed a numerical model for a rectangular area of 100 by 150 miles that enclosed GMD3 and extended approximately 6 miles to the north, east, south (into Oklahoma), and west (into Colorado) of the GMD3 boundaries. The active cells included the paleovalley of the Arkansas River in Hamilton and western Kearny counties. The KGS model utilizes MODFLOW, a widely used software program for modeling ground-water flow and stream-aquifer interactions developed by the U.S. Geological Survey. The KWO formed a Technical Advisory Committee to oversee the project, which included staff of the KWO, GMD3, KDA-DWR, and a consulting firm retained by KDA-DWR to provide technical review.

The main focus of the project was the development of a calibrated transient model that simulated ground-water flow and stream-aquifer interactions during the period 1947-2007. Predevelopment conditions were simulated for 1944-1946. The model included 12,083 active model cells (each a mile square), involved one layer, and simulated ground-water flow in the HPA and associated alluvial aquifers. Six recharge zones were used and the types of recharge included that from precipitation, enhancement of precipitation recharge in irrigated land, and return recharge below fields irrigated with ground-water and river water diverted from the Arkansas River. The precipitation applied to each cell varied depending on the distribution for each year across the model area.

Ground-water pumpage from the HPA for Kansas during 1990-2007 was based on reported water-use records, and for earlier years was estimated from regression equations based on a de-trended ratio of water use/authorized quantity versus precipitation and the Palmer drought severity index for 1990-2007. Similar approaches were applied to estimating pumpage in the Colorado and Oklahoma portions of the model, although the procedures varied because the data and data access for pumping records are not as readily available as those for Kansas. The pumpage rate from the HPA increased from 78,000 acre-ft/yr for predevelopment to a maximum of 2,708,000 acre-ft/yr in 1991 and was 1,844,000 acre-ft/yr for 2007 in the modeled area. The percentage of irrigation return recharge was calculated for each year in Kansas counties based on data for changes in irrigation type and applied to adjacent counties in Colorado and Oklahoma. Results from the calibrated model indicated that the long-term recharge from areal precipitation averaged over the model area was 0.41 in/yr during 1946-2007. Stream-aquifer interactions were simulated for the Arkansas and Cimarron rivers and Crooked Creek. Hydraulic conductivity (K) and specific yield (Sy) were estimated using lithologic data from about 15,000 well logs examined by the KGS PST+ (practical saturated thickness) program.

In order to account for the impact of declining water levels on the calculation of K and Sy during the transient period, the calibrated model was broken into six step models: 1) predevelopment, 2) predevelopment to 1966, 3) 1967 to 1976, 4) 1977 to 1986, 5) 1987 to 1996 and 6) 1997 to 2007. In each step model, K and Sy were dynamically updated using the observed water levels for the corresponding time period. During model calibration, the K and Sy values were adjusted by matching streamflows and observed water levels during each step to simulated values. A recharge function with different parameters for each of the six recharge zones was also incorporated into the calibration. The parameter estimation program PEST was employed to optimize parameters during the calibration process.

The model indicates that ground-water pumping has caused substantial decreases in aquifer storage. The storage decline rate started to increase in the 1950s, accelerated in the 1960s to mid-1970s, and then approximately leveled from the late 1970s to 2007, although it varied substantially each year depending on pumping. The accumulated decline in ground-water storage simulated for the entire model area for 1947-2007 is 66,409,000 acre-ft, which comprises 29.3% of the simulated predevelopment storage. The storage decreases have been accompanied by a decrease in streamflow out of the model. Water-level declines in the HPA have resulted in the "capture" of ground water that otherwise would have discharged to streams; without this capture, the aquifer storage loss would have been approximately 12% greater than simulated.

The total storage volumes simulated for the HPA only within the GMD3 area for predevelopment and the end of 2007 are 193,454,000 and 133,622,000, respectively, giving a storage decline of 59,832,000 acre-ft, which is 30.9% of the predevelopment value. The total storage volumes computed for the GMD3 area from measured water levels are 191,216,000 and 133,726,000 acre-ft for predevelopment and 2007, respectively. These values give a storage decrease of 57,490,000 acre-ft, which is 30.1% of the predevelopment volume. The storage volumes from the model and estimated from observations for the GMD3 area differ by only 1.2% and 0.1% for predevelopment and 2007 conditions. The average water-level decline simulated for all the model cells within the GMD3 area is 69.89 ft in comparison with 67.01 ft for the difference between contoured water-level surfaces based on observations in the predevelopment period to 2007.

The calibrated model will be used to simulate ground-water flow and stream-aquifer interactions for future conditions involving continuation and changes in pumping, and different climatic conditions as selected by the KWO and GMD3. A separate report that presents and discusses the results of these scenarios will be prepared.

INTRODUCTION

Owing to extensive irrigation pumping, ground-water levels have been declining during the last several decades in most of the Ogallala-High Plains aquifer (HPA) in western Kansas. Over the years, ground-water resources have sustained irrigated crops production that has given rise to one of the world's premier livestock and food processing industries in the region (Leatherman et al., 2003). However, given the past and current usage trends, portions of the HPA have been exhausted for large-volume irrigated agricultural use (in west-central Kansas), and other areas will soon become exhausted, severely impacting the long-term economic viability of the region. A growing concern is how to better plan for and manage the diminishing water resources so that a healthy balance can be achieved between ground-water usage for current development and for future generations.

Southwest Kansas Groundwater Management District No. 3 (GMD3), which covers all or parts of 12 counties in southwest Kansas, is the largest of the five groundwater management districts in Kansas. The HPA within GMD3 contains a substantially greater amount of ground-water storage than in the other districts. Much like the rest of western Kansas, GMD3 has seen intensive development of ground-water rights since the 1960s, primarily to meet irrigation demands. By the early 1980s, the water right development leveled off and the consumptive use of ground-water resources became relatively stable. Because of limited natural recharge, ground-water pumping has drawn water mainly from aquifer storage and, as a result, the water levels in the HPA have steadily declined.

Project Objectives

The Kansas Water Office (KWO) contracted with the Kansas Geological Survey (KGS) in December of 2007 to develop a numerical ground-water model for the GMD3 area. The KWO contract was funded by the U.S. Bureau of Reclamation and the Kansas Water Plan. The primary objective of the model is to better characterize the hydrological system and water availability in the underlying HPA. Upon its completion, the model will be used to simulate different future climatic and water-use scenarios and their effects on the HPA in this region.

The project period covered December 2007 through September 2010. The calibrated transient model was completed in April 2010. The final report was completed in November 2010.

Model Oversight

As part of the model development process, the KWO formed a Technical Advisory Committee (TAC) to oversee the project. The TAC met approximately once every two months in Topeka and the meetings included conference calls and internet-based display options that allowed for Powerpoint presentations to be viewed by individuals outside of Topeka. Members of the TAC included staff from the KWO, the Topeka headquarters and Garden City field office of the Kansas Department of Agriculture, Division of Water Resources (KDA-DWR), GMD3, and S.S. Papadopulos & Associates, Bethesda, MD. The KGS made the in-progress and final model files available to the TAC for their examination.

DESCRIPTION OF STUDY AREA AND GENERAL MODEL SETUP

The study area includes the area of GMD3 in southwest Kansas and extends approximately 6 miles beyond all four borders of a rectangle enclosing GMD3 (Figure 1). The total area covered by the model is 15,000 square miles and includes parts of Colorado and Oklahoma.

Previous Geohydrologic and Modeling Studies

Several KGS bulletins present descriptions of and data for geohydrologic characteristics and conditions for the HPA in the predevelopment period over the model area. These include Latta (1941) for Stanton County, Frye (1942) for Meade County, McLaughlin (1942) for Morton County, McLaughlin (1943) for Hamilton and Kearny counties, Latta (1944) for Finney and Gray counties, McLaughlin (1946) for Grant, Haskell, and Stevens counties, Waite (1947) for Scott County, Byrne and McLaughlin (1948) for Seward County, Latta (1948) for Kiowa County, McLaughlin (1949) for Pawnee and Edwards counties, Prescott (1951) for Lane County, and Prescott et al. (1954) for Greeley and Wichita counties. Later bulletins reported on the geohydrology of the HPA in GMD3 during early ground-water development. These include Stramel et al. (1958) for part of Finney and Gray counties along the Arkansas River, and Fader et al. (1964) for Grant and Stanton counties. Publications that provide information on the HPA in the GMD3 area during the development phase include Meyer et al. (1970) for Finney County, Spinazola and Dealy (1983) for Ford County, Gutentag et al. (1981) for southwestern Kansas, Stullken et al. (1985) for western Kansas, and Gutentag et al. (1984) for the entire eight-state area of the HPA.

Some of the earliest projects that involved modeling of the HPA simulated stream-aquifer interactions in the Arkansas River valley in southwestern Kansas (Barker et al., 1983; and Dunlap et al., 1985). Stullken et al. (1985) modeled the HPA in southwest Kansas as a part of steady-state simulations of the aquifer in western Kansas for predevelopment conditions (prior to 1950). Their model grid size was 15,000 ft (2.84 mi) on a side giving a cell area of 8.07 square miles. The model domain did not incorporate the paleovalley of the Arkansas River through Hamilton to central Kearny County nor did it include as large an area of the thinly saturated HPA as the model described in this report. The U.S. Geological Survey constructed a ground-water flow model to provide information for managing the HPA in western Oklahoma (Luckey and Becker, 1999). The model included both predevelopment and development (1946-1997) periods and incorporated parts of southwest Kansas, southeast Colorado, northeast New Mexico, and the northern panhandle of Texas surrounding the north, west, and south sides of the HPA in Oklahoma. The model cell size was 6,000 ft on a side (1.14 mi). They used the model to simulate water-level changes from 1998 to 2020 using mean 1996-97 pumpage, which gave a prediction that water levels would decline more than 100 additional feet in several areas in southwest Kansas from 1998 to 2020.

The most recent modeling project within the current model domain was conducted as part of the Upper Arkansas River Corridor Study (Whittemore et al., 2001), in which ground-water flow in the river corridor was simulated for steady-state conditions for predevelopment and the 1990s. The primary purpose of that investigation was to determine the distribution and fate of saline water from the Arkansas River that seeps into and migrates within the HPA largely as a result of water-level declines.

Physiographic Setting

Most of the model domain lies within the High Plains physiographic region. Cutting across this region is the Arkansas River lowlands. Other physiographic regions in the model comprise areas where the HPA is not present: the southwestern corner of the Smoky Hills in Hodgeman County and far eastern Finney County, and the westernmost portion of the Red Hills in Meade and Clark counties. Most of the High Plains region is a flat to nearly flat plain, although streams and rivers have created valley walls with moderate to steep slopes in some locations such as to the north of the Arkansas River in Hamilton and western Kearny counties, and in the Cimarron River valley in Seward County. Sand dunes of varying height cover broad areas to the south of the Arkansas River and portions of Morton, Stevens, Seward, and Meade counties and appear as very gentle to more pronounced small rolling hills. Parts of the Arkansas River lowlands include sand-dune topography.

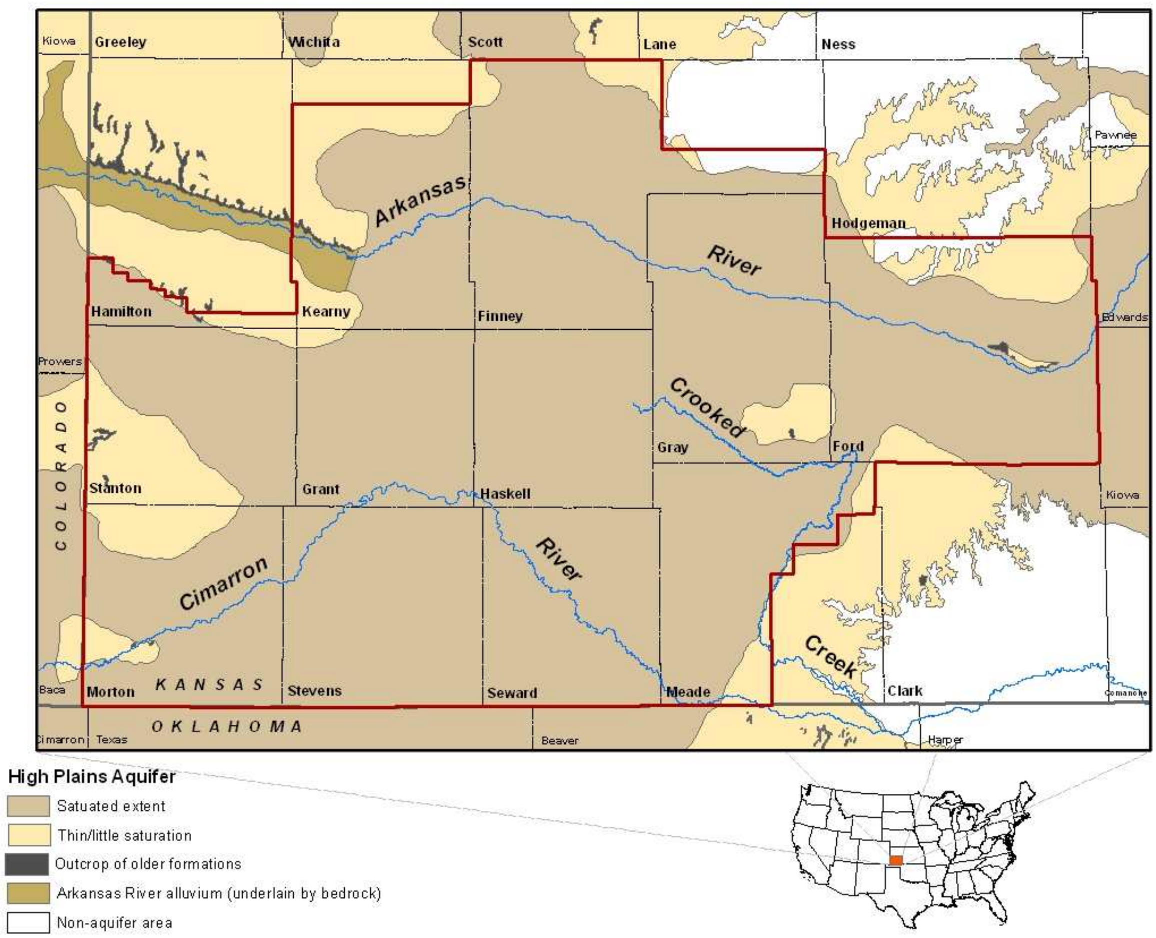


Figure 1. Map of the GMD3 model area in Kansas, Colorado, and Oklahoma. The red line indicates the physical boundaries of GMD3.

Model Design

The ground-water flow model employed in this project was constructed using MODFLOW. Developed by the United States Geological Survey (USGS), this modeling software is based on a finite-difference approximation of the ground-water flow equation (Harbaugh et al., 2000). MODFLOW has been the most widely used ground-water flow model in the world. It can simulate the effects of many processes, such as areal recharge, stream-aquifer interactions, drains, evapotranspiration, and pumping.

The stream package (STR) was used to compute stream-aquifer interactions (Prudic, 1989). Streams are superimposed on the aquifer and divided into reaches and segments. A reach is the portion of a stream that corresponds to an individual cell in the finite-difference grid. A segment is a group of reaches with uniform conditions for which streamflow from surface sources (such as tributaries) is added at the beginning of the segment and streamflow diversion subtracted at the end. Streamflow in a segment is accounted for by specifying inflow for the first reach and then computing streamflow to the adjacent downstream reach as equal to the upstream inflow plus or minus leakage from or to the aquifer along the reach. Leakage is calculated for each reach based on the head difference between the reach 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.

Groundwater Vistas was used for displaying results during model development. Due to the use of a minimum saturated-thickness option that is not supported by Groundwater Vistas, the model could not be run directly with Groundwater Vistas. Instead, the model was run by entering the executable file of MODFLOW in a DOS command prompt window. The results were then imported into Groundwater Vistas to produce various graphics.

The model uses uniform and equally spaced cells, 1 x 1 mile in size. The model grid encompasses 100 rows and 150 columns resulting in 15,000 individual model grid cells. The model uses a single convertible layer that allows both confined and unconfined aquifer conditions to be simulated, depending on water levels. Time-varying specified-head boundaries are located along the northern and southern edges of model, and time-varying flux boundaries are used along the eastern and western model edges (Figure 2). The lower boundary of the model is the top of the Permian and Cretaceous bedrock (mainly shale or sandstone) that has much lower permeability than the HPA and is treated as a no-flow boundary. The upper boundary of the model is specified as the land surface, although only the saturated portion below the water table is actually involved in the model simulations.

The modeling work was divided into two major phases. First, a steady-state simulation was performed for the predevelopment period before 1947 (data were used for 1944-1946, during which large-scale, intensive pumping activities were not present). Second, a transient simulation was conducted for the period between 1947 and 2007 to model the historic evolution of the ground-water system and stream-aquifer interactions. The predevelopment simulation established the initial conditions for the subsequent transient simulation.

To take full advantage of the detailed lithologic information from the KGS practical saturated thickness plus (PST+) program (ongoing), the model was divided into six step models: 1) predevelopment, 2) predevelopment to 1966, 3) 1967 to 1976, 4) 1977 to 1986, 5) 1987 to 1996 and 6) 1997 to 2007. In each step model, the hydraulic conductivity and specific yield are dynamically calculated using the observed water levels and the lithologic PST+ information. A total of ~15,000 lithologic well logs from the PST+ study were used in the model construction.

The model was calibrated to match predevelopment water levels, long-term hydrographs of selected wells, and flow conditions (especially low flow) in the Arkansas River, Cimarron River, and Crooked Creek. Precipitation recharge, hydraulic conductivity, and specific yield were used as the calibration parameters due to their relatively large uncertainties and high impacts on model results.

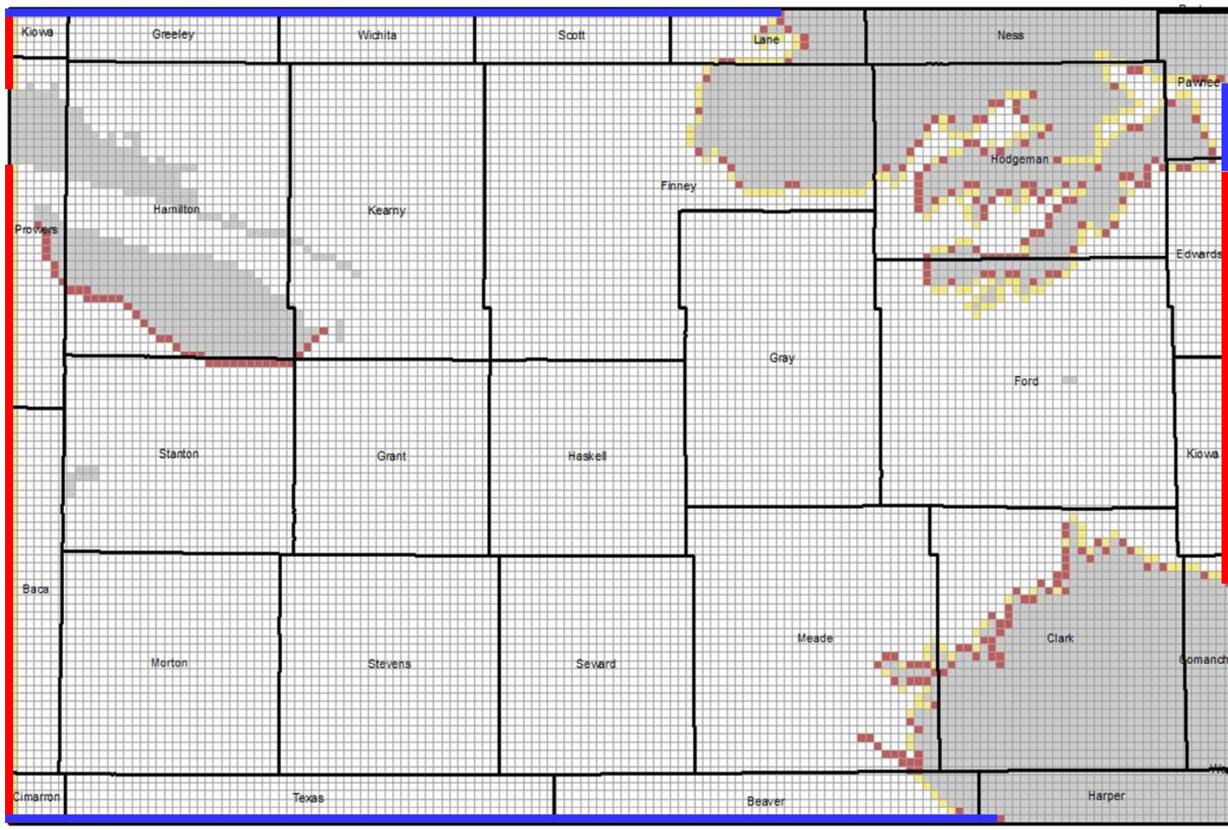


Figure 2. Model boundaries and active area. The unshaded area is the active area of the model. The shaded areas are treated as inactive due to either bedrock outcrops at or near the land surface or water levels below the top of the bedrock surface. Blue and red lines at the model edges represent time-varying constant heads and specified fluxes, respectively. The yellow cells along the edges of inactive areas are also treated as time-varying constant heads in the model. The brown cells along the edges of inactive areas are time-invariant fixed heads.

Active and Inactive Areas

Most regional ground-water models include "active" and "inactive" areas. No flow is assumed within inactive cells and the actual ground-water flow calculations are only conducted within the active cells. In this study, due to the low permeability of the underlying bedrock, a cell is defined as "inactive" when its area contains greater than 50% outcropping or near-surface bedrock (e.g., in Hodgeman and Clark counties) or the observed water level is at or below the bedrock surface (e.g., in Hamilton County). The number of active cells in the model is 12,083, giving a total active model area of 12,083 square miles, a little over 80% of the model domain (Figure 2).

REVIEW AND SETUP OF DATA PARAMETERS

Land Use/Land Cover

Cropland is the primary land-cover type and accounts for over 80% of the model area (Figure 3). Grassland is present in the upland, bedrock-capped hills bordering the rivers and their tributary streams, on sand-dune topography along the Arkansas and Cimarron rivers, and along steeper slopes such as the Cimarron River valley in Seward County. Most of the acreage for the Conservation Reserve Program (CRP) is also located in the sand dune area along the Arkansas River corridor. Except for the paleovalley of the Arkansas River, the downstream portion of Cimarron River and the Crooked Creek, most of the rivers (represented by the blue lines in Figure 3) and their tributaries are dry, especially during the latter part of the model simulation period.

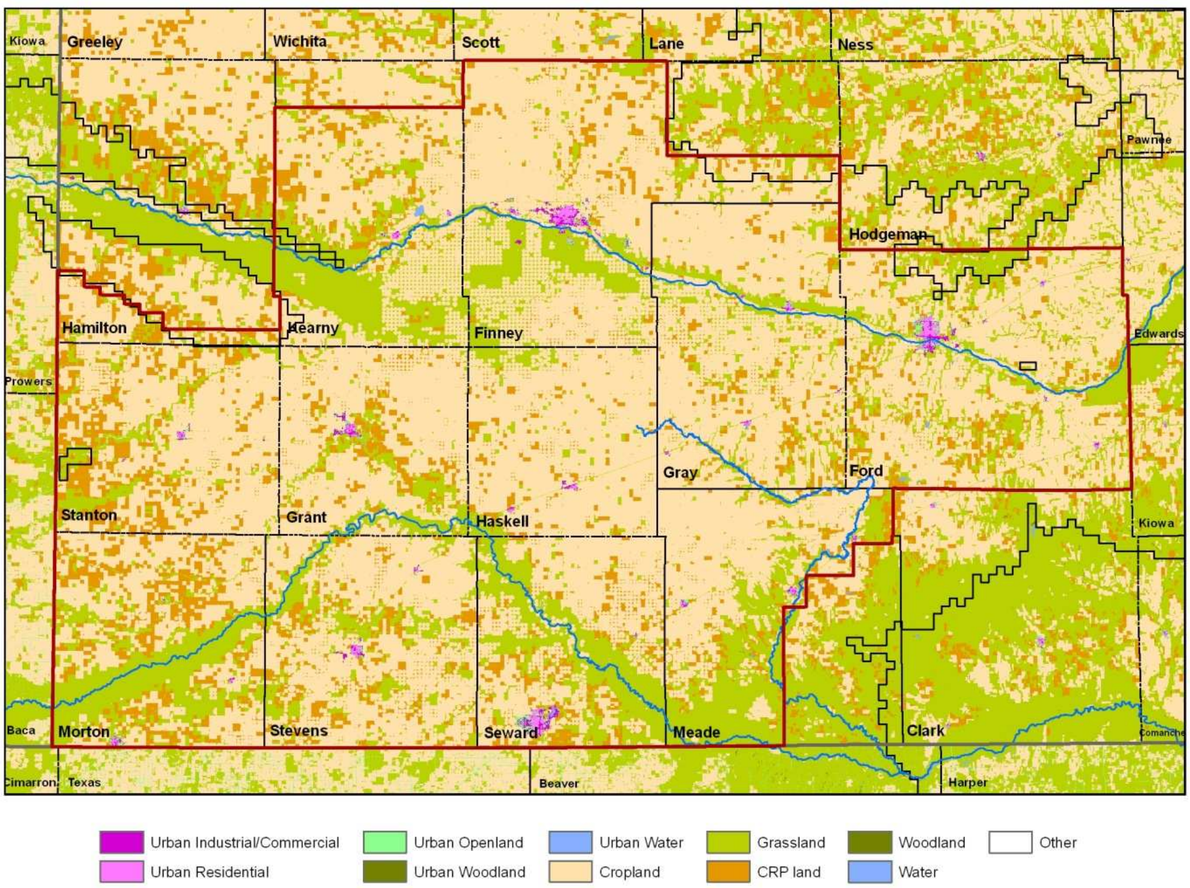


Figure 3. Land use/land cover classifications in the model area.

Precipitation

Long-term monthly precipitation data were obtained from the National Climatic Data Center (NCDC). This data set focused on NCDC site locations within 30 miles of the model domain. During some years, the total monthly precipitation value was not recorded for a particular weather station. Using methodologies outlined in previous studies (Wilson and Bohling, 2003), missing monthly values were replaced with averages from surrounding weather stations if a station was missing four or fewer monthly values during a calendar year. If a weather station was missing more than four months of precipitation values during a single calendar year, that year of data for that station was removed from the data set.

For each year from 1944 to 2007, the annual precipitation and "seasonal" precipitation (monthly totals between April and September) were calculated for each station. These same totals were interpolated to create continuous 500 x 500 meter gridded surfaces across the model area. Values from each of the interpolated surfaces were overlain over the model area and assigned to each of the model grid centers.

The average annual precipitation over the model area from 1944 to 2007 was 19.71 inches, with almost three-quarters of that amount falling during the months of April to September. The average precipitation over the "seasonal" or "growing" period of April to September was 14.77 inches (Figure 4). The year of lowest annual precipitation over the period was 1955 with 8.51 inches and the highest occurred was 1944 with 27.49 inches.

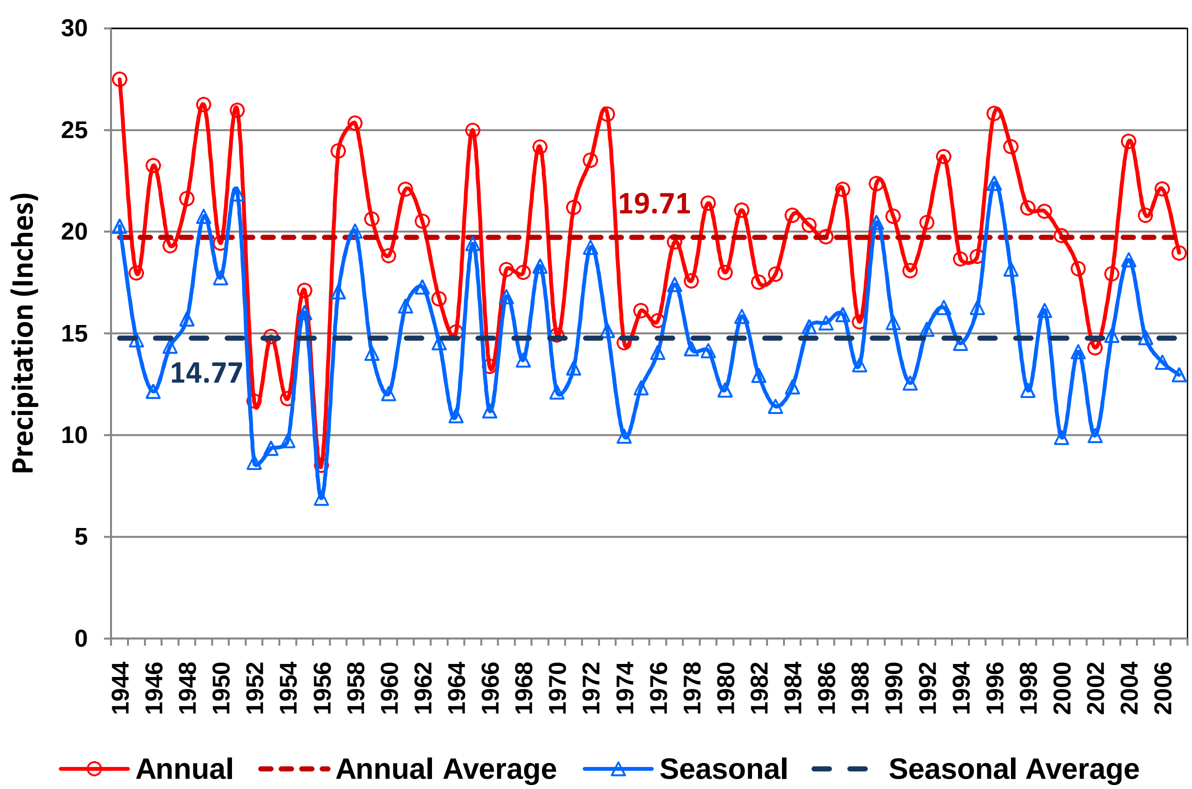


Figure 4. Interpolated annual and seasonal (April-September) precipitation totals for 1944-2007.

The general spatial patterns in the normal precipitation (average precipitation over the period of the last full three decades, 1971 to 2000) across the region of the model (Figure 5) are similar to those at the statewide level. For example, lower precipitation generally occurs along the western portion of the model area and increases eastward to maximum levels in the southeast, just as they do across the entire state of Kansas.

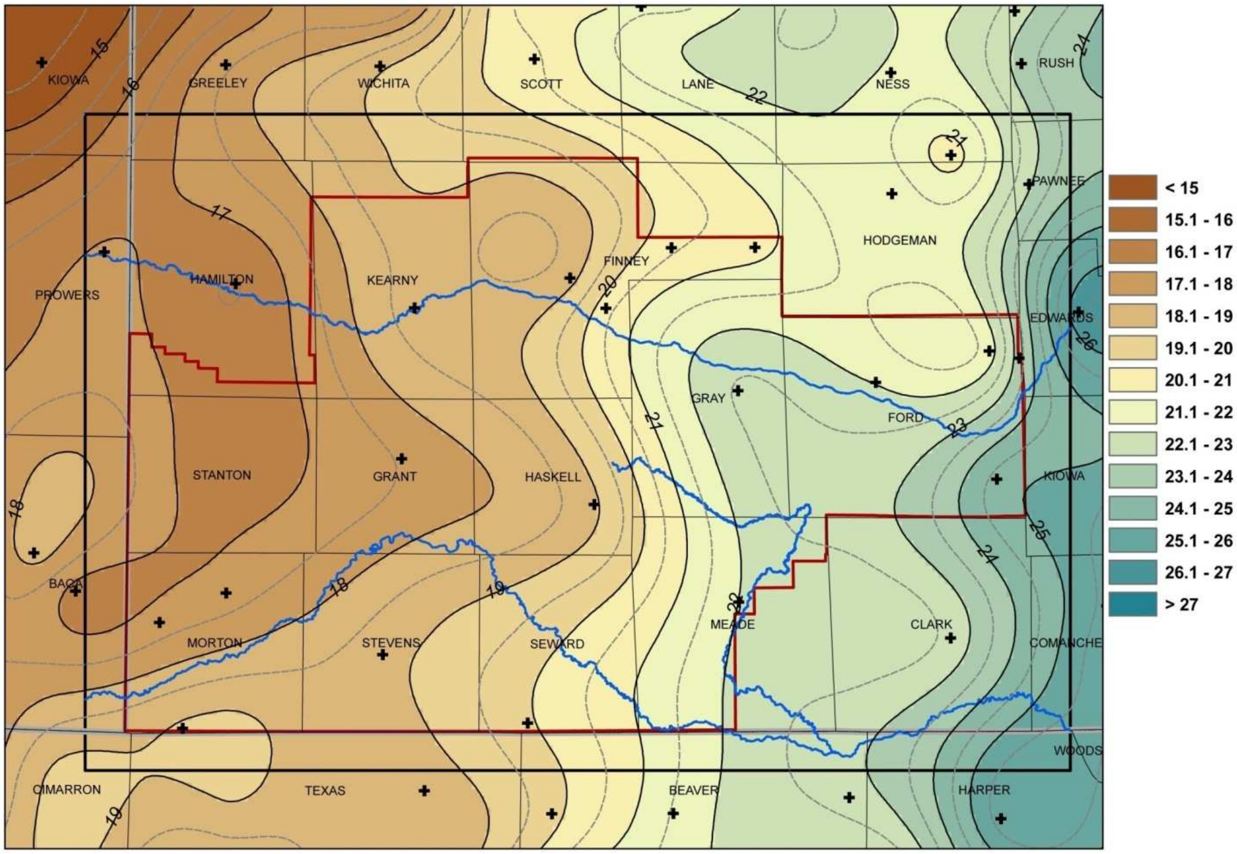


Figure 5. Interpolated normal precipitation (average 1971 to 2000). The"+" markers represent all NDCD site locations within 30 miles of the model domain. Unit is inch/year.

Geology and Lithology

Surface Geology and Soils

Detailed soils digital data for each county can be obtained from the Soil Data Mart (http://soildatamart.nrcs.usda.gov) of the USDA Natural Resources Conservation Service (NRCS). Figure 6 shows the four major groups of surface soils in the model area based on STATSGO data (STATSGO is a digital soils map and database developed by the NRCS as a part of the National Cooperative Soil Survey). Bedrock is plotted as the white background in the map.

Group A soils include sands and gravelly sands that have the highest precipitation infiltration rate of the groups displayed in Figure 6. This group includes the sand dunes to the south of the Arkansas River. Group B, which covers much of the model area, represents soils of moderately fine to coarse texture that have a moderate rate of precipitation infiltration. The main soil type in this group is Quaternary loess, which occurs across the majority of the study area. Group C represents soils of moderately fine to fine texture that have a relatively slow rate of precipitation infiltration. This group includes soils in the floodplain of the Arkansas River prior to its transition into group A soils. However, the wide channel of the Arkansas River, which has usually been dry in Finney and Gray counties and most of Ford County during the last three decades, is within the group A area and typically includes coarse sands and gravels with a very high infiltration rate. Group D soils have clays at or near the surface that are characterized by a very low rate of precipitation infiltration. This group is mainly located in Texas County, Oklahoma.

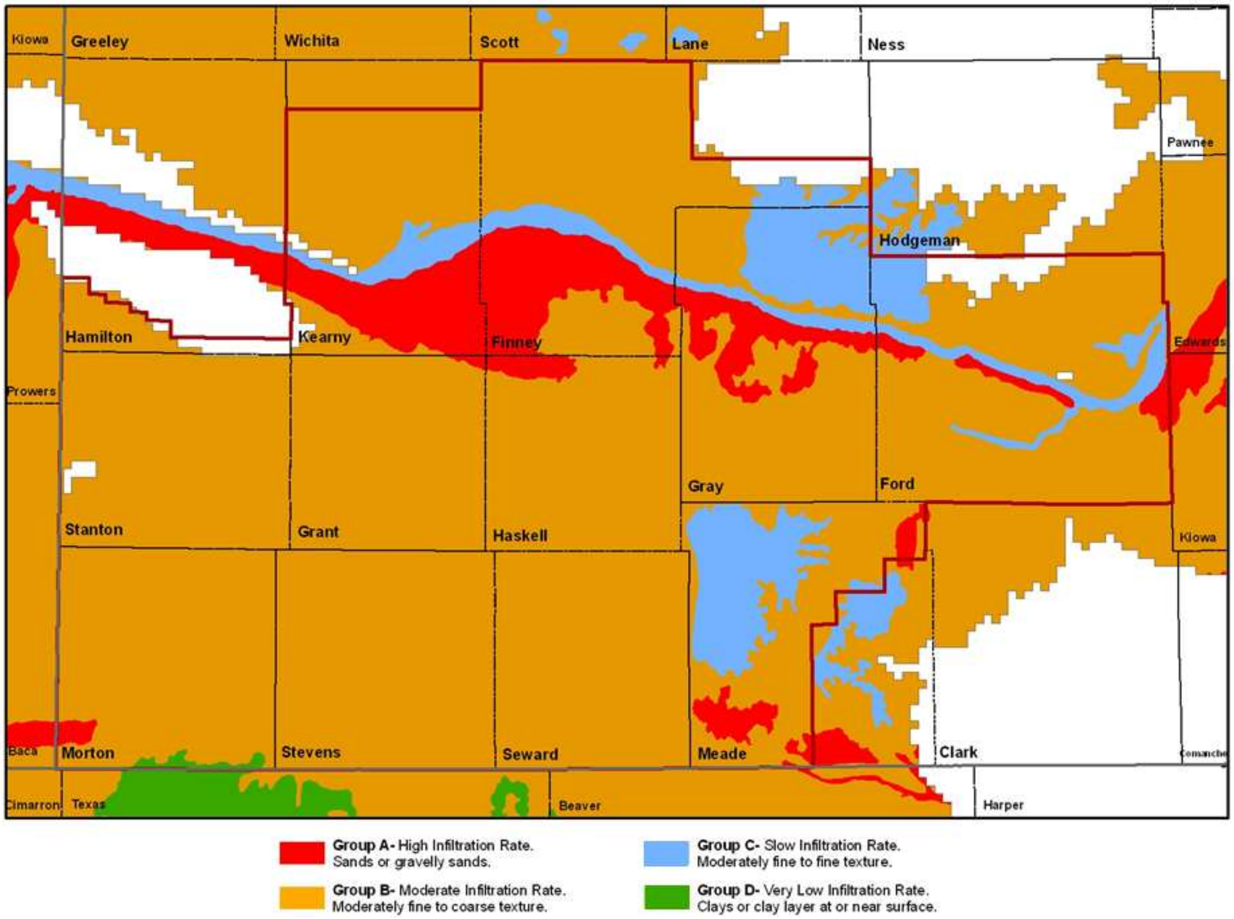


Figure 6. Grouping of soils at the surface in the model area.

Unconsolidated Deposits

The unconsolidated sediments in the model area are primarily composed of three groups, the Ogallala Formation of the HPA that belongs to the Neogene System (Miocene and earliest Pliocene in age, approximately 10 to 14 million years old), undifferentiated Pleistocene (approximately 2.5 million years old) deposits overlying the Ogallala Formation in some areas, and more recent alluvial deposits along the valleys of the Arkansas and Cimarron rivers, Crooked Creek, and their tributaries. The Ogallala and undifferentiated Pleistocene deposits, which consist of clay, silt, sand, and gravel, accumulated as an apron of clastic sediments that were shed eastward from the uplifting Rocky Mountains by streams (Ludvigson et al., 2009). Eolian (wind-deposited) sand dunes are also common to the south of the floodplain of the Arkansas River. Figure 7 shows the thickness of unconsolidated sediments in the model area.

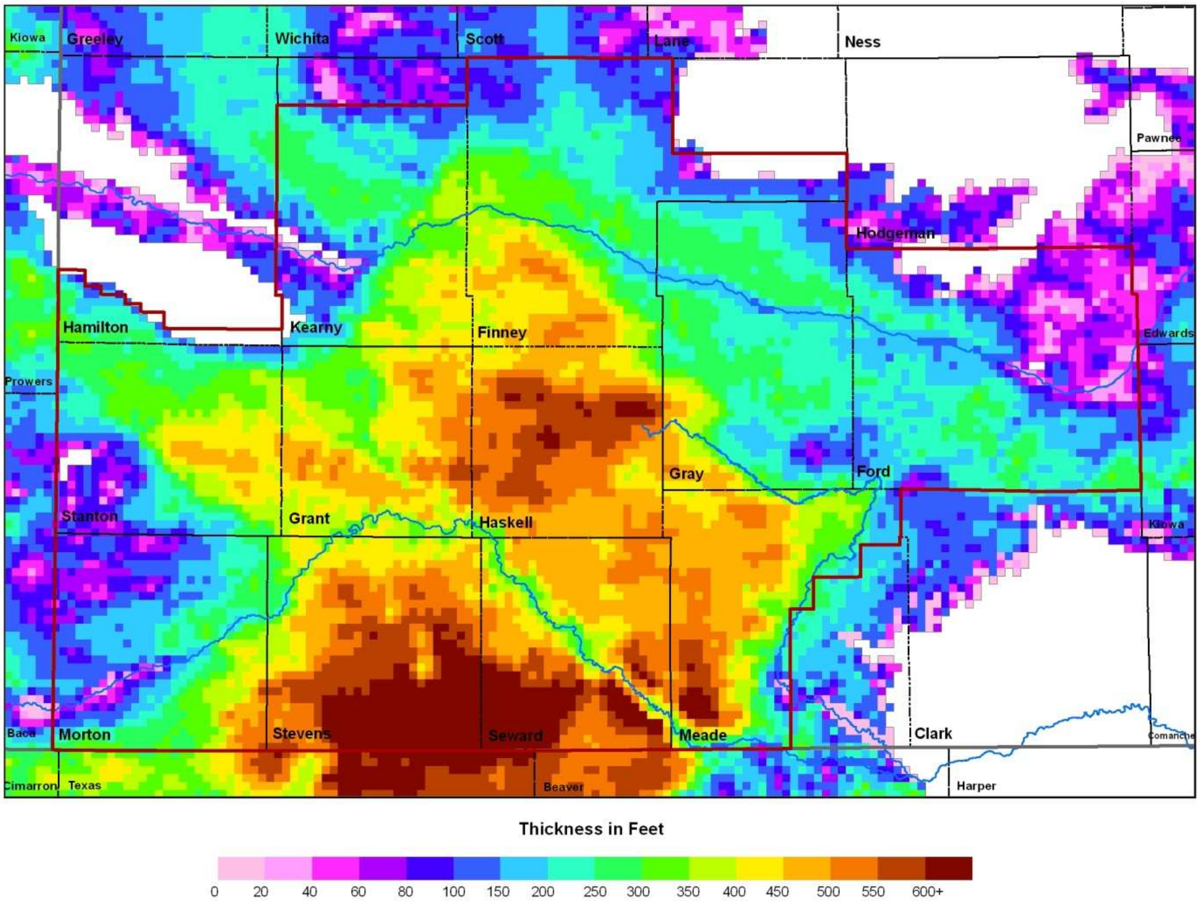


Figure 7. Thickness of unconsolidated sediments in southwest Kansas

The thickness of alluvial deposits is greater in the valleys of the Arkansas and Cimarron rivers than in Crooked Creek. A clear difference exists in the hydraulic connection between the alluvial aquifer and the underlying HPA in the Arkansas and Cimarron river valleys. Figure 8 compares lithologic cross sections along the valleys of the Arkansas and Cimarron rivers. In Figure 8a, a layer of fine-grained, low-permeability material generally underlies the shallow, coarser alluvium of the Arkansas River valley from central Kearny County through the part of Ford County shown in the figure, which restricts the vertical hydraulic connection between the alluvium and deeper HPA. In Hamilton through central Kearny counties, the alluvium directly overlies bedrock in the paleochannel of the Arkansas River. In the Cimarron River valley, however, no distinct separation exists between the shallow alluvium and deeper HPA sediments.

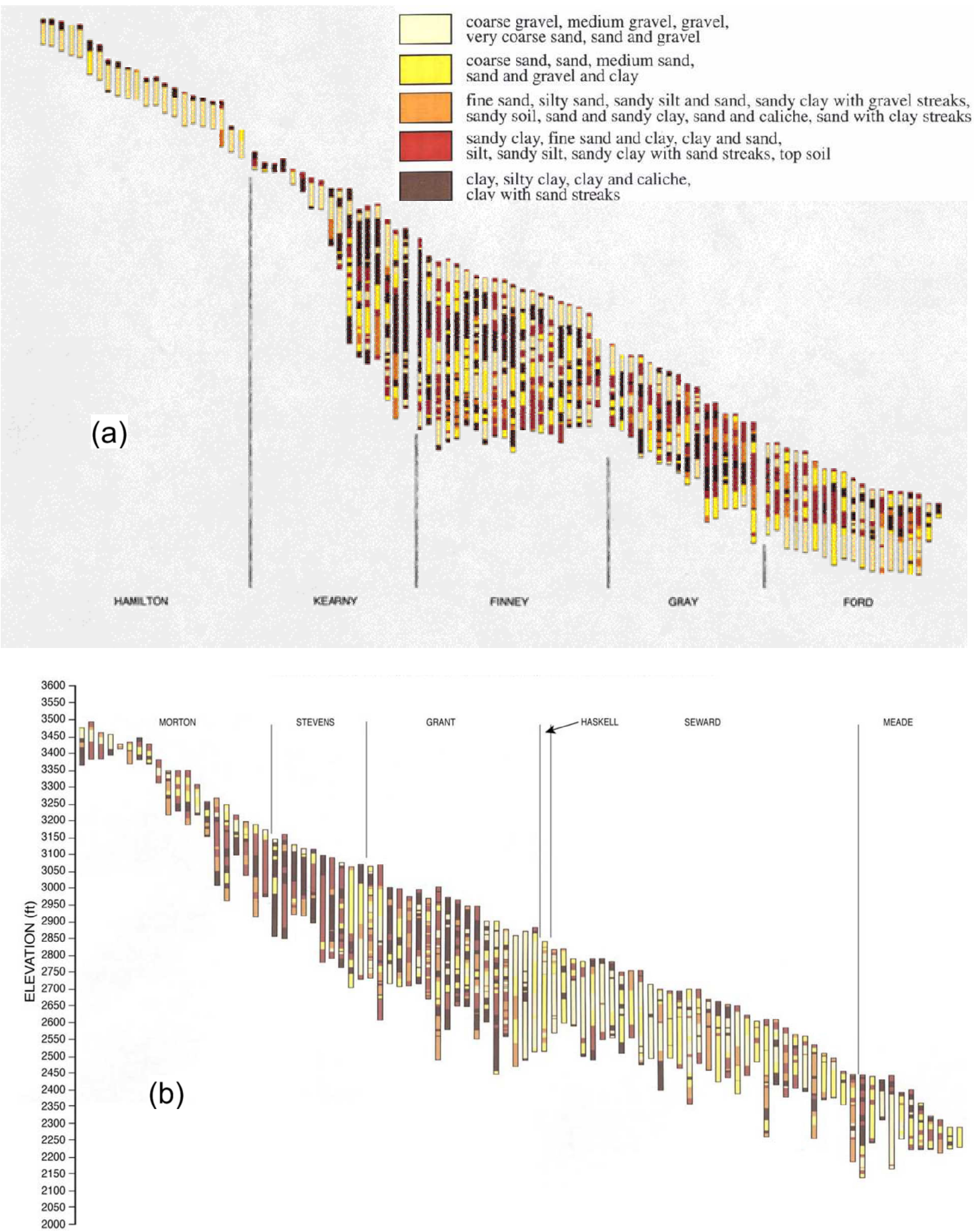


Figure 8. Lithologic cross sections along (a) the Arkansas River and (b) the Cimarron River. The positions of the logs do not match actual horizontal distance and the figure is vertically exaggerated. Figure (a) is from Young et al. (2000) and Figure (b) from Young et al. (2005).

Bedrock

The bedrock that is in direct contact with HPA sediments includes Permian, Cretaceous, and Jurassic rocks. Figure 9 shows the relationships of High Plains sediments with other geological units in southwest Kansas (Macfarlane et al., 2000). The Permian rocks in the study area 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). Except for parts of Morton and Stevens counties, the water in the Permian strata is too saline for human or agricultural use. Where shales of the Dakota Formation are not present to separate them, these bedrock units can be in good hydraulic connection with the overlying High Plains aquifer (e.g., in parts of Morton, Stevens, Seward and Meade counties). This allows downward movement of recharge from the HPA to the bedrock in areas such as Morton County, and upward movement of saltwater from the dissolution of naturally occurring salt such as that beneath the Cimarron River valley in southeast Seward and southwest Meade counties. The area where Jurassic rocks occur underlying High Plains sediments is small and is restricted to Morton County.

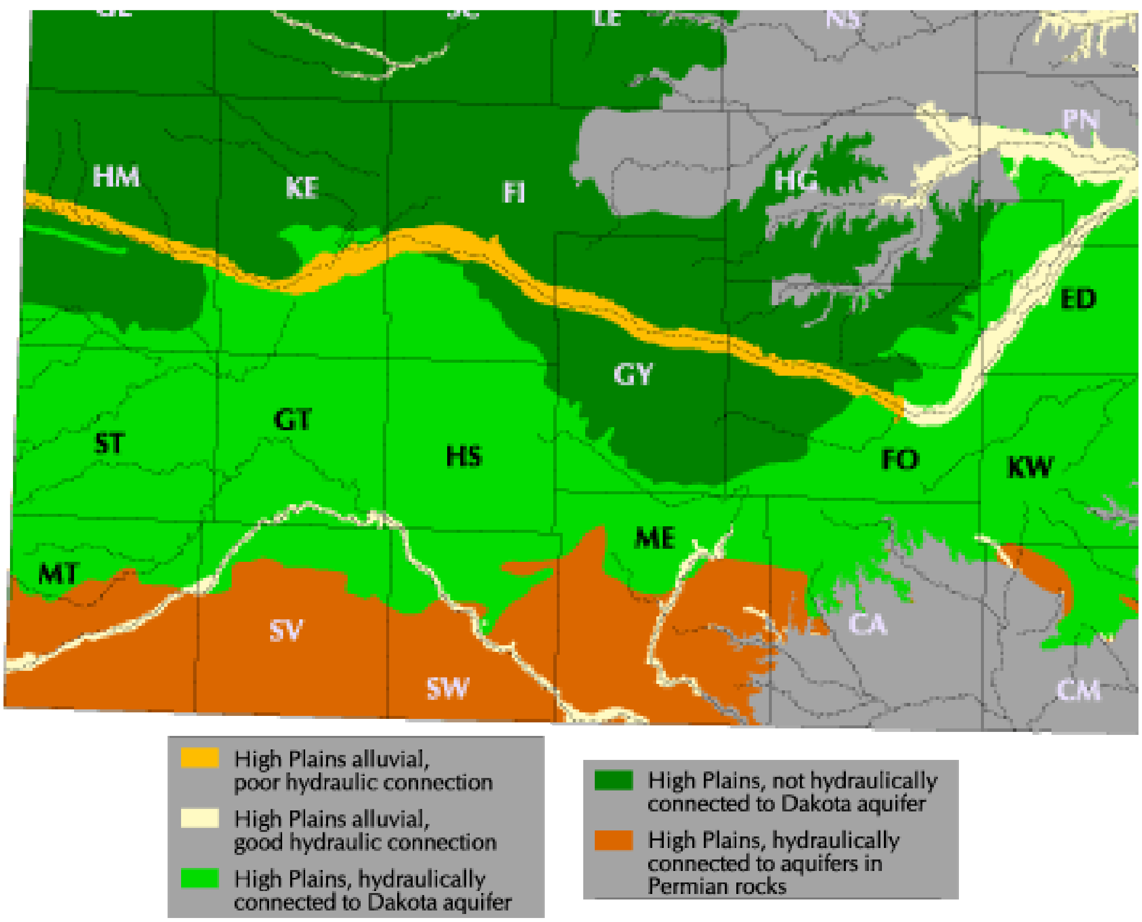


Figure 9. The relationships between High Plains aquifer deposits and other geologic units (from Macfarlane et al., 2000). Alluvium is considered part of High Plains sediments for the purposes of this figure.

The Cretaceous rocks can be divided into the Dakota aquifer system (Lower Cretaceous) and the low-permeability Graneros Shale and Greenhorn Limestone (Upper Cretaceous). In the central portions of the model where the Graneros Shale and Greenhorn Limestone are not present (e.g., Stanton, Grant, Haskell counties in Figure 9), the Dakota aquifer underlies and is in good hydraulic connection with the High Plains aquifer. Significant water exchange between the High Plains and Dakota aquifers can occur in certain local areas where sandstone units directly underlie HPA sediments. However, the predominance of shale in Dakota aquifer strata retards inter-aquifer exchange at a large scale. In the northern part of the model area, the thick sequence of low-permeability Graneros Shale and Greenhorn Limestone hydraulically isolates the Dakota from the High Plains aquifer (Figure 9).

Bedrock cropping out in the model area includes Upper Cretaceous shale and limestone in the northeast and along the northern valley wall of the Arkansas River in Hamilton through central Kearny counties, and Permian rocks in the southeast. Due to no or essentially no saturated thickness in the High Plains sediments (i.e. water levels at or below the bedrock surface), the areas adjacent to bedrock cropping out along the north side of the paleovalley of the Arkansas River valley in Hamilton through central Kearny counties, and to the south of the paleovalley in southern Hamilton County, are treated as inactive model cells even though the bedrock is below land surface.

<u>Bedrock Surface</u>

Data for the bedrock surface were obtained from the bedrock study of Macfarlane and Wilson (2006). In that study, lithologic logs were obtained from water well completion records, county geologic bulletins, and geophysical logs stored at the KGS, along with additional data from the Oklahoma Water Resources Board, U.S. Geological Survey, and the Henkle Drilling and Supply Company in Garden City, Kansas. The locations of the lithologic logs reached about 10 miles beyond the state line of Kansas (beyond the model extent) and allowed extension of the bedrock contour lines beyond the state boundaries (Figure 10).

The bedrock elevation contours were interpolated to form a continuous 0.5 x 0.5 mile gridded surface. The model cells were overlain on the gridded surface and the average bedrock elevation within each model cell computed. In some minor cases (e.g., 28 out of the 15,000 grid cells), the bedrock elevation was manually adjusted to be at least 10 feet below the land surface. In these areas of bedrock highs or stream channels, the model's 1x1 mile grid size was too coarse to adequately capture the local elevation changes.

The bedrock surface elevation follows the same general slope as the land surface, with highs located along the western edge of the model and lower values to the east. The lowest bedrock elevations in the model area are in southern Meade County, Kansas, and northern Beaver County, Oklahoma. The bedrock depth ranges considerably, running from near the land surface to a depth of 700 feet or more along the Kansas-Oklahoma border in Stevens and Seward counties. The average depth to bedrock across the model area is around 226 feet below land surface.

A three-dimensional version of the bedrock surface (Figure 11) facilitates visualization of the bedrock topography. The sharp angles of Crooked Creek, caused primarily by subsidence along a front of dissolution of underlying salt formations, can readily be seen. The bedrock high in southern Gray County is also apparent as is the Arkansas River valley.

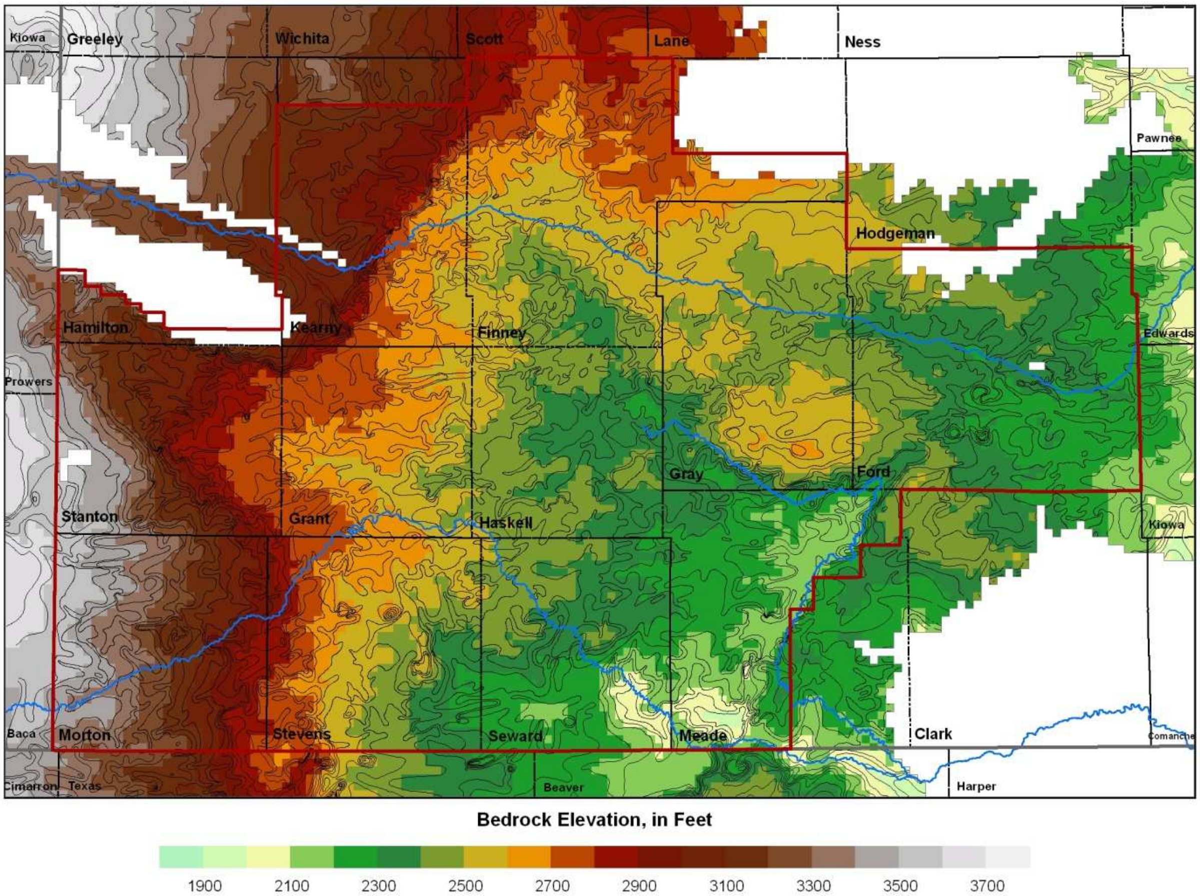


Figure 10. Elevation of the bedrock surface in the study area interpolated from well log data.

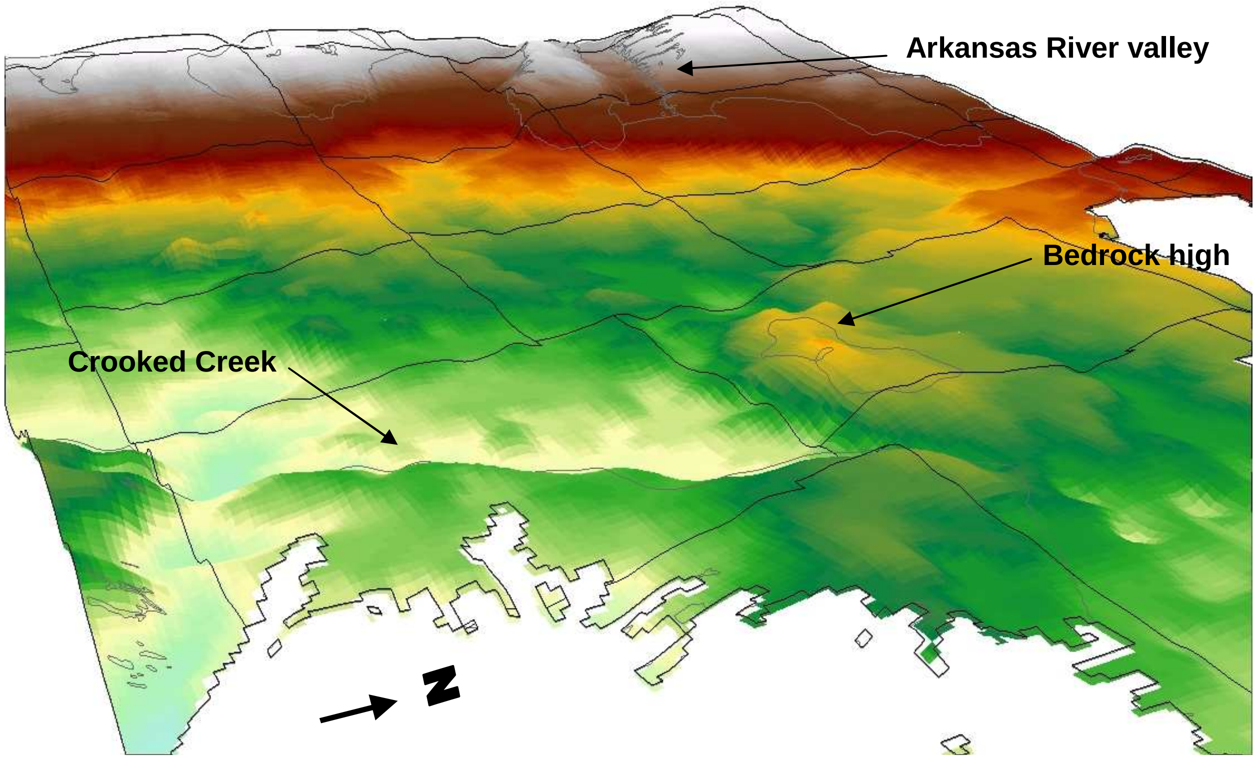


Figure 11. Three-dimensional view of the bedrock surface, looking to the northwest.

Unconsolidated Aquifer Characteristics

Although the Dakota aquifer system is used for water supply in a few locations within the active model area, this model is only intended to simulate ground-water flow in the unconsolidated deposits that form the HPA and the alluvial aquifers along river and creek valleys. Thus, the Dakota aquifer system is not considered in this modeling effort. All water-level and water-right data known to be associated with bedrock strata (the Dakota and other bedrock aquifers) were removed before any model simulations were performed.

Lithology from PST+

PST+ is an ongoing program that builds upon a previous PST (practical saturated thickness) project by Macfarlane and others (Macfarlane et al., 2005; Macfarlane and Schneider, 2007). PST is a relatively new concept and is defined as the total thickness of saturated strata that significantly contribute to well yield from the water table down to the bedrock surface. The PST is a better measure of the portions of the aquifer that can readily yield water to a pumping well than the total thickness of saturated sediments, which is often misused and can lead to overestimation of the readily extractable water resources for aquifer development and management. In highly heterogeneous aquifers such as the HPA, the total saturated thickness includes low-permeability strata that do not readily contribute to the yield of a well. By assigning a zero or lower contributing percentage for those layers, PST provides a more accurate indicator of characterizing water availability for practical water resources applications (Macfarlane et al., 2005). In order to estimate PST, lithologic information was obtained from well logs from three sources: (1) WWC-5 records of water wells completed since 1975 and maintained at the KGS, (2) test-hole logs from water-well contractors, and (3) test-hole logs from KGS county bulletins. Macfarlane et al. (2005) and Macfarlane and Schneider (2007) provide details on the extraction of lithologic information from driller's logs. PST+ is different from the original PST project in that instead of computing a practical saturated thickness for each wellbore based on the interpreted permeable fraction of the sediment column that is then stored in a database, the detailed lithologic information from the driller's log is stored in the database. This information can then be manipulated in a variety of ways. For example, hydraulic conductivities can be assigned to each lithologic type and then, in conjunction with a dynamic water-level observation (or estimated value), a transmissivity estimate can be computed. This is important because the well yield is primarily controlled by the transmissivity of the aquifer.

In the GMD3 model, the lithologic data from PST+ are used to estimate both hydraulic conductivity (K) and specific yield (Sy). The distribution of the ~15,000 lithologic logs used in the model area is displayed in Figure 12. The large variety in lithologic descriptions for different log depth intervals was condensed into 62 classifications (henceforth, synonymies) for PST+ (Table 1).

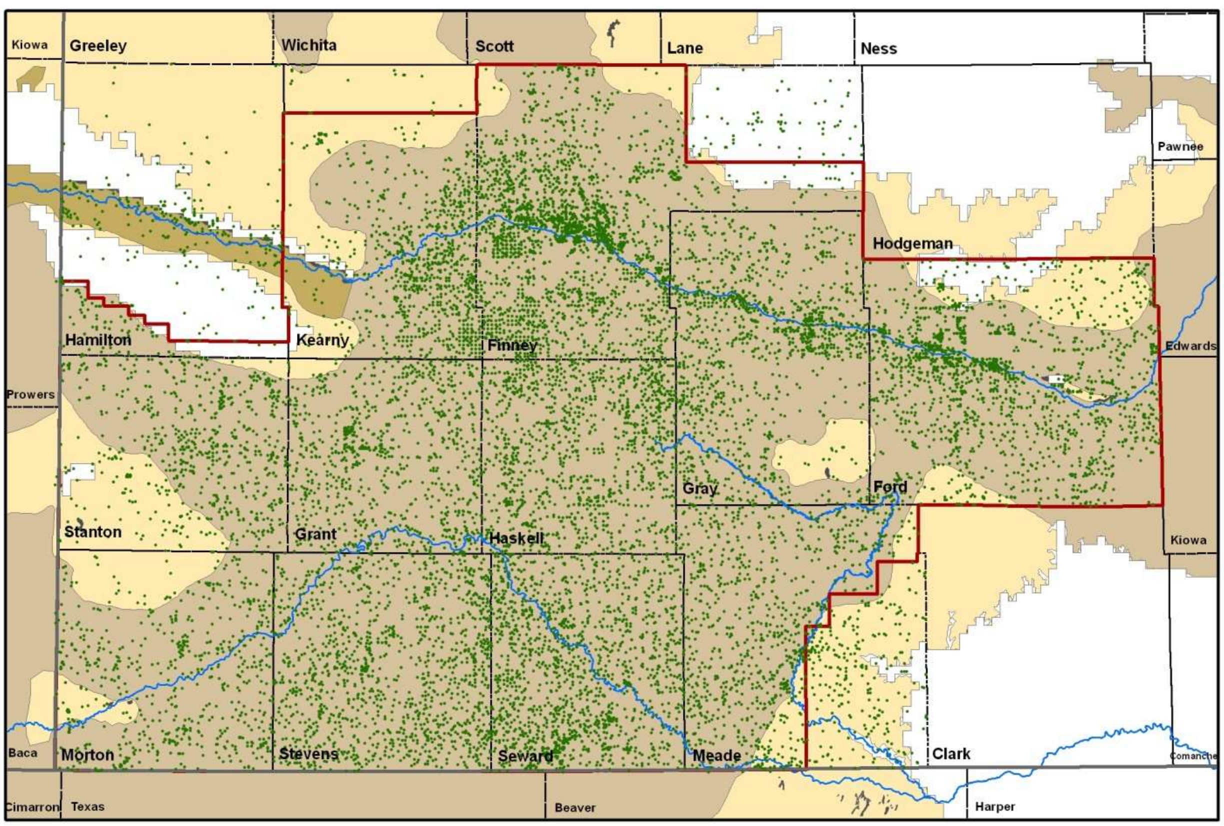


Figure 12. Distribution of PST+ lithologic wells used in the model.

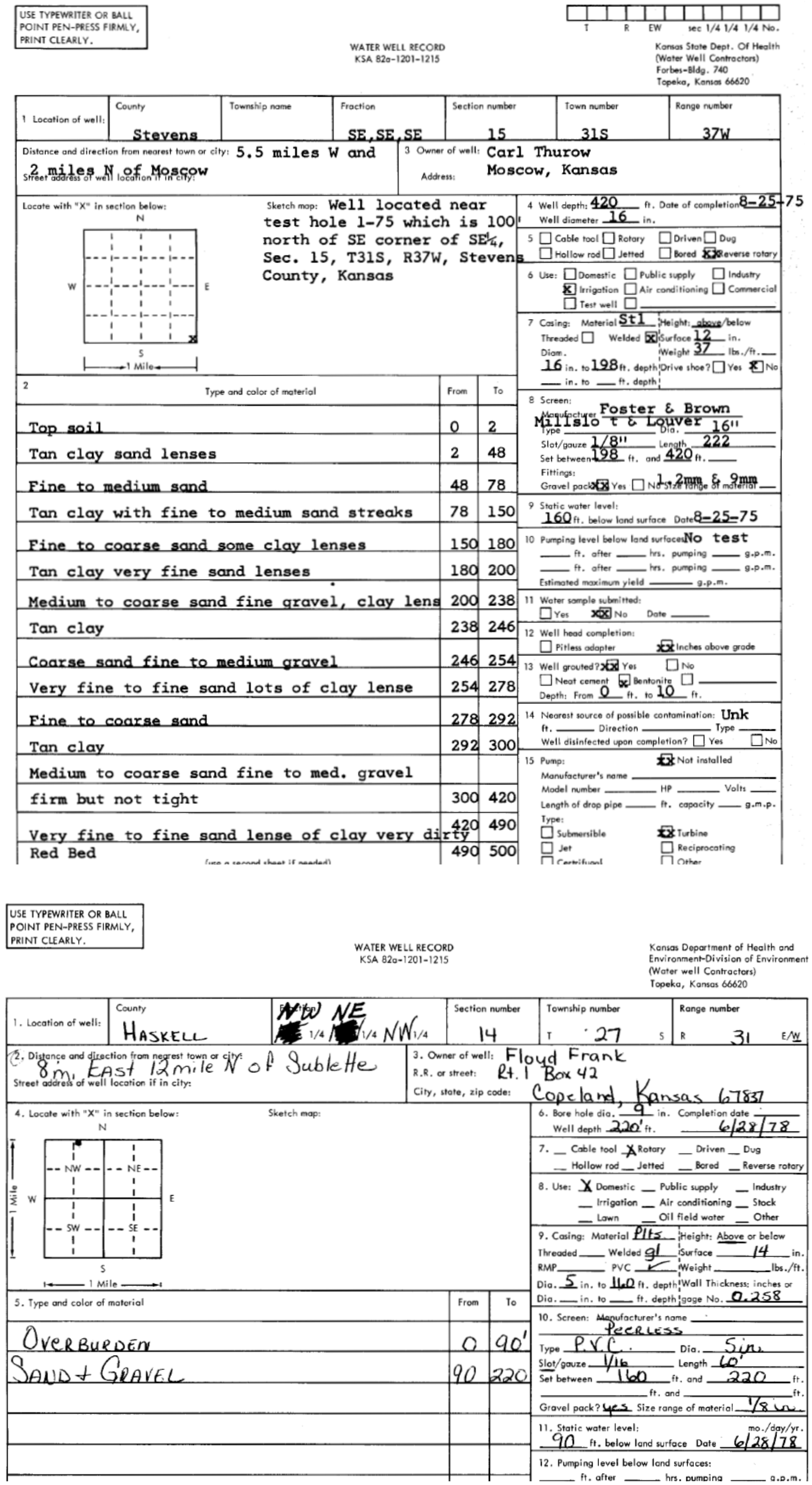
The quality of lithologic data from PST+ varies substantially for different driller's logs. Figure 13 shows two examples of drillers' logs of vastly different quality. A high-quality driller's log contains detailed lithologic descriptions and corresponding depth intervals. A low-quality log, on the other hand, does not provide accurate information on lithology and, if used without caution, may adversely impact the accuracy of the K and Sy estimates. Currently, the clearly bad logs like Figure 13b are not used in the PST+ lithology database. All logs, once entered into the database, are treated equally in the K and Sy calculation. One of the future improvements in PST+ will be to develop an option that allows driller's logs that differ in quality to be handled differently.

Table 1. PST+ synonymy codes and lithology descriptions.

Synonymy	Lithology	Synonymy	Lithology	Synonymy	Lithology
sh	Shale	sc	Sandy Clay or Silty Sand	fsnd	Fine Sand
c	Clay	fds	Fine Sandy Silt	fmgsnd	Fine to Medium Sand
coal	Coal	fmds	Fine to Medium Sandy Silt	fmsnd	Fine to Medium Sand
br	Bedrock	fcrsds	Fine to Coarse Sandy Silt	snd	Sand
rb	Red Bed	ds	Sandy Silt	fcrssnd	Fine to Coarse Sand
r	Rock	mds	Medium Sandy Silt	msnd	Medium Sand
sst	Siltstone	gc	Gravelly Clay	mcrssnd	Medium to Coarse Sand
ca	Limestone/caliche	mcrsds	Medium to Coarse Sandy Silt	cg	Clayey Gravel
o	Overburden	crsds	Coarse Sandy Silt	crssnd	Coarse Sand
ts	Topsoil	cesd-cg	Cemented Sand and/or Gravel	sg	Silty Gravel
fs	Fine Silt	fss	Fine Silty Sand	fsdg	Fine Sand and Gravel
fsc	Fine Sandy Clay	fmss	Fine to Medium Silty Sand	fmsdg	Fine to Medium Sand and Gravel
fmsc	Fine to Medium Sandy Clay	ss	Silty Sand	msdg	Medium Sand and Gravel
m	Marl or Ochre	mss	Medium Silty Sand	sdg	Sand and Gravel
msc	Medium Sandy Clay	fcrsss	Fine to Coarse Silty Sand	fcrssdg	Fine to Coarse Sand and Gravel
s	Silt	mcrsss	Medium to Coarse Silty Sand	mcrssdg	Medium to Coarse Sand and Gravel
crssc	Coarse Sandy Clay	crsss	Coarse Silty Sand	crssdg	Coarse Sand and Gravel
fcrssc	Fine to Coarse Sandy Clay	u	Unknown (most likely unintelligible)	fg	Fine Gravel
mcrssc	Medium to Coarse Sandy Clay			fmg	Fine to Medium Gravel
				fcrsg	Fine to Coarse Gravel
				fcrssg	Fine to Coarse Gravel
				g	Gravel
				mg	Medium Gravel
				mcrsg	Medium to Coarse Gravel
				crsg	Coarse Gravel

Figure 14 shows a typical PST+ well log that has been coded with the synonymies. Each log has a well ID, followed by a list of synonymy lithology descriptions and their corresponding depth intervals. Figure 14 shows that more than one synonymy code can be used for a specific depth interval. For the current K and Sy calculation, the percentage contribution of each synonymy to the final value of a depth interval is equal (regardless of the order in which the synonymy codes are listed), although a weighted method can be easily implemented if needed.

Figure 15 shows the location of three example cross sections based on data processed early in the PST program prior to this modeling project. These early cross sections cover the same area as the model, but the density of wells is not as great as those shown in Figure 12 and the logs had not been assessed using the synonymy classification system. The color-coded lithologies for these three cross sections are illustrated in Figure 16. The cross sections indicate that significant vertical variations in lithology occur in the HPA. In this model, these vertical variations are taken into account by a series of one-layer step models.



(a)

USE TYPEWRITER OR BALL POINT PEN–PRESS FIRMLY, PRINT CLEARLY.

WATER WELL RECORD
KSA 82a-1201-1215

T R EW sec 1/4 1/4 1/4 No.

Kansas State Dept. Of Health (Water Well Contractors) Forbes-Bldg. 740 Topeka, Kansas 66620

1 Location of well: County: Stevens | Township name: | Fraction: SE,SE,SE | Section number: 15 | Town number: 31S | Range number: 37W

Distance and direction from nearest town or city: 5.5 miles W and 2 miles N of Moscow
Street address of well location if in city:

3 Owner of well: Carl Thurow
Address: Moscow, Kansas

Locate with "X" in section below: N W E S — 1 Mile

Sketch map: Well located near test hole 1-75 which is 100' north of SE corner of SE¼, Sec. 15, T31S, R37W, Stevens County, Kansas

4 Well depth: 420 ft. Date of completion 8-25-75
Well diameter 16 in.

5 Cable tool / Rotary / Driven / Dug / Hollow rod / Jetted / Bored / X Reverse rotary

6 Use: Domestic / Public supply / Industry / X Irrigation / Air conditioning / Commercial / Test well

7 Casing: Material Stl Height: above/below Threaded / X Welded Surface 12 in.
Diam. Weight 37 lbs./ft.
16 in. to 198 ft. depth Drive shoe? Yes X No
in. to ft. depth

8 Screen: Manufacturer Foster & Brown
Type Millslot & Louver Dia. 16"
Slot/gauze 1/8" Length 222
Set between 198 ft. and 420 ft.
Fittings:
Gravel pack X Yes No Size range of material 1.2mm & 9mm

9 Static water level: 160 ft. below land surface Date 8-25-75

10 Pumping level below land surface: No test
ft. after hrs. pumping g.p.m.
ft. after hrs. pumping g.p.m.
Estimated maximum yield g.p.m.

11 Water sample submitted: Yes X No Date

12 Well head completion: Pitless adapter / X Inches above grade

13 Well grouted? X Yes No
Neat cement / X Bentonite
Depth: From 0 ft. to 10 ft.

14 Nearest source of possible contamination: Unk
ft. Direction Type
Well disinfected upon completion? Yes No

15 Pump: X Not installed
Manufacturer's name
Model number HP Volts
Length of drop pipe ft. capacity g.p.m.
Type: Submersible / X Turbine / Jet / Reciprocating / Centrifugal / Other

2 Type and color of material	From	To
Top soil	0	2
Tan clay sand lenses	2	48
Fine to medium sand	48	78
Tan clay with fine to medium sand streaks	78	150
Fine to coarse sand some clay lenses	150	180
Tan clay very fine sand lenses	180	200
Medium to coarse sand fine gravel, clay lens	200	238
Tan clay	238	246
Coarse sand fine to medium gravel	246	254
Very fine to fine sand lots of clay lense	254	278
Fine to coarse sand	278	292
Tan clay	292	300
Medium to coarse sand fine to med. gravel firm but not tight	300	420
Very fine to fine sand lense of clay very dirty	420	490
Red Bed	490	500

(use a second sheet if needed)

(b)

USE TYPEWRITER OR BALL POINT PEN–PRESS FIRMLY, PRINT CLEARLY.

WATER WELL RECORD
KSA 82a-1201-1215

Kansas Department of Health and Environment–Division of Environment (Water well Contractors) Topeka, Kansas 66620

1. Location of well: County: Haskell | NW NE 1/4 1/4 NW 1/4 | Section number: 14 | Township number: T 27 S | Range number: R 31 E/W

2. Distance and direction from nearest town or city: 8 mi. East 12 mile N of Sublette
Street address of well location if in city:

3. Owner of well: Floyd Frank
R.R. or street: Rt. 1 Box 42
City, state, zip code: Copeland, Kansas 67837

4. Locate with "X" in section below: N — NW NE SW SE — W E S — 1 Mile

Sketch map:

6. Bore hole dia. 9 in. Completion date 6/28/78
Well depth 220' ft.

7. Cable tool X Rotary Driven Dug Hollow rod Jetted Bored Reverse rotary

8. Use: X Domestic Public supply Industry Irrigation Air conditioning Stock Lawn Oil field water Other

9. Casing: Material Plts Height: Above or below
Threaded Welded gl Surface 14 in.
RMP PVC ✓ Weight lbs./ft.
Dia. 5 in. to 160 ft. depth Wall Thickness: inches or
Dia. in. to ft. depth gage No. 0.258

10. Screen: Manufacturer's name Peerless
Type P.V.C. Dia. 5 in.
Slot/gauze 1/16 Length 60'
Set between 160 ft. and 220 ft.
ft. and ft.
Gravel pack? yes Size range of material 1/8 in.

11. Static water level: 90 ft. below land surface Date 6/28/78 mo./day/yr.

12. Pumping level below land surfaces:
ft. after hrs. pumping g.p.m.

5. Type and color of material	From	To
Overburden	0	90'
Sand + Gravel	90	220

Figure 13. Example driller logs of (a) excellent quality and (b) poor quality (not used in PST+).

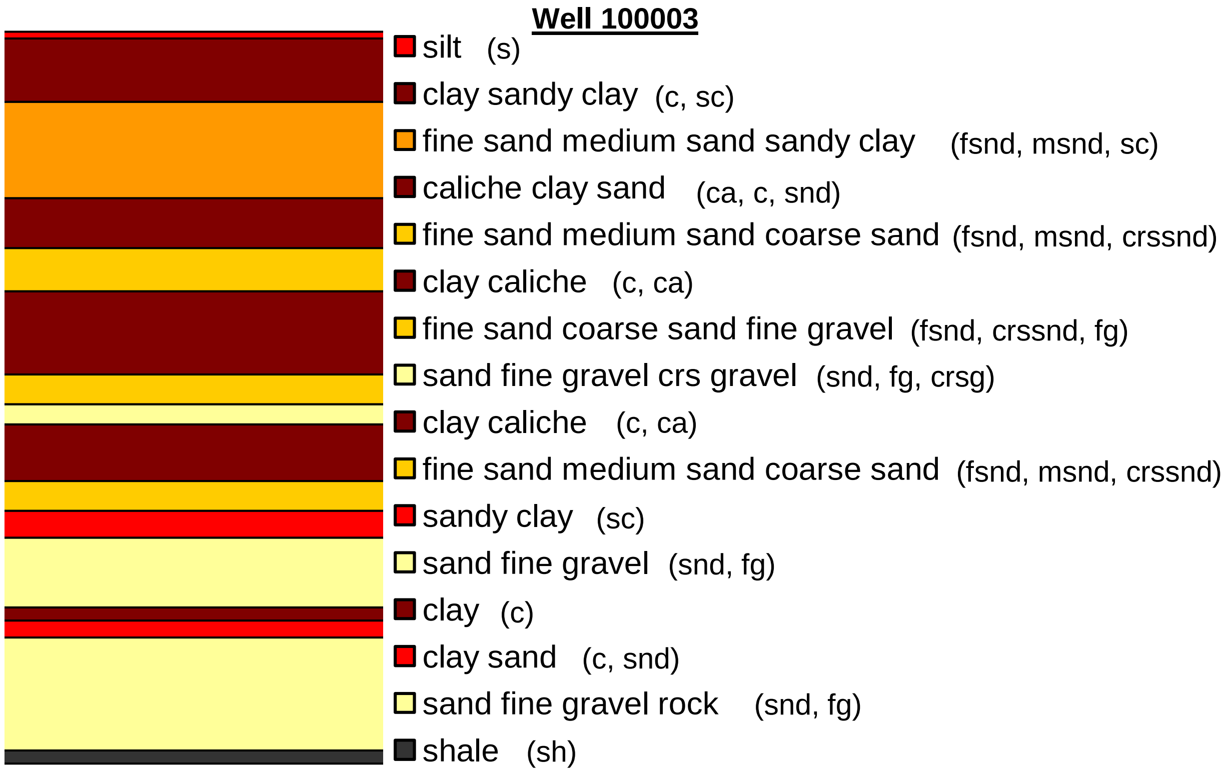


Figure 14. An example PST+ well log. Synonymy codes are in parentheses in the legend.

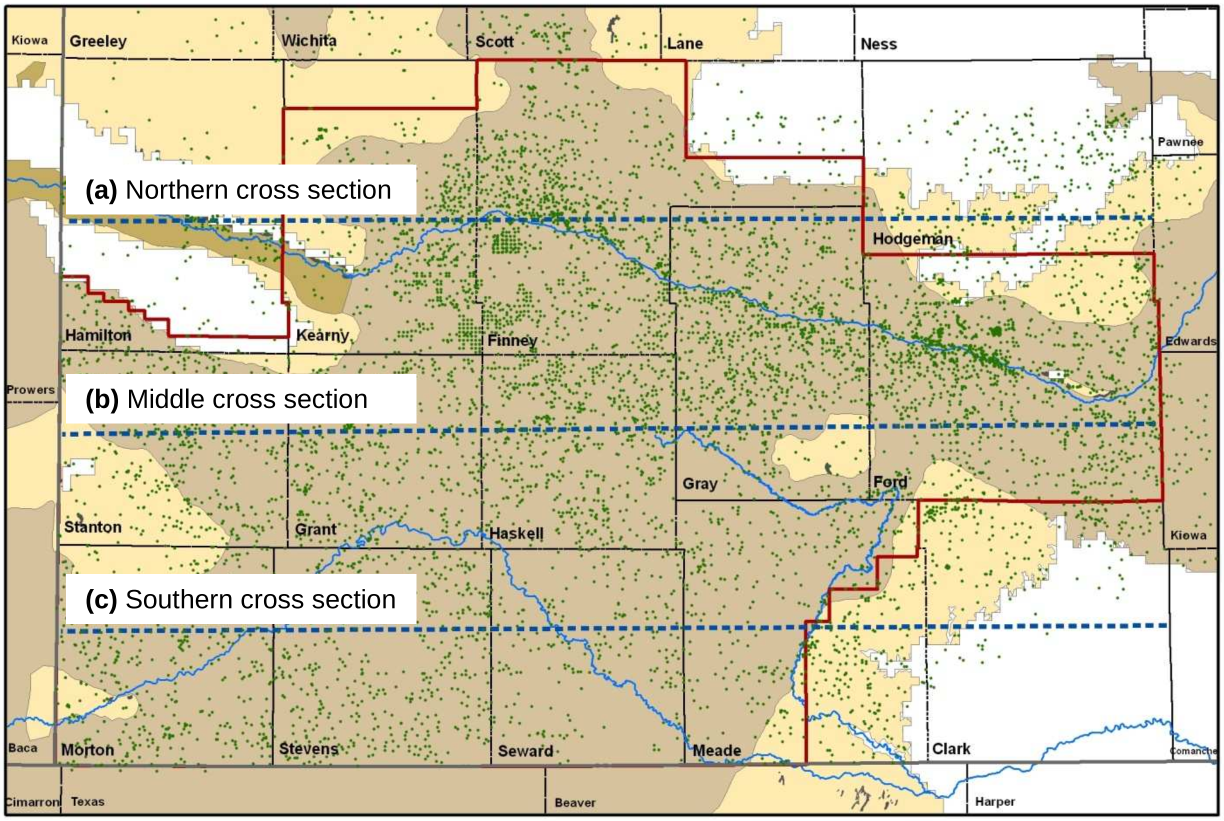


Figure 15. Location of the three PST cross sections in the HPA displayed in Figure 16.

(a) Northern cross section

(b) Middle cross section

(c) Southern cross section

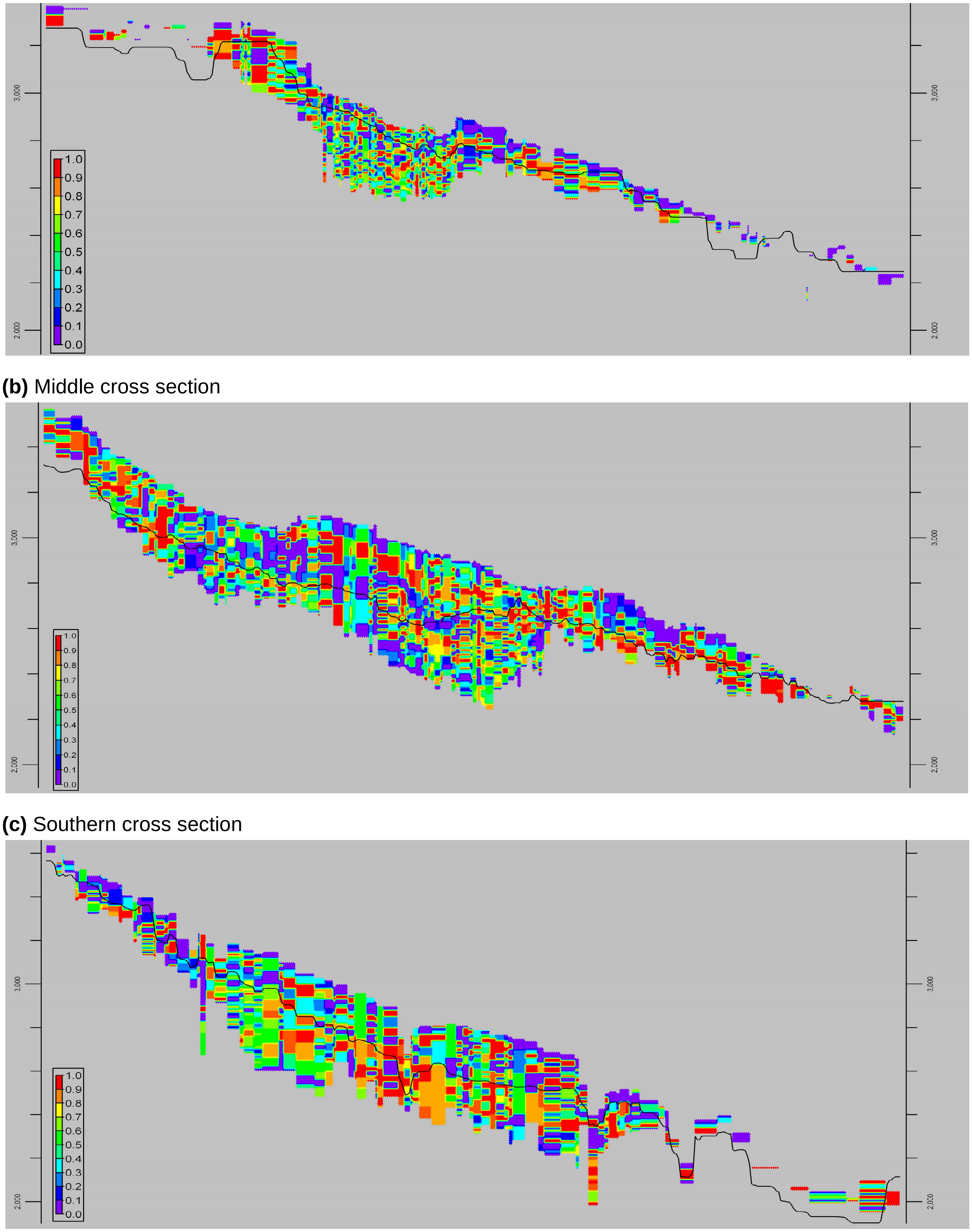


Figure 16. Three cross sections of early PST lithology classifications. Higher numbered colors indicate more transmissive, coarser sediment. The lines at each wellbore are the average 2007-2009 water levels.

Water Levels

Predevelopment water levels were estimated in and around the model domain from a variety of sources. Kansas water levels are based primarily from well data recorded in county-based geologic bulletins. Most of the depth-to-water measurements in these reports range from the late 1930s to 1948. In addition, the KGS Water Information Retrieval and Storage Database (WIZARD) was queried for additional well measurements taken before 1949. Pre-1949 depth-to-water values measured in the surrounding states of Colorado and Oklahoma were obtained from the U.S. Geological Survey's National Water Information System (NWIS). Figure 17 shows the spatial distribution of wells containing a predevelopment water-level measurement. Although some of the wells in Greeley and Wichita counties, Kansas, were measured in the early 1950s, these values should still represent predevelopment conditions for the area (Prescott et al., 1954).

Predevelopment water-table measurements are generally expressed as a depth below the land surface. In some cases, a value was listed as a height above sea level with a land surface and a measuring-point height also provided. For a few of these types of records, the measuring-point heights were unknown, in which case, a value of 0.5 feet was assumed. Wells that were known to be screened in aquifer units other than the High Plains aquifer were removed from the record set.

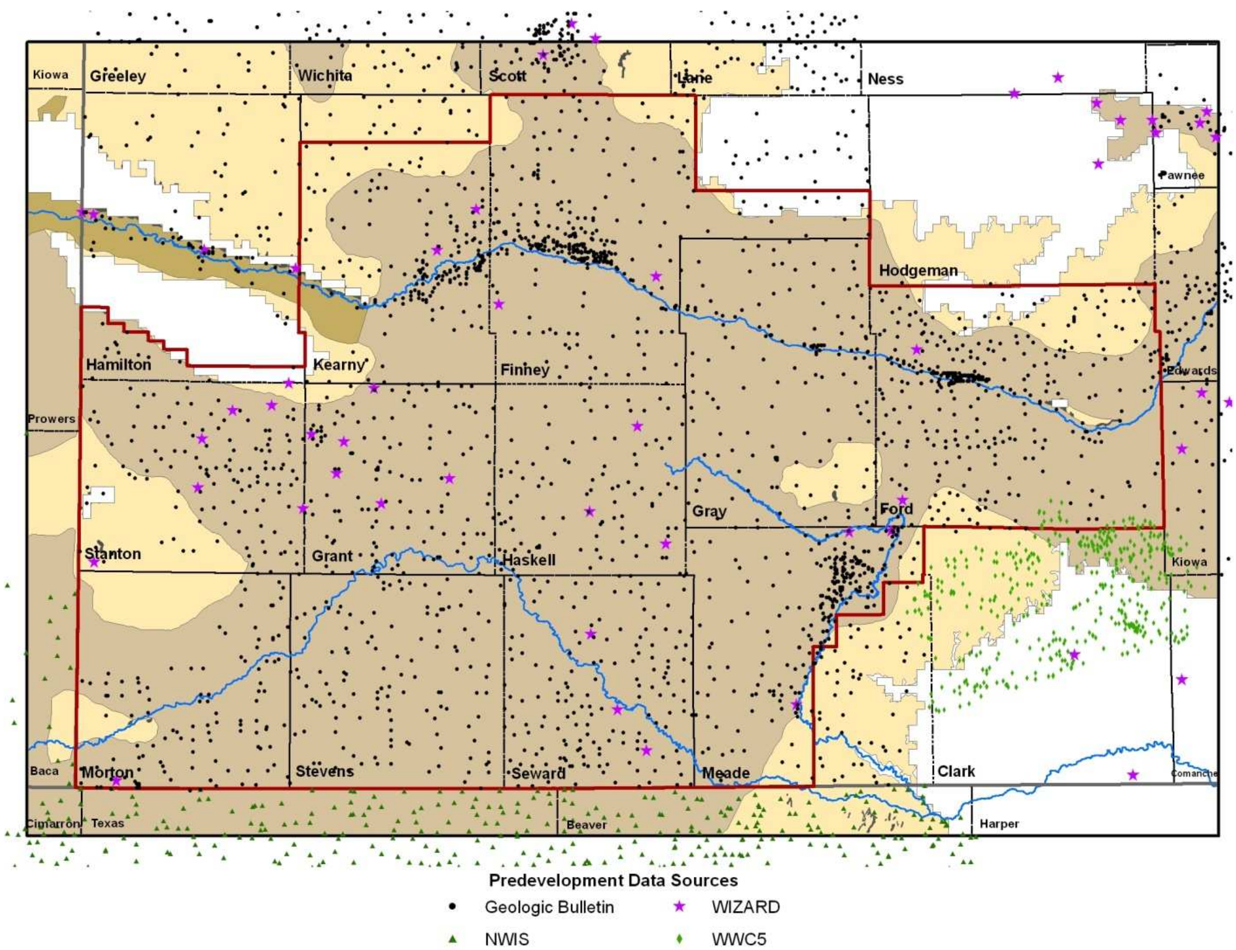


Figure 17. Spatial distribution of ground-water wells with a predevelopment depth-to-water measurement.

Given the complete lack of any predevelopment values for northern Clark County, Kansas, static water levels from the Water Well Completion Records (WWC-5) were used as a proxy for predevelopment conditions. Since 1974, Kansas drilling companies have been required by State law to submit a WWC-5 well log form each time a ground-water well is drilled, plugged, or reconstructed. Part of the information obtained from a WWC-5 form for a constructed well is the static water level and the date of measurement. In 1982, a line was added to the WWC-5 form for depth at which water was first encountered when the well was drilled, although information on this line is seldom recorded. Within Clark County, the WWC5 static water levels run from the mid-1970s to present day. However, given that the aquifer is thin in this location with little ground-water development in terms of large-volume water demands, it can be assumed that water-level elevations have been relatively static over time. The inclusion of the WWC5 records gives a realistic estimate of water levels in lieu of no data at all. Figure 18 shows elevation contours for the predevelopment water-level surface based on both the predevelopment measurements and WWC-5 records.

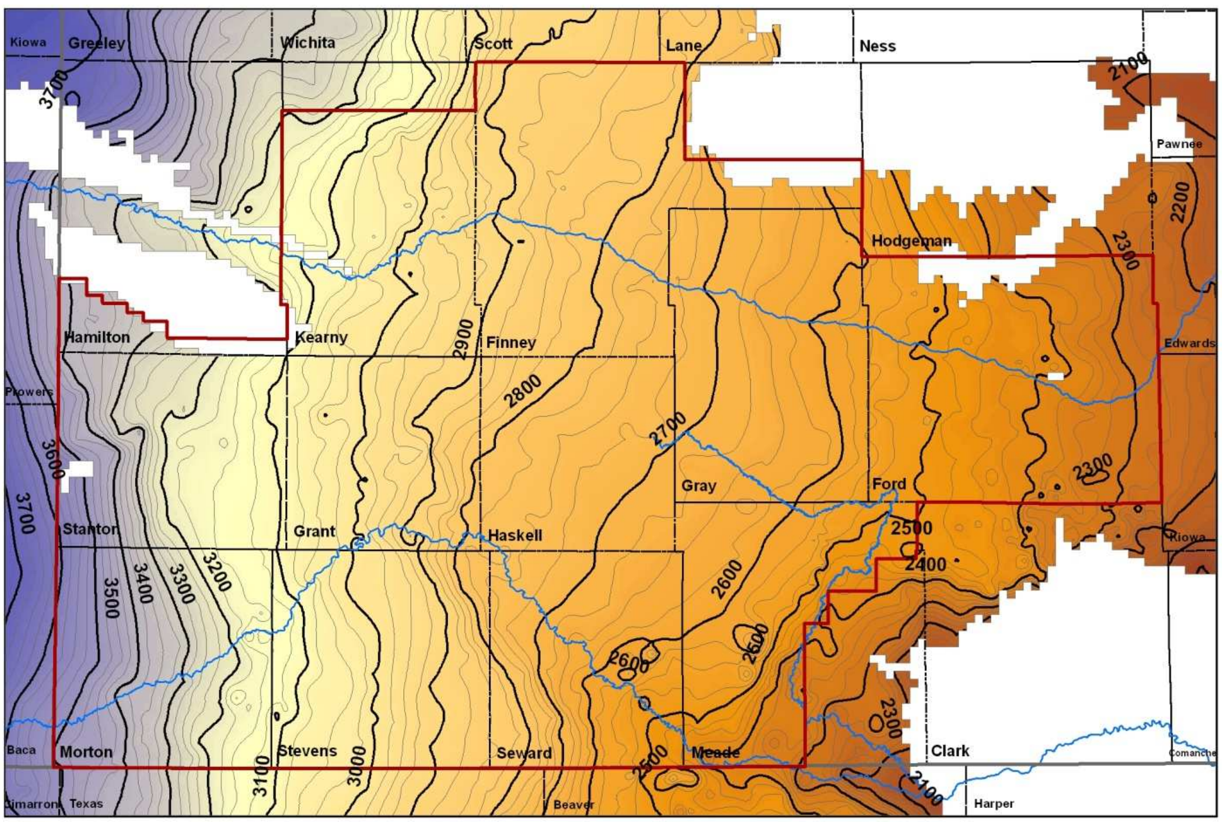


Figure 18. Interpolated predevelopment water table for the High Plains aquifer. The contours represent elevations in feet.

The interpolated predevelopment water-level surface mimics the land surface in that it trends from highs along the western edge of the model area to lows in the east and southeast. The depth-to-water averages around 74 feet over the model area and ranges from 250 feet below the land surface to artesian conditions, which occurred in the lower part of the HPA along the Crooked Creek valley in central Meade County and to the west of Crooked Creek in part of northeast Meade County (Frye, 1942). Predevelopment artesian heads were as much as 10 to 17 feet or more above land surface, which required special adaptation to obtain a measurement at the time of the geologic bulletin measurements in 1939 (Figure 19).

Figure 19. Test well in Meade County State Park, drilled 1939 (head of 17.4 feet above the land surface). Taken from Plate 7b of Frye (1942).

Water-level measurements after the predevelopment period vary greatly both in terms of the number of wells measured and their spatial distribution. Most of the measurements were obtained in the winter months of December, January, and February. Data coverage across the model area is relatively poor between predevelopment and middle 1960s Since 1966, a slight declining trend exists in the number of wells measured over the model area (Figure 20). The Kansas Cooperative Water Level Program, operated by the KGS in cooperation with KDA-DWR, started in 1996 and continues to this day.

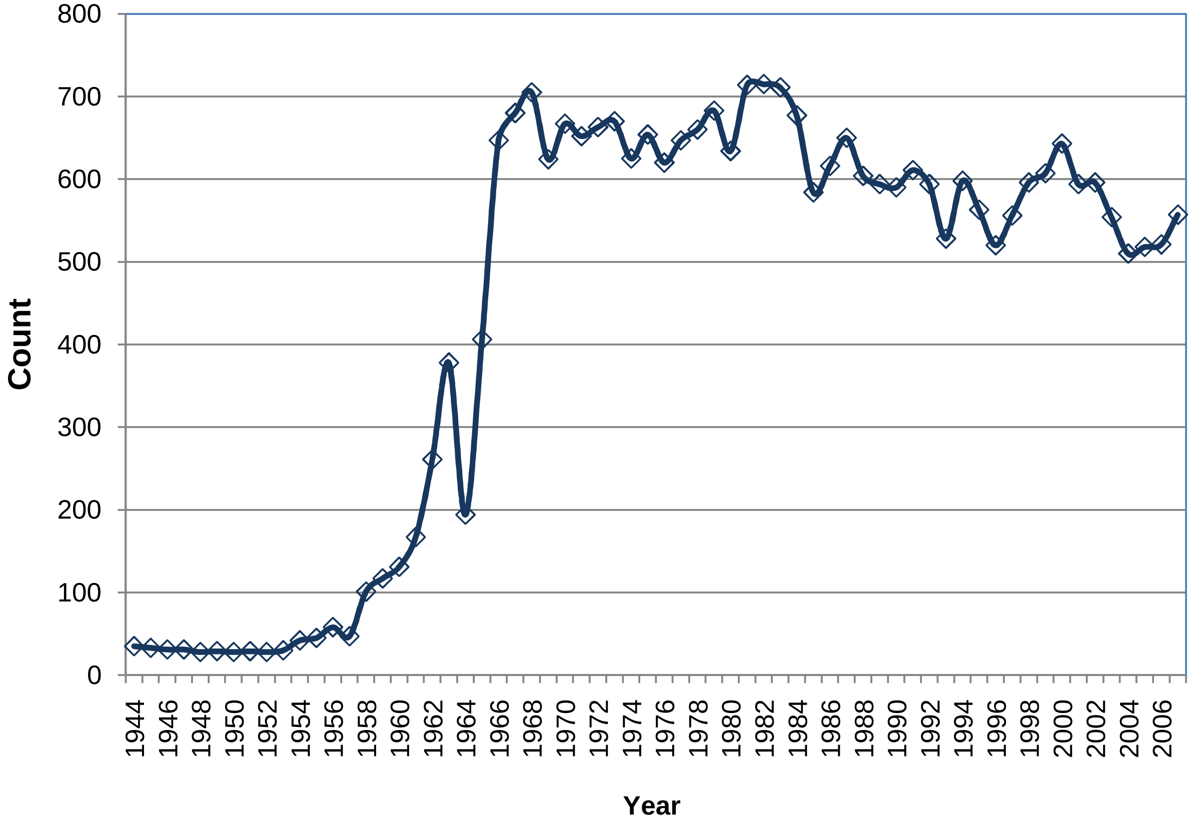


Figure 20. Number of wells in the model domain with winter (December to February) measurements.

Boundary Conditions

The model uses time-varying specified head boundaries on the northern and southern edges of the active model area and a portion of the edges surrounding the inactive bedrock area within the model (Figure 2). On the eastern and western borders, time-varying fluxes are specified, which were based on determination of head gradients from water levels estimated for the eastern and western boundaries and two columns just inside those boundaries (Figure 21). Time-varying specified heads or fixed values that do not change over time were established based on a time- and labor-intensive process of reviewing each model cell in relation to surrounding water-level measurements.

Starting with the interpolated predevelopment water levels, each time-varying head cell was reviewed in relation to well measurements taken over the transient period. The model has over 2,400 wells that were measured sometime during the transient period. However, only 125 of them contain long histories of consistent measurements taken in the winter months (Figure 21). In cases where these wells are located near the head-boundary cells, the water-level trends shown in the measurement histories were applied to the head-boundary cells, starting in predevelopment.

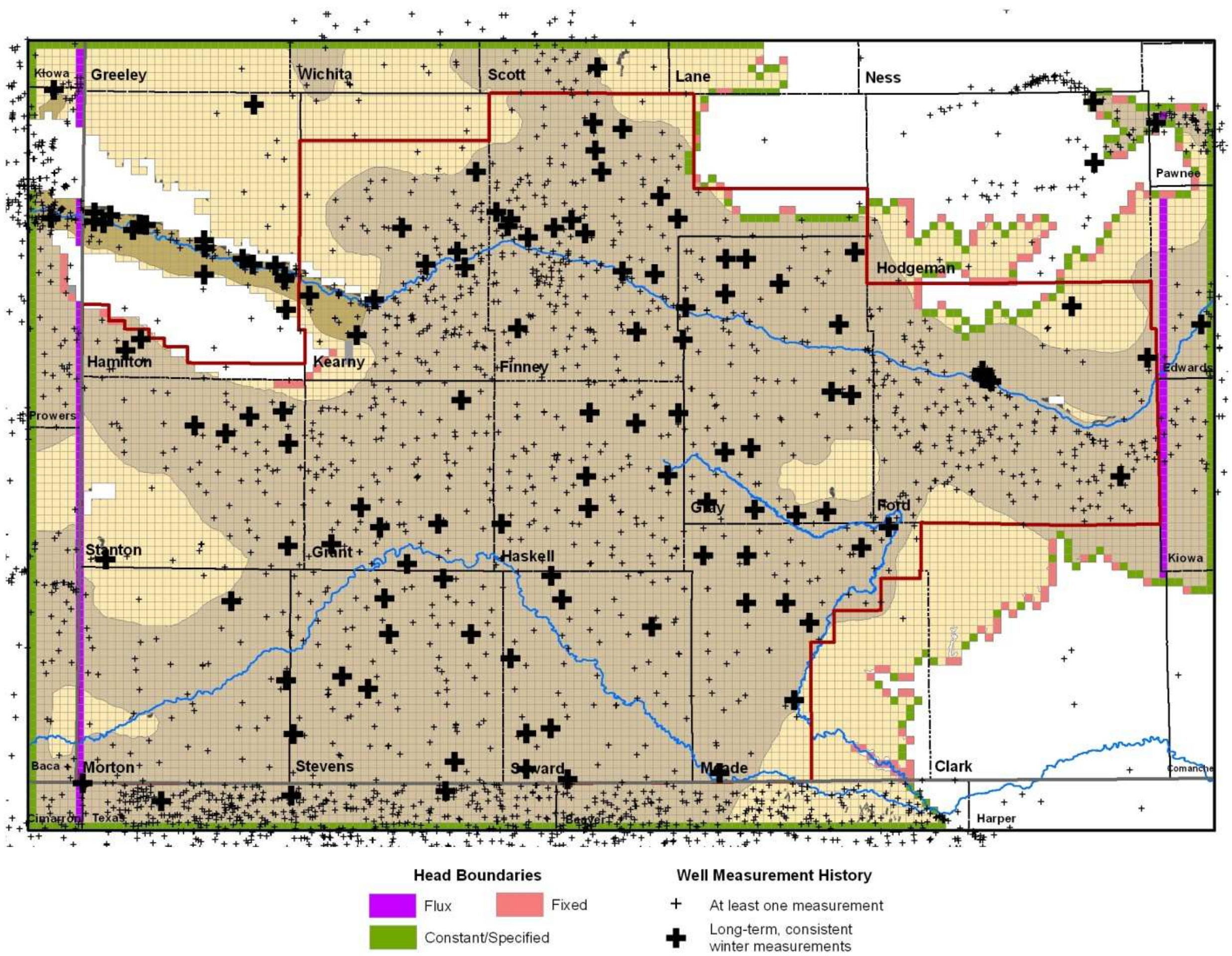


Figure 21. Distribution of 125 long-term water level measurement wells (solid crosses). The green cells are time-varying specified heads; the purple cells are time-varying specified heads that are used for gradient calculations for determining time-varying fluxes on the western and eastern boundaries; the pink cells along some of the bedrock edges are the fixed heads that do not change with time.

Measurements from wells without long-term, winter-based measurements were still used when possible. Many of these wells, especially in Oklahoma, had numerous measurements from 1966 to 1970. If these wells fell within any head-boundary cells, then their water levels were transferred to the head-boundary cells and linear regression equations were established with those water levels and the predevelopment estimate to fill in the transient period of record. If the wells were located near but not in the head-boundary cells, the water levels were still transferred to the head-boundary cells but only after making slight subjective adjustments based on the predevelopment water-level gradient. This process of filling in the holes with nearby data and using regression equations to fill in the gaps worked well where there are some data. The process is still very subjective in areas with little to no data, such as along the northern model boundary (Greeley, Wichita counties), western boundary (south of the Arkansas River along the state line on the western sides of Stanton and Morton counties), and portions of Meade, Clark, Kiowa, Finney, and Lane counties.

In areas of little saturated thickness or along some of the edges of the inactive cells, fixed head-boundary cells were established after reviewing static water levels listed in the WWC5 records, which, in many cases, provided the only data available. The fixed head-boundaries in these locations generally keep the saturated thickness around 10 feet although it may range from 5 to 30 feet. Some time-varying specified heads in these locations (e.g., Meade, Clark, and Hodgemen counties) change so little over time that the head-boundaries are effectively fixed.

Stream Characteristics and Flow

River History

The Arkansas River drains from its headwaters in the Rocky Mountains in Colorado through southeast Colorado and across southwest Kansas. The river flowed unrestricted across the High Plains in Colorado and Kansas until the early 1870s when the first substantial diversions were constructed in southeast Colorado for irrigation purposes. Large ditches started diverting water from the river in southwest Kansas starting in the early 1880s. John Martin Reservoir on the river in southeast Colorado started storing water in 1943 and was completed in 1948. Other reservoirs on tributary streams and fed by river diversions were also created in the greater river corridor in southeast Colorado. Ground-water pumping from the alluvial aquifer along the river valley in Colorado further reduced the flow until a lawsuit of Kansas against Colorado restored some flow in the 1990s as required by the Arkansas River Compact. The ditch diversions, ground-water pumping, evapotranspiration from the irrigated fields, and evaporation from the reservoirs all contributed to decreasing the river flow with time. The decreased flow and the operation of John Martin Reservoir changed the flow characteristics of the river substantially such that it modified the channel morphology downstream in southwest Kansas.

In Kansas, water-level declines associated with pumping from the HPA became substantial enough in the 1970s that the river ceased to flow in the Garden City area downstream into Ford County. The only time the river now flows in this stretch is when a greater than normal snowpack accumulates in the Rocky Mountain headwaters such that snowmelt fills the John Martin Reservoir and results in large flow releases, or when substantial rainstorms occur across the watershed in southeast Colorado and southwest Kansas.

The Cimarron River flows from its headwaters in northeast New Mexico and a small part of southeast Colorado through the northwesternmost part of the Oklahoma panhandle and across the southern part of southwest Kansas before entering northwest Oklahoma. In New Mexico, it is known as the Dry Cimarron River. Small irrigation diversions have existed on the river in New Mexico and northwesternmost Oklahoma. These and the removal of beaver dams in the past and the effect of cattle on the floodplain have somewhat affected the stream morphology in New Mexico and Oklahoma.

Flow in the Cimarron River across southwest Kansas was historically episodic, with no to very low flow in dry periods from Morton through northwest Stevens and southern Grant counties, interspersed with high flows from substantial precipitation events. Perennial flow of the river generally began in the northwest corner of Seward County. The flow in the river has generally decreased with time, both entering Kansas in southwest Morton County and leaving the model area in southern Meade County. The main cause of the decreased flow in Kansas is the decline in HPA water levels thereby decreasing baseflow. The riverbed is now usually dry from Morton County downstream to near the Highway 54 bridge in southeast Seward County.

Stream Channel Characteristics

The original channels of the Arkansas and Cimarron rivers were generally broad, shallow, and braided. The flow modifications by ditch irrigation and reservoir operation caused the channel of the Arkansas River to become entrenched in Kansas, primarily in the area where the HPA underlies the river. The entrenchment became substantial enough that the USGS had to change the datum for stream gages at Garden City, Dodge City, and Kinsley from one to three times. At the Garden City gage station, the datum was lowered three feet in 1964, 1976, and 1987 for a total of 9 feet entrenchment. The Dodge City station shifted 0.7 mile upstream from its past location in 1981, so it is difficult to compare the datum changes. However, the datum record at the former station suggests a period of entrenchment followed by filling; the filling might be related to the constriction of the river channel by the flood levees. At the gage station near Kinsley, the datum indicates an entrenchment of 3 feet. Based on the gage data and visual evidence, the channel appears to be generally entrenched by several feet within the model area downstream of the paleovalley that extends through Hamilton County to south-central Kearny County.

The streambed elevations for the Arkansas and Cimarron rivers and Crooked Creek were obtained by determining where elevation contours in USGS 7.5-minute topographic quadrangles crossed the stream channel. The streambed elevation in the model was adjusted for entrenchment from south-central Kearny County (starting at T.25S., R.37W., Sec. 14), the western extent of where the HPA underlies the river valley, to the eastern model boundary. The dates of the USGS topographic maps that cover the area of the Arkansas River channel within the model area are 1958-1965, and most are 1965. An average maximum entrenchment of 6 ft was assumed along the river channel based on data at gage stations and visual appearance. A maximum mean entrenchment of 3 ft was assumed for the channel before 1965 and 3 ft for after 1965. The riverbed elevation was adjusted in the GMD3 model as up to 3 ft higher than the topographic map values for the pre-development period to 1955, the values from the maps were used for 1955-1975, and the elevations were adjusted as up to 3 ft lower for 1975 to 2007. A smooth transition in elevation adjustments was used for where the entrenchment was assumed to start at the end of the paleovalley in south-central Kearny County (Table 2).

Table 2. Adjustment of the streambed elevation in the Arkansas River channel for channel entrenchment (relative to USGS topographic map elevations).

Predevelopment to 1955	
Location	Adjustment, ft
25S-37W-14	-1
25S-37W-12	-2
25S-36W-07	-3
Downstream from 25S-36W-07	-3
1975 to 2007	
Location	Adjustment, ft
25S-37W-14	+1
25S-37W-12	+2
25S-36W-07	+3
Downstream from 25S-36W-07	+3

Gaged Streamflow

Mean annual (calendar year) streamflows were obtained from the USGS for past and currently operated gage stations on the Arkansas and Cimarron rivers and Crooked Creek. The input streamflow in the model for the Arkansas River is based on the USGS gage near the town of Coolidge on the Kansas side of the Colorado-Kansas state line. The Coolidge gage record for annual flow extends from 1951 to the present. The Syracuse gage station on the Arkansas River, which is only 18.4 channel miles downstream of Coolidge, has annual records since 1923. Flows at Coolidge and Syracuse have historically been very similar because stream-aquifer interactions between the stations do not change the flow appreciably and no significant tributaries enter the river between the gages. Thus, data from the Syracuse gage were used for Coolidge from predevelopment to 1950. The minimum, maximum, and average flows for the river near Coolidge (assuming the Syracuse values for 1944-1950) for 1944-2007 are 20.4 ft^3/sec (in 1979), 1,067 ft^3/sec (in 1965, the year of the greatest recorded flood on the river), and 228 ft^3/sec, respectively. There is a ditch diversion (i.e. the Frontier ditch) upstream (west) of the USGS gage in Coolidge. As a result, the annual diversions of that ditch were added to the Coolidge streamflows in computing the final values of input flows for the Arkansas River in the model.

The input streamflow data for the Cimarron River in the model are based on the gage located near the town of Elkhart in southwest Morton County. The Elkhart gage record for annual flow extends from 1972 to the present. Annual records exist for two gage stations on the Cimarron River upstream of the Elkhart gage (near Kenton, Oklahoma, 1951-present, and above Ute Creek near Boise City, Oklahoma, 1943-53). The mean annual flows for 1944-1971 for Elkhart were estimated by multiplying the ratio of the Elkhart to Kenton total flows for 1972-1982 times the Kenton annual flows for 1944-1971. The Kenton flows for 1944-1950 were estimated by multiplying the ratio of the Kenton to Boise City total flows for 1951-1953 times the Boise City annual flows for 1944-1950. The minimum, maximum, and average flows (measured and estimated) for 1944 to 2007 for the Cimarron River near Elkhart are 0 (in 1985, 1992, and 1994), 156 ft^3/sec (in 1965), and 17.6 ft^3/sec, respectively. The flow near Elkhart has generally decreased with time and the mean annual flows for 2000-2007 were all <1 ft^3/sec.

The streamflow input is zero for Crooked Creek because the stream originates from within the model.

Stream-Aquifer Interactions

Ground-water levels in the alluvial aquifer of the streams in the model are expected to respond relatively rapidly to fluctuations in river stage because the sediments in the channel are sands and gravels. 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. Ground-water levels have remained at or below the channel bottoms of substantial stretches of the Arkansas and Cimarron rivers during the last few decades. Thus, little to no baseflow has occurred in these areas.

When substantial flows derived from Colorado reach the stretch of the Arkansas River overlying the HPA with a dry riverbed, 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 model area. Thus, substantial, continuous flow in the Arkansas River from eastern Kearny County to the eastern model boundary in selected years of the last few decades has not been produced by baseflow from the HPA, but instead has been primarily 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 in the eastern part of the model area decrease substantially. Additional description of stream-aquifer interactions for the Arkansas River within the GMD3 model area are in Whittemore et al. (2001).

Similar stream-aquifer interactions occur in the normally dry streambed of the Cimarron River except that the high flows from upstream that have entered the model area within the last few decades have been substantially smaller than the high flows in the Arkansas River. As indicated above, the perennial portion of the Cimarron River (baseflow fed by discharge from the HPA) during predevelopment was around the northwest corner of Seward County, while the current start of HPA baseflow to the river is in southeast Seward County. The perennial portion of Crooked Creek sustained by HPA discharge has also moved downstream from its predevelopment location due to declining ground-water levels. Intense rain storms within Kansas have produced flow in the dry riverbed stretches of the Arkansas and Cimarron rivers and Crooked Creek in the normally dry riverbed stretches, but these are generally short-term events except where the water levels in the alluvial aquifer were close to the bottom of the streambed before the storms. Substantial rainstorms are responsible for appreciably increasing annual flows in the rivers and creek in the reaches where ground-water levels are at or above the streambed.

Irrigation Diversions and Seepage

Water has been diverted from the Arkansas River into irrigation ditches in Kansas from the early 1880s until the present. The diverted volume depends upon the available Arkansas River flow, which is controlled by the amount of snowmelt, precipitation, and storage in John Martin Reservoir in Colorado, and by the Arkansas River Compact. In the early 1900s, pumping of ground water into the ditches started, which made water supplies more reliable for irrigation. The joint use of water diverted from the Arkansas River and well water for irrigation in the areas served by the ditches continues today. The primary diversions in Kansas are for the Frontier, Amazon, Garden City, South Side, Farmers, and Garden City ditches (Figure 22). The Alamo and Fort Aubrey canals formerly diverted water from the river several miles west of Syracuse and carried water for irrigation along the northern side of the river to several miles east-southeast of Syracuse. The Alamo Canal was abandoned in 1974 (Sherow, 1990). Part of the water rights of the Fort Aubrey Canal have been transferred to the Frontier Ditch (KDA-DWR, personnel communication). Data for the annual diversions of each ditch were obtained from KDA-DWR.

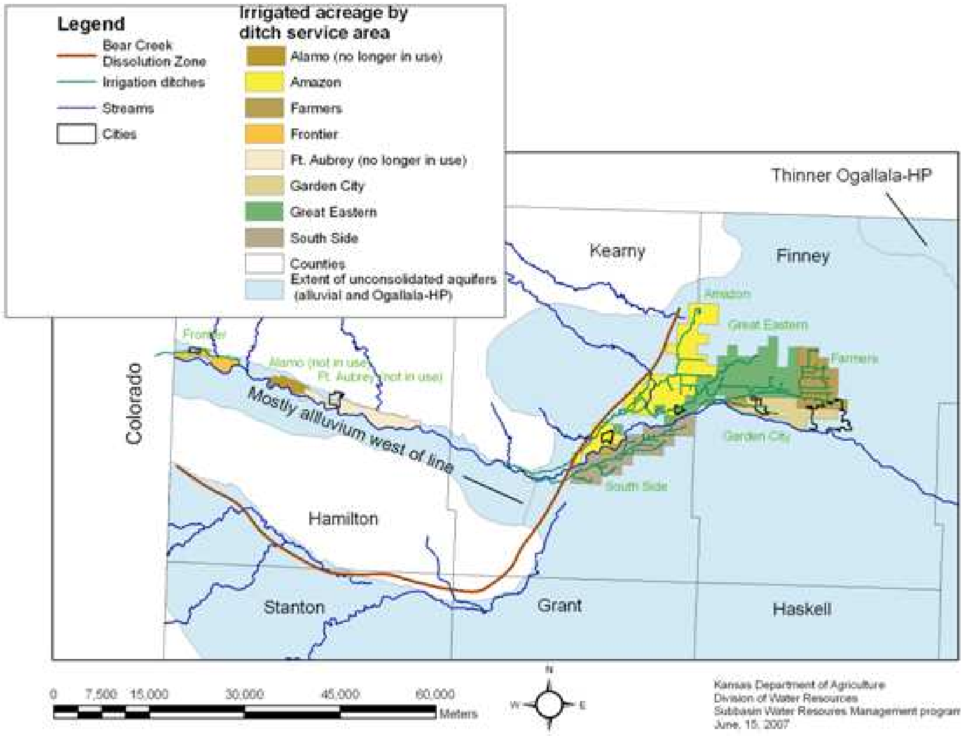


Figure 22. Location of irrigation ditch service areas in the Arkansas River corridor (from KDA-DWR).

Most of the ditches in Kansas serve eastern Kearny County and the area to the west and northwest of Garden City (Figure 22). The Amazon Ditch currently diverts the largest quantity of water from the Arkansas River in Kansas. The headgate of the Amazon Ditch is in central Kearny County; the canal extends in an east then northeast direction before irrigating cropland around Lakin and to the north of Deerfield into westernmost Finney County. The former headgate of the Great Eastern Ditch was just downstream of the Amazon Canal and the two canals generally paralleled each other. In 1955 the operators of the Great Eastern and Amazon ditches entered into an agreement to jointly operate (KDA-DWR, personal communication). The Amazon Ditch was widened to accommodate increased flow to allow it to serve the irrigation areas for both ditch systems. Water is now diverted from the Amazon Ditch into Lake McKinney to the northeast of Lakin. The Great Eastern Ditch system obtains its water from Lake McKinney and irrigates land in western Finney County to the northwest of Garden City. The South Side Ditch diverts water from the southern bank of the Arkansas River about 3 miles downstream of the Amazon Ditch headgate. South Side Ditch water irrigates land along its extent south of the river before ending near the Kearny-Finney counties line. The headgate of the Farmers Ditch is a couple miles east of Deerfield. The headgate of the Garden City Ditch was originally about a mile farther downstream. Both ditch systems later entered into a cooperative arrangement involving the use of the headgates of the Farmers Ditch as the diversion from the Arkansas River. Water for the Garden City Ditch is now diverted from the

Farmers Ditch in western Finney County. These ditches carry water to irrigate land to the west and northwest of Garden City.

The range and means of annual diversions from the start of model predevelopment time (1944) to 2007 are, respectively, 0-57,590 and 18,830 acre-ft for the Amazon Ditch, 1800-41,790 and 21,340 acre-ft for the Great Eastern Ditch, 0-43,410 and 11,980 acre-ft for the South Side Ditch, 0-30,830 and 13,940 acre-ft for the Farmers Ditch, and 0-11,000 and 1,910 acre-ft for the Garden City Ditch. The minimum values occurred during the mid- to late 1970s, although the diversions were also zero in 2003 for all of the five ditches except the Great Eastern.

The coverage for the areas irrigated by the ditches was taken from the Upper Arkansas Corridor Study (Whittemore et al., 2001). The amount of seepage from the main canals of the river diversions was assumed to be the same as used in the Whittemore et al. (2001) model for the upper Arkansas River corridor, i.e. 1% per mile. The amount of HPA recharge from the applied river water was estimated to be 25% because the use is generally as flood irrigation (also the same value used in Whittemore et al., 2001).

Water Right Development

Obtaining and processing water rights information (e.g., pumping amounts) across three states required varied approaches. Kansas has a substantial amount of data that are readily available online and the modeling team has strong working knowledge of that information and the variation of the water appropriation doctrine upon which it is based. However, obtaining data for Oklahoma and Colorado and then determining how that data represented each state's water rules and regulations was more time-intensive. Although the other states maintain public access sites via the web, they are structured more for individual water right/well review and are not designed for mass download. Like Kansas, the states of Oklahoma and Colorado each follow their own version of the water appropriation (first in time, first in right) doctrine but only Kansas maintains a robust, State-sponsored water-use reporting program.

Kansas

Water rights in Kansas can be very dynamic and change over time in a variety of fashions and for a number of reasons. This requires any extensive data processing operations to be time-stamped. The authorized quantity of water right locations used in the model represents conditions as of July 3, 2008. The data characterizes active, non-dismissed, appropriated or vested water rights. Data were accessed from the WIMAS website located at http://hercules.kgs.ku.edu/geohydro/wimas/index.cfm. Ground-water wells known to be screened in layers other than the HPA were removed from the data set.

Within the model domain, there are 10,367 individual water rights in Kansas (Figure 23). The vast majority of water authorized under these rights, 96.41 percent, is for ground-water-based irrigation (Table 3). Some surface-water development exists; the largest users are the ditch irrigation companies on the Arkansas River. A few appropriations divert water directly from the Cimarron River and Crooked Creek, but they are insignificant in terms of their allocation totals and have only once reported any use since 1990. The model handles the larger stream diversions from the ditch irrigation companies on the Arkansas River as part of the Stream Package in MODFLOW. The rest of the authorized surface-water diversions are considered to be insignificant in comparison to overall streamflow, and all pumping/water right work in this report focuses on the much larger and more numerous ground-water diversions.

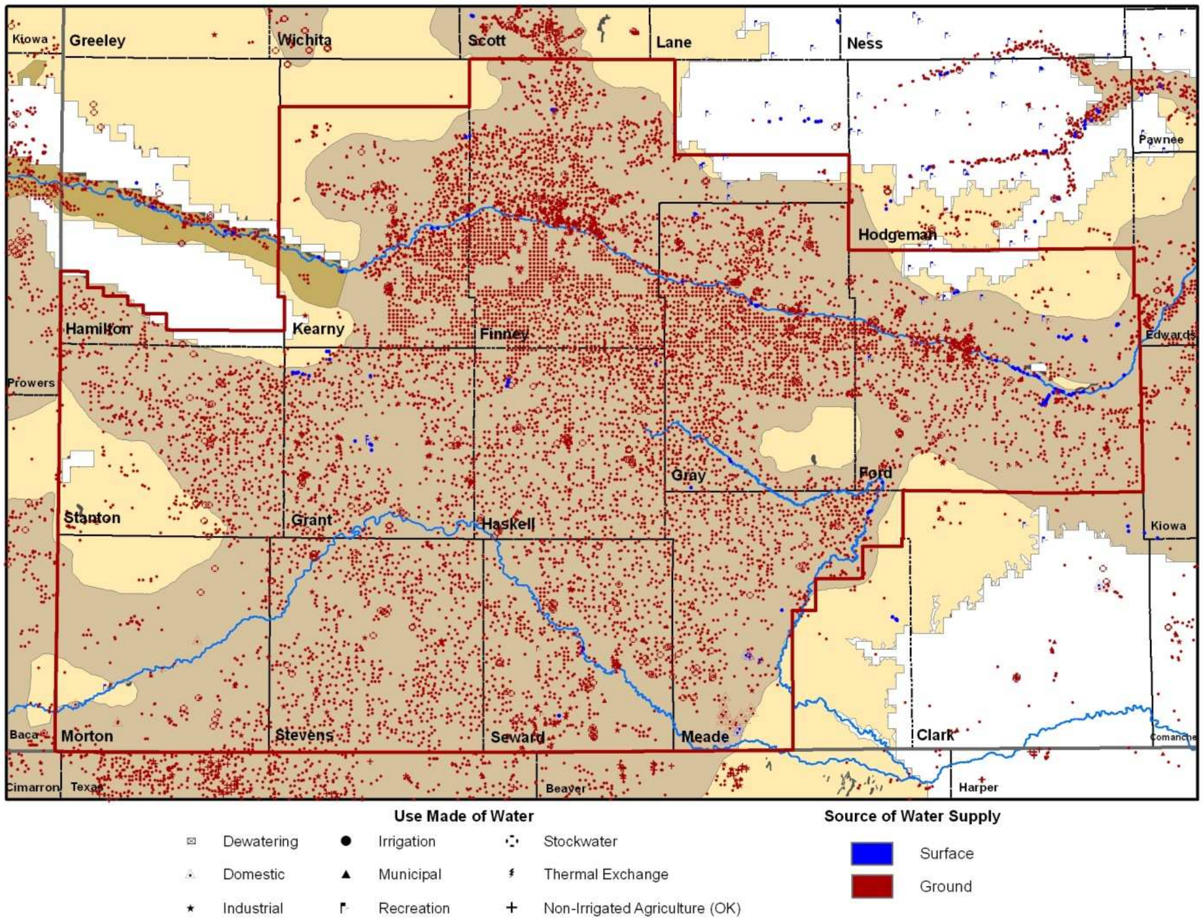


Figure 23. Water right development in Kansas, Colorado, and Oklahoma.

Table 3. Total Authorized Quantity, in Acre-Feet, by Use Made of Water and Source of Supply for the Kansas Portion of the GMD3 Model Area Represents Conditions as of July 3, 2008.							
	Domestic	Industrial	Irrigation	Municipal	Recreation	Stockwater	Other
Surface	7.4	0	170,295.5	52	9,783.0	0	0
Ground	85.2	40,905.5	3,426,406.0	44,778.7	2,660.0	35,180.8	435.2
Total	92.6	40,905.5	3,596,702.0	44,830.7	12,443.0	35,180.8	435.2

The WIMAS database only stores the present-day authorized quantity for water rights. Historic trends in the authorized quantity are based on that current value in relation to the priority date of the water right and are assumed to be representative of past conditions (i.e. the authorized quantity assumed not to be changing with time). One of the complexities with Kansas authorized quantities is they can be stored by the water right (regardless of how many wells a single water right may have), by the water right use(s) made of the water, or by one or more of a water right point(s) of diversion.

If the appropriated quantity was stored by water right or use, then the total amount of water authorized was divided by the number of authorized points of diversion so that each point of diversion would have an associated quantity. This was necessary because the multiple points of diversion for a water right could be located in different model cells. This allowed for the total quantity by model cell to be summarized over time and space. If the quantity was already stored by the point of diversion, it remained unchanged.

The trend in authorized quantity over time (water right priority dates) shown for Kansas in Figure 24 is typical throughout much of western Kansas. Starting in the late 1960s with the proliferation of center-pivot irrigation systems, the number of new water rights applications submitted each year greatly increased until the late 1970s/early 1980s where the trend begins to level off.

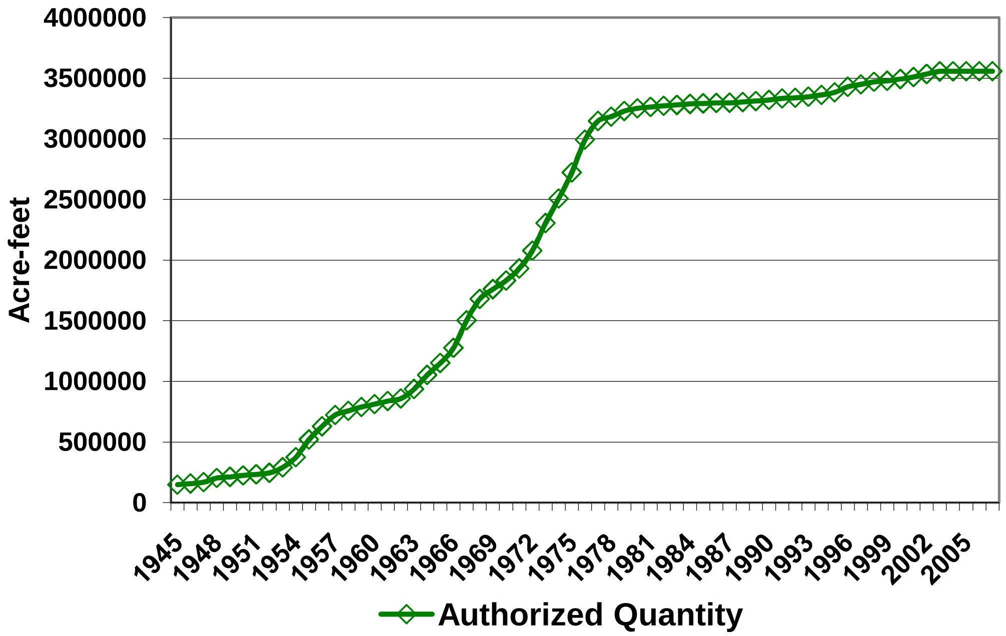


Figure 24. Total authorized quantity of ground water in water rights, Kansas model area.

Estimation of historic water use

Reported water use records in Kansas from 1990 to 2007 were downloaded from WIMAS (at the time of the model development, 2007 was the most recent year available for access). The Water Use Program of the Kansas Water Office was initiated in 1990. Now operated through KDA-DWR, this program provides quality control and assurance to water use reports submitted annually to KDA-DWR.

Reported water use is tied to specific points of diversion, which makes summarizing by model cells straightforward. Irrigation is the dominant use type, accounting for roughly 97% of the total ground-water withdrawals each year. Therefore, annual rates of precipitation and the total amount of water reported diverted are inversely related (Figure 25), for which the statistical correlation coefficient is -0.440. This relationship is statistically significant at the 0.10 level (which represents a 1 in 10 chance that this relationship exists by mere chance).

In order to estimate historical pumping levels prior to 1990, linear regression equations were first determined based on the ratio of water use/authorized quantity versus precipitation between 1990 and 2007, similar to past KGS model efforts done by Whittemore et al. (2006) and Wilson et al. (2008). However, unlike those past modeling efforts, the regression coefficent using this approach for the GMD3 model was low. Correlations based on selected, isolated subsets of water use years and model areas were also poor and never achieved R-squared values above 0.2. The exception to this were the water rights along the eastern edge of the model area, which is the same area covered by the Middle Arkansas River subbasin model (Whittemore et al., 2006).

The primary reason why linear regression of the water use/quantity ratio and annual precipitation failed may be that water use from 1990 to 2007 shows a slight but notable declining trend, while the authorized quantity over the same time period rises slightly. Many factors control changes in water use that are unrelated to precipitation, such as the economics of fuel costs and crop prices, which may account for these observations. However, in past KGS modeling activities, reported water use and quantity both trended in the same direction.

A solution was to de-trend the change in the water use/quantity ratio (Figure 26). This linear trend equation was used to calculate an overall de-trended ratio based on the average water use versus authorized quantity ratio over the period 1990-2006. The de-trended ratio was then regressed against annual precipitation, which yielded an R-squared value of 0.697. The regression was further improved by including the Palmer drought severity index (PDSI) as another independent variable to the regression equation. The resultant R-squared value was 0.745, meaning that almost 75 percent of the variation of ground-water pumping in the Kansas portion of the model can be statistically explained by variations in annual precipitation and the PDSI.

Figure 27 shows the results of the regression-based water use estimates along with the variables used in the regression and the 1990-2007 reported water use. The ratio of water use/authorized quantity is computed based on variations in the annual precipitation and Palmer drought index for a given year. That ratio is then multiplied against the authorized quantity for a given year to yield an estimate of the amount of water used. The transient model uses the regressed water use from predevelopment until 1989 and the reported water use data for 1990-2007.

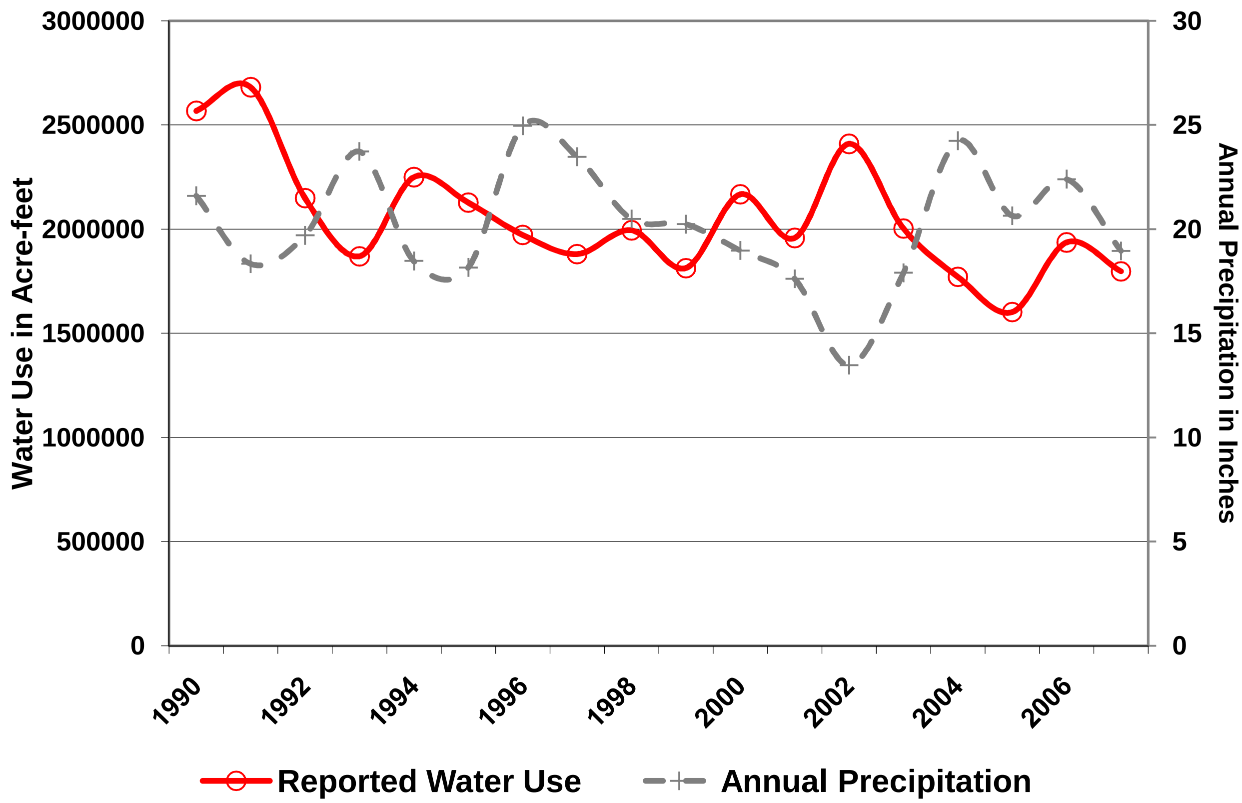


Figure 25. Total reported annual water use and annual precipitation for Kansas, 1990 to 2007.

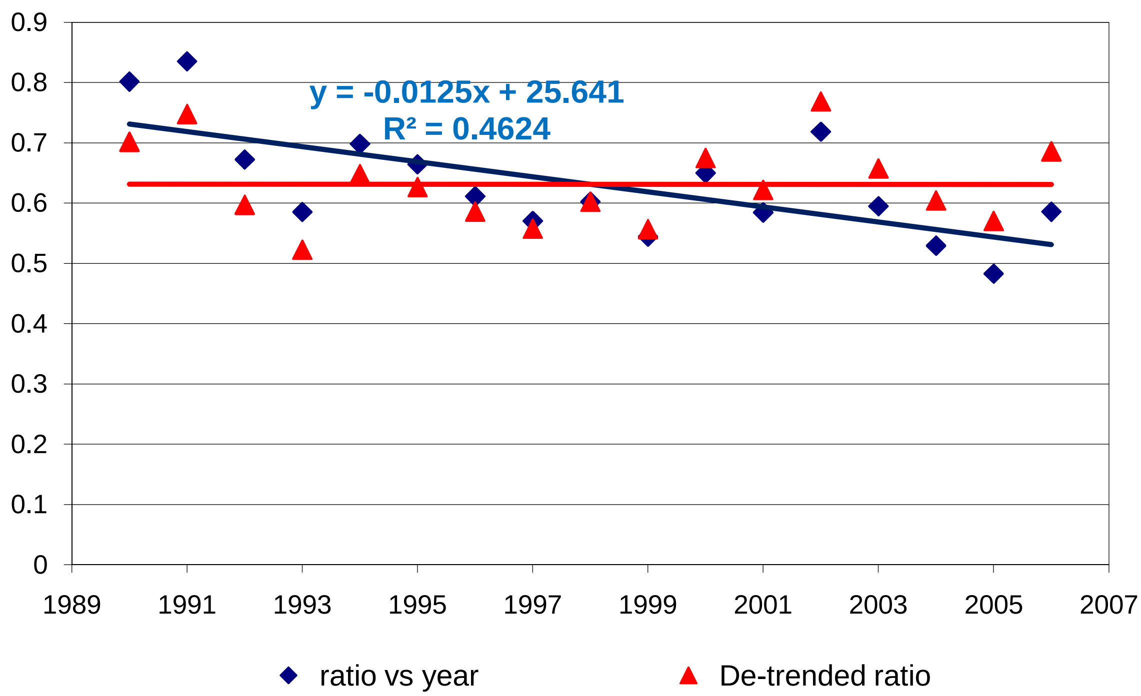


Figure 26. Trended and de-trended water use/quantity ratios, Kansas 1990 to 2006.

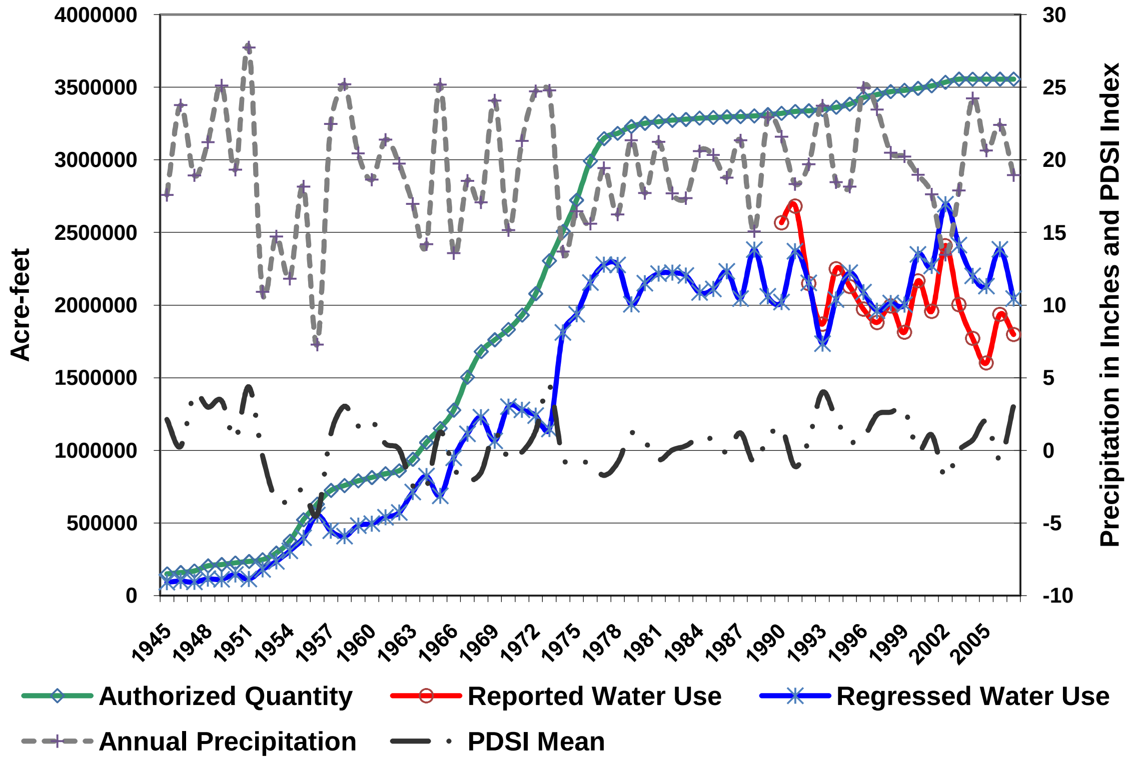


Figure 27. Regression-based and reported water use for the Kansas portion of the model.

After several test runs of the model over the transient period, it appeared that the regressed ground-water use was too high in the service areas where irrigation ditch companies divert Arkansas River water. Overall ground-water use in that area is expected to be a little less, given that it is supplemental to what is delivered by the ditch companies. Thus, for those model cells overlying the ditch service areas, a separate water use regression function was established using the same independent variables (PDSI and annual precipitation) as for the main model but based on the water use and quantity data for the ditch areas.

The R-squared value for the ditch area regression is 0.745, which is the same as for the overall Kansas portion of the model area. Figure 28 shows that the revised estimates of ground-water use for the ditch service areas are lower than the original. As indicated before, for those model cells overlying the ditch service areas, pumping estimates from the revised water use regression are used up to 1989 and the actual reported water use values applied to the model for 1990-2007.

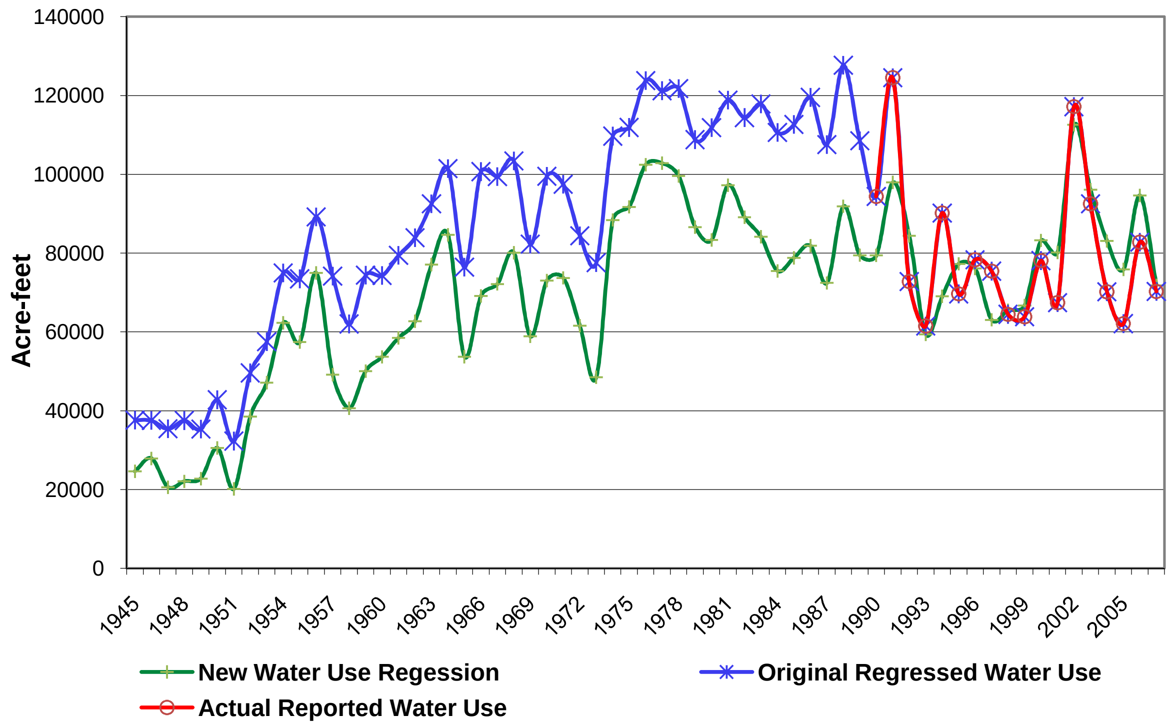


Figure 28. Regressed ground-water use in the ditch service areas utilizing diverted Arkansas River water for irrigation.

Oklahoma

Determining ground-water development in Oklahoma required several steps. Like Kansas, Oklahoma has more than one online inventory of ground-water well data, which are available from the Oklahoma Water Resources Board (http://www.owrb.ok.gov/) web site. The first data set reviewed was the "Reported Well Logs" since it was statewide and is available in a GIS-ready data format. This data set is similar to the Kansas WWC5 database in that it records actions filed by licensed well drillers for new well construction. There is some permit (aka Water Right) information but no quantity or annual water use information.

The Oklahoma Water Resources Board also serves another data application entitled the Water Information Mapping System (WIMS), which is an online interactive mapping site that contains a variety of data layers. One of the data layers is the "Permitted Groundwater Wells" under a Water Rights Layer section that contains database fields for permit numbers, permit dates, use made of water, and the total amount of water permitted annually (Figure 29).

Although the WIMS is very interactive and contained a lot of useful information, the lack of a download option was an impediment. All data queries were returned to a Query Selection window that only displayed 25 records at a time. As such, the permitted wells along the Kansas/Oklahoma state-line were manually selected within WIMS along the model's domain (1,242 records in all) and the records copied/pasted from the Query Selection window into an ASCII editor.

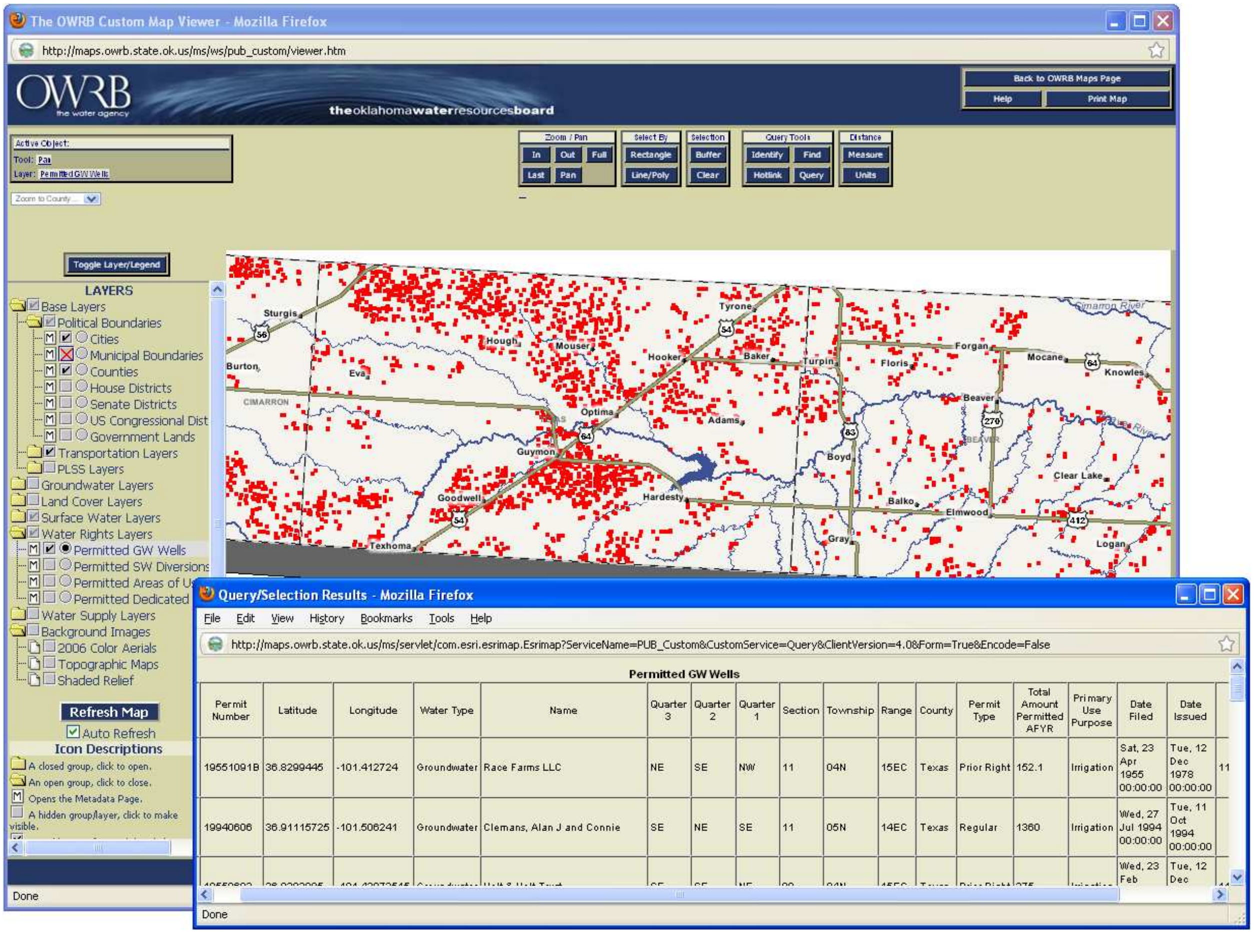


Figure 29. Computer screen snapshot of Oklahoma's Water Information Mapping System (WIMS).

The downloaded permitted well data contain latitude and longitude coordinates, which allowed them to be readily incorporated into GIS and included with other model data sets. In a similar manner to the Kansas authorized quantities values, the annual permitted Oklahoma quantities were pro-rated by the number of wells authorized under each permit and then summarized by model cell and the year the permit was issued.

Figure 30 shows the total permitted quantity of ground water over the Oklahoma portion of the model area. In comparison to an equivalent area in Kansas (approximately 6 miles north of the state line), the permitted quantity for Oklahoma increases at almost twice the rate although the patterns in changes are similar. Oklahoma bases its reasonable quantities for permits at 3 acre-feet per acre whereas Kansas water rights traditionally have been 2 acre-feet per acre. The Oklahoma data do not contain any means to identify aquifer types or proxy values (e.g., well depths), which may result in some overestimation of HPA quantities. Attempts to apply the Kansas water use regression equations to the Oklahoma permitted quantities also resulted in the overall water use to be double that of the Kansas side of the state line.

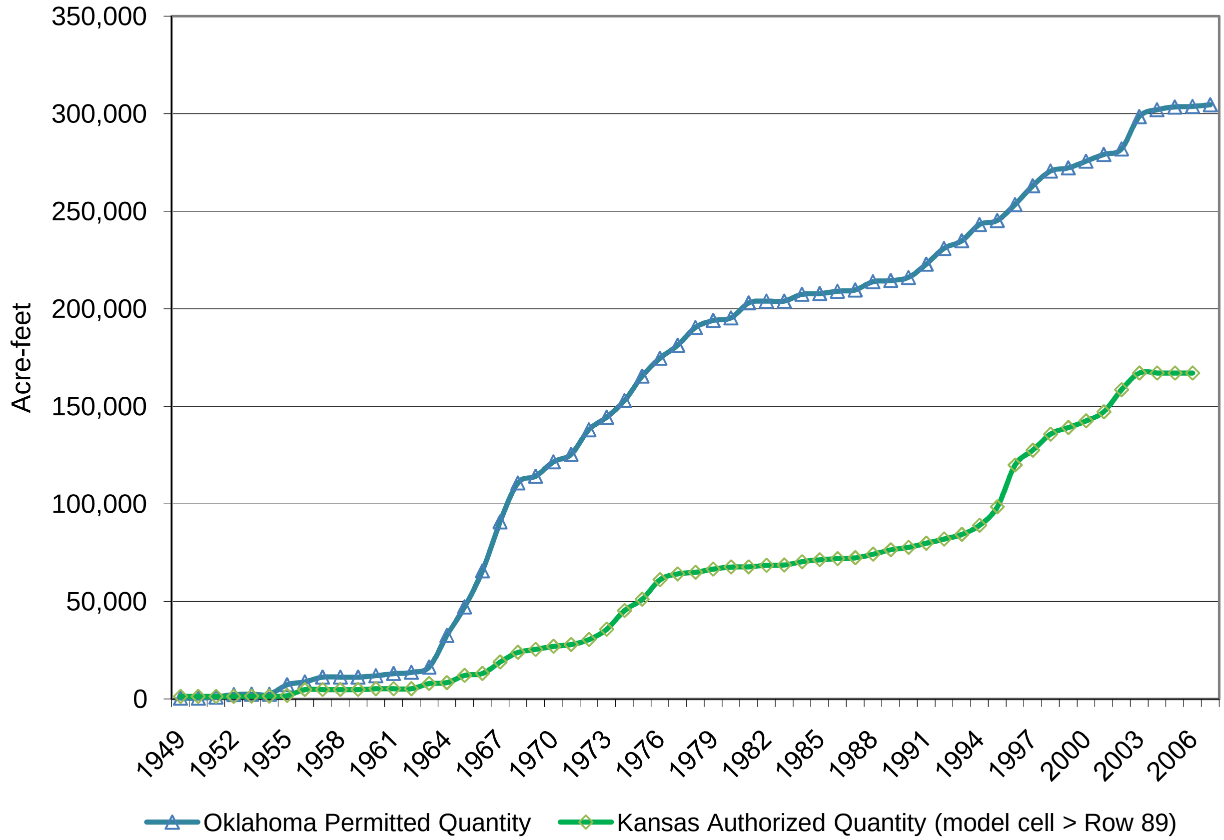


Figure 30. Total permitted quantity of ground water for the Oklahoma part of the GMD3 model. The authorized quantity in an equivalent area in Kansas on the northern side of the Oklahoma-Kansas border in the model area is also shown for comparison.

Estimation of historic water use

In personal communication with staff members of the Oklahoma Water Resources Board, it was discovered that the State does maintain reported water use records, and data are available under special requests. Like Kansas, Oklahoma water use is self reported. However, no State-sponsored quantity control program is in place. In addition, reports are not mandatory, although most water users submit them each year.

A list of permits in the Oklahoma portion of the model area was emailed to the Oklahoma Water Resources Board, and they returned all self-reported water use on file. Oklahoma water use is stored by permit number and year, ranging from 1967 to 2007. Initial summaries quickly revealed exceptionally high reported water use over several years, which appeared to be simple database entry errors. For example, one permit had 671,705 acre-ft reported to be used in a single year. A review of the permit's annual quantity and other years of water use suggested that the decimal place was incorrect for this value and that the actual use was 672 acre-ft for the year.

Exceptionally high water use totals were relatively easy to identify but it was difficult to justify changes for years of low to non-use. In some years, 1992 as an example, a notably smaller number of permits reported use. Overall, the Oklahoma water use data are good for small-scale, individual permit review, but the lack of mandatory reporting and a water use checking program introduces uncertainty into regional summaries. One method of overcoming extremes is to use averages, assuming the highs and lows cancel each other out.

After what appeared to be erroneously high water use records were adjusted, the average water use, by model cell and year, in the Oklahoma portion of the model was determined. This usage was compared to the average permitted quantities, average annual precipitation, and the PDSI to attempt to establish unique water use regression relationships. Regression results for average use in relation to the Oklahoma PDSI and average permitted quantity resulted in an R-squared value of 0.833.

Regressed water use in Oklahoma was still notably higher in comparison to the equivalent area in Kansas, which is likely due to the higher permitted quantities. However, it is expected that water usage is relatively the same on either side of the state line, both in terms of system types and usage. As such, an estimate of two-thirds of the Oklahoma's regressed water use was used for the model. The estimated values are more similar to, although still generally a little greater than, those in the equivalent Kansas area (Figure 31).

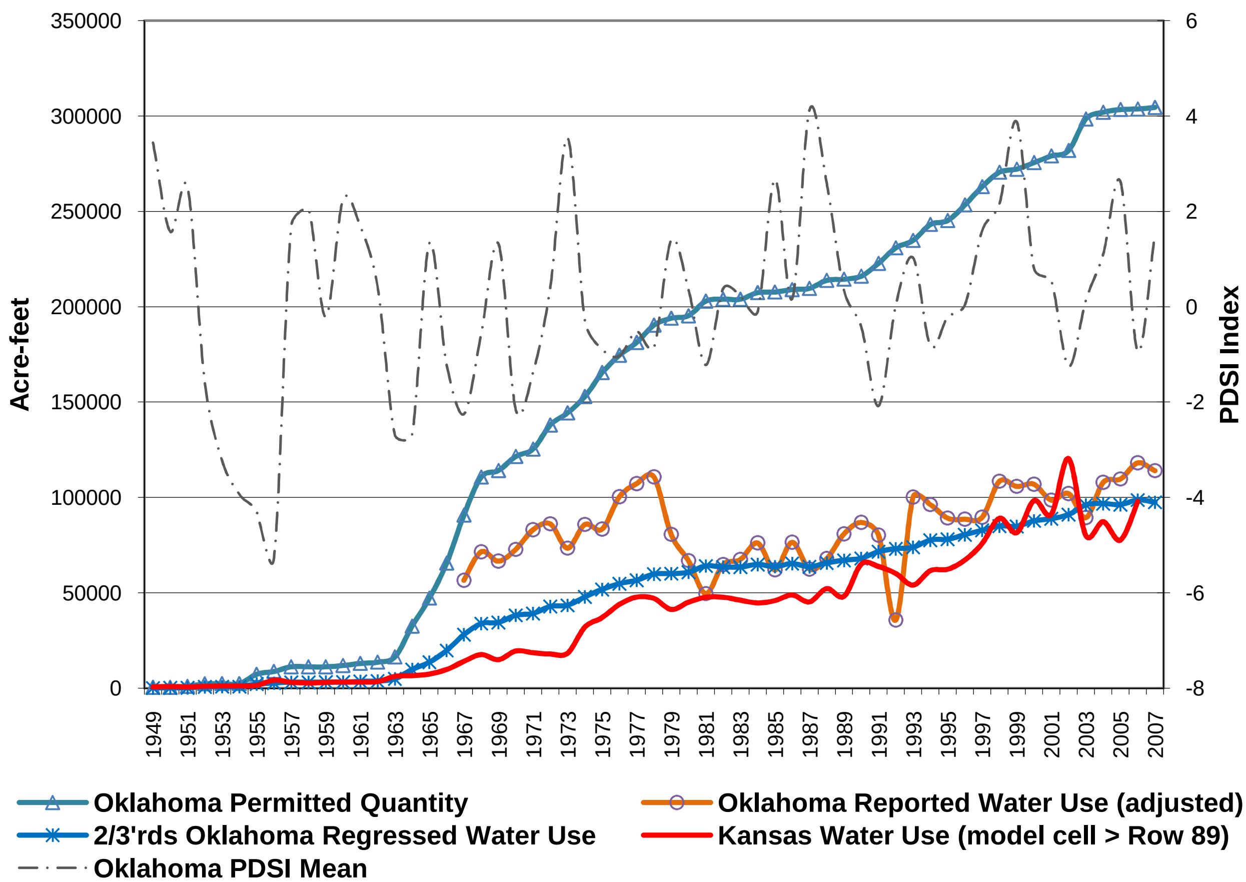


Figure 31. Total permitted, reported, and regression-based water use estimated for the Oklahoma portion of the model. The total water use for an equivalent area in Kansas applied in the model is shown for comparison.

<u>Colorado</u>

The State of Colorado has ground-water diversion data at various scales, different stages of completeness, under varying levels of administration actions (i.e. adjudicated basins), and from differing web sites. At the time of the model's development, the Colorado Decision Support System (CDSS) developed by the Colorado Water Conservation Board and Colorado Division of Water Resources was deemed to be the most comprehensive and informative. In a similar manner to what was experienced on the Oklahoma side, the CDSS is very interactive with pertinent information provided in the "Well Applications" layer but lacked any means to download data, other than data selections limited to 25 record displays at a time (Figure 32).

Records from the CDSS to the west of the Kansas/Colorado state line were manually selected for the model's domain (1,855 records in all) and the records copied and pasted into an ASCII editor. The CDSS data contains information related to permit number, uses of water, well characteristics, aquifer sources, and dates of use. However, no coordinates are provided to locate the well sites, although a field listing is available for how the unlisted coordinates were obtained (at the time of this report, the CDSS site now provides UTM coordinates as their data listings). Each well site did have a PLSS legal description down to the 40-acre tract and/or footage distances from a specified PLSS section corner.

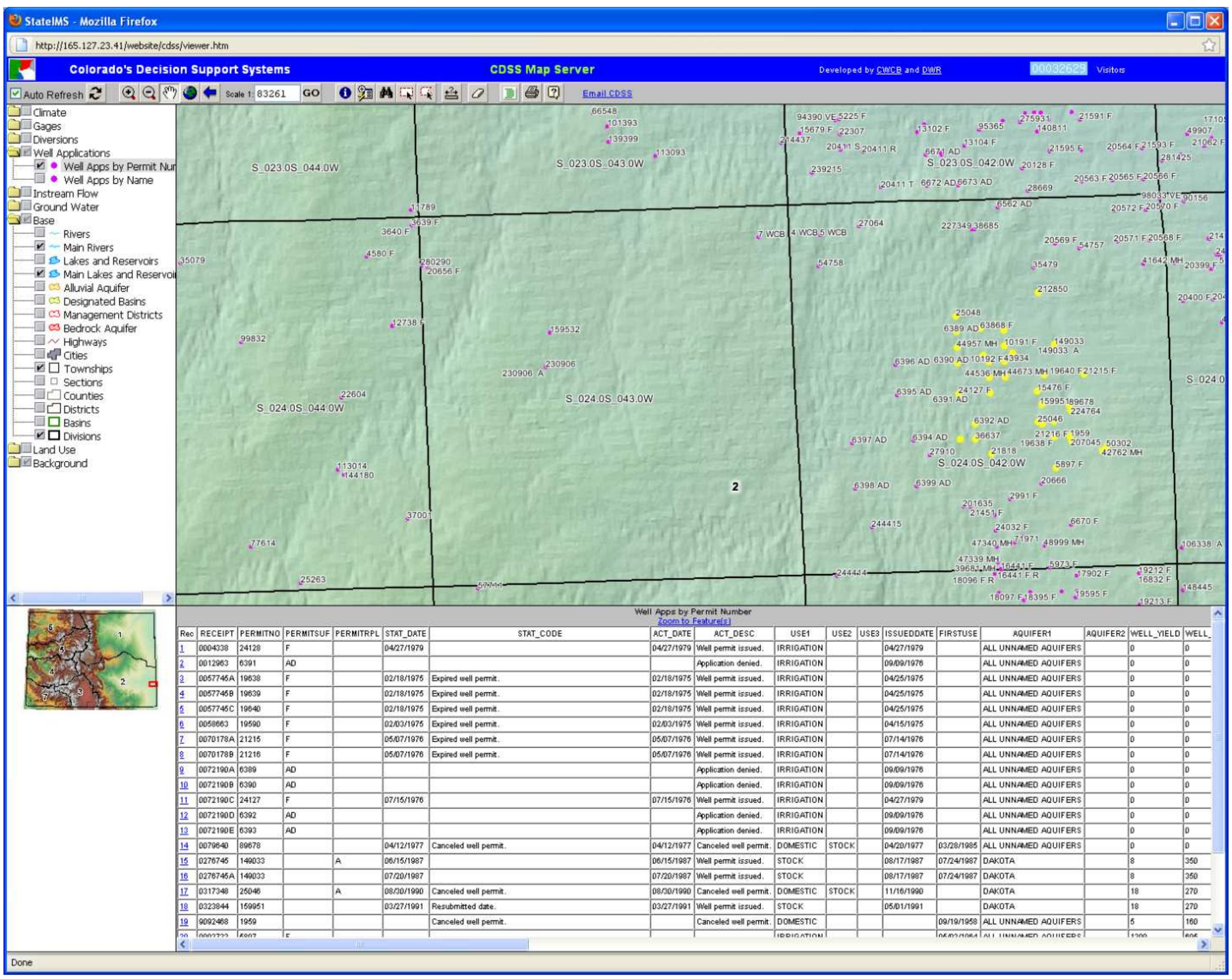


Figure 32. Computer screen snapshot of Colorado's online Decision Support System (CDSS).

In order to spatially plot the CDSS data in GIS, a Colorado version of the KGS Leo Program was developed. Leo is a computer program that converts Kansas PLSS legal descriptions to geographic coordinates and vice versa (Gagnon, 2008). The computer processing subdivides the known coordinates between section corners into halves, quarters, eighths, and sixteenths, depending on the smallest qualifier listed, and then returns the coordinates of the center of the rectangle of that smallest qualifier. Another program option returns the coordinates of a point based on footage distances from one of the section corners.

A series of GIS data processing scripts were applied against a data layer of Colorado PLSS sections that subdivided them into 40-acre tracts and then computed the center coordinates of each tract. In addition, GIS data processing scripts identified the coordinates for each corner in each section. This information was then joined back to the CDSS data and the well sites were assigned latitude/longitude coordinates representing where the well is located based either on any footage adjustment from the listed section corner (preferred) or the center of the smallest rectangular qualifier.

The CDSS data were then queried to remove non-pumping wells (e.g., monitoring wells), denied or dismissed permitted wells, non-HPA wells (based on aquifer codes), records with no use of water listed, and small use wells (e.g., domestic and stockwater with less than 30 gpm flow rates). This left 360 well records for what are considered to be the large-capacity wells, which is a similar number for an equal area on the Kansas side of the border.

Personal communication with staff members at the Colorado Division of Water Resources (CDWR) indicated the data obtained and methodology applied were sound. Although the CDWR does not maintain any water use information, they did provide a spreadsheet that contains some annual permitted quantities for some of the larger capacity wells and suggested reviewing Colorado's "Decreed Wells" for more annual permitted volumes. Decreed wells are part of GIS-ready data downloads and represent well sites and water usage that have undergone the State's adjudication process. Colorado Decreed Wells are only available in the valley along the Arkansas River. In this small area where the CDSS data and the Decreed Wells overlapped, well records from the two data sets were reviewed and common information combined into a single source.

After combining the annual permitted quantities from the Decreed wells and the CDWR spreadsheet, around 70 well records were left that have no annual quantity estimates. The following water permit values were assigned to these remaining wells: 4 acre-feet per year for stock wells (non-commercial), 3 acre-feet for domestic uses, and 25 acre-feet for municipal use (the four wells of the town of Holly). The locations of unassigned irrigation wells were reviewed with aerial photography to identify possible field boundaries (e.g., center pivots) along with neighboring irrigation wells with permitted quantities, and most were assigned a permitted annual value around 480 acre-feet. This equates to 3 acre-feet per acre on a 160-acre pivot.

Figure 33 shows the Colorado permitted quantities by the year water was listed to be first put to use. In comparison to an equivalent area in Kansas, the overall trend in the accumulated permitted quantity is similar but almost three times as high.

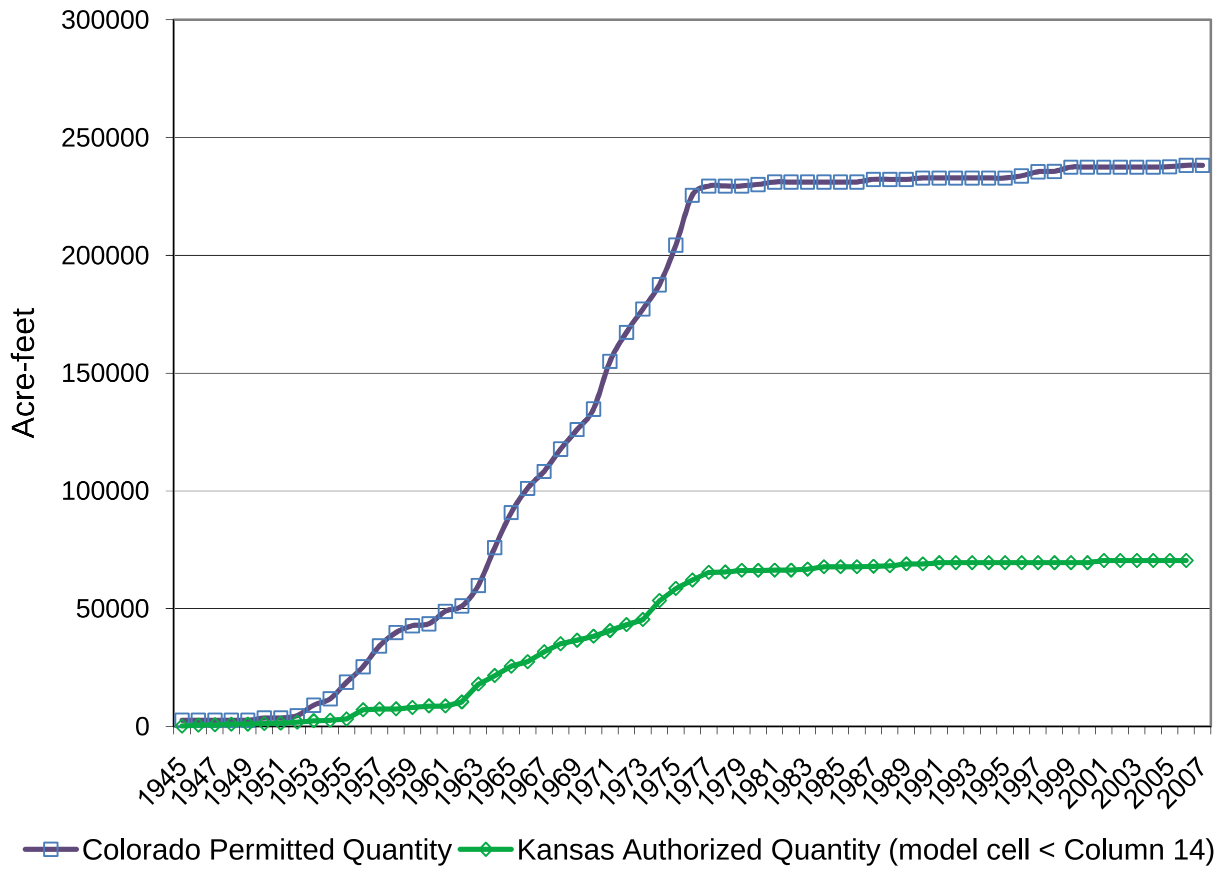


Figure 33. Total estimated permitted quantity of ground water for the Colorado part of the model area. The authorized quantity in an equivalent area in Kansas on the east side of the Colorado-Kansas border in the model area is also shown for comparison.

Estimation of historic water use

Given the lack of any type of water use data in Colorado, the Kansas water use regressions were applied against the Colorado permitted quantities, annual precipitation amounts, and the Palmer Drought index for each year. The high Colorado permitted quantities resulted in regressed water use values that were substantially greater than for the equivalent area on Kansas side of the border. Following the same premise that water use along the state line is probably more similar than not (used for estimating the Oklahoma water use), one-third of the Colorado regressed water use was applied in the GMD3 model (Figure 34). The reduced Colorado use is relatively close to, although somewhat higher than, the water use in the adjacent Kansas area where the uncertainties in the data are appreciably lower.

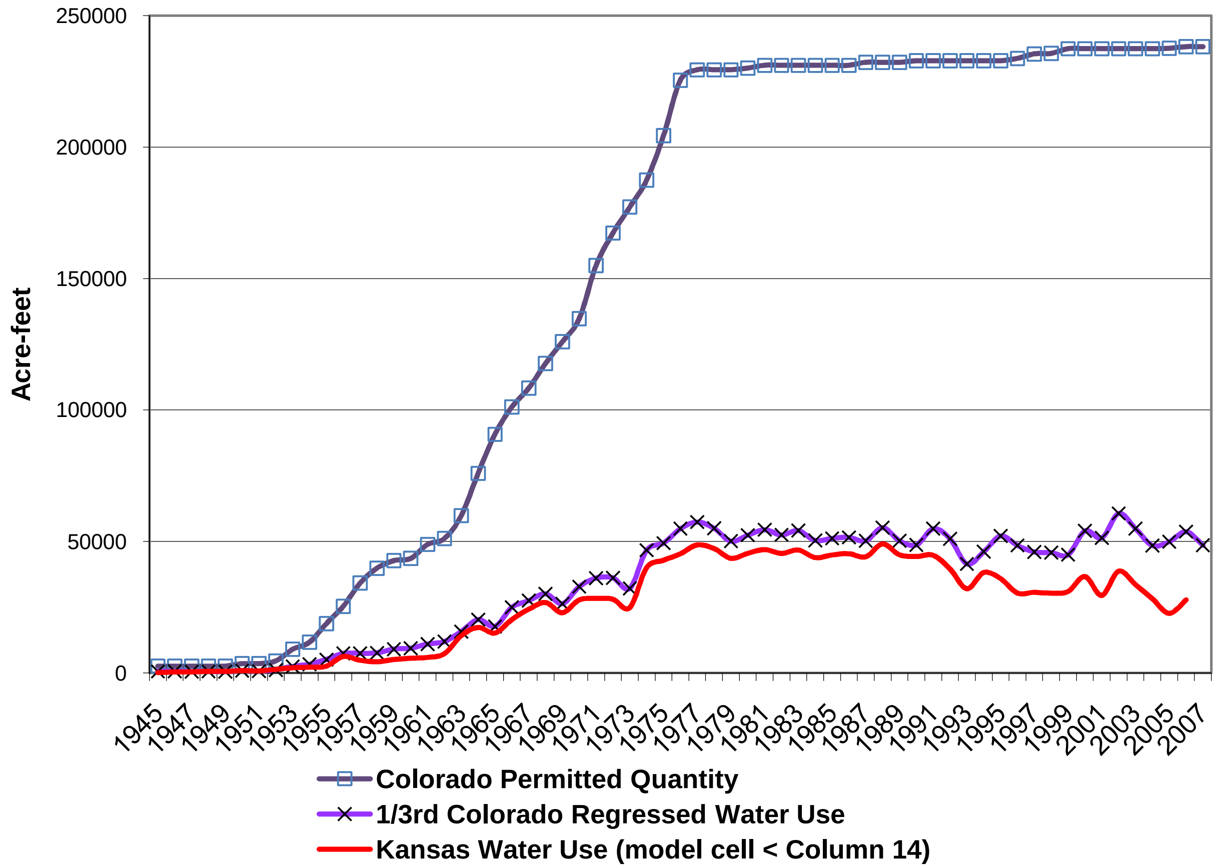


Figure 34. Total permitted and regression-based water use estimated for the Colorado portion of the model. The total water use for an equivalent area in Kansas applied in the model is shown for comparison.

Irrigation Return Recharge

A certain amount of water applied by irrigation systems is not consumed by the targeted field crops and evaporation, and returns to the aquifer in the form of irrigation return recharge. The rate of this aquifer recharge is determined by a variety of factors, one of which is the type of irrigation system deployed. A review of the reported system type from the Kansas water use reports, 1991 to 2006, by county shows that flood irrigation was generally the most common system type in the early 1990s. Center-pivot irrigation was estimated to have begun in the model area in 1955 and more efficient systems employing drop nozzles were used starting in the late 1980s to 1990. Figures 35 to 37 show county examples of the trends in reported system types for Finney, Haskell, and Seward counties. Irrigation efficiencies have generally increased over time as technologies developed and farm management practices improved. This tends to decrease the amount of water applied to specific fields and also reduces the amount of irrigation return recharge over time.

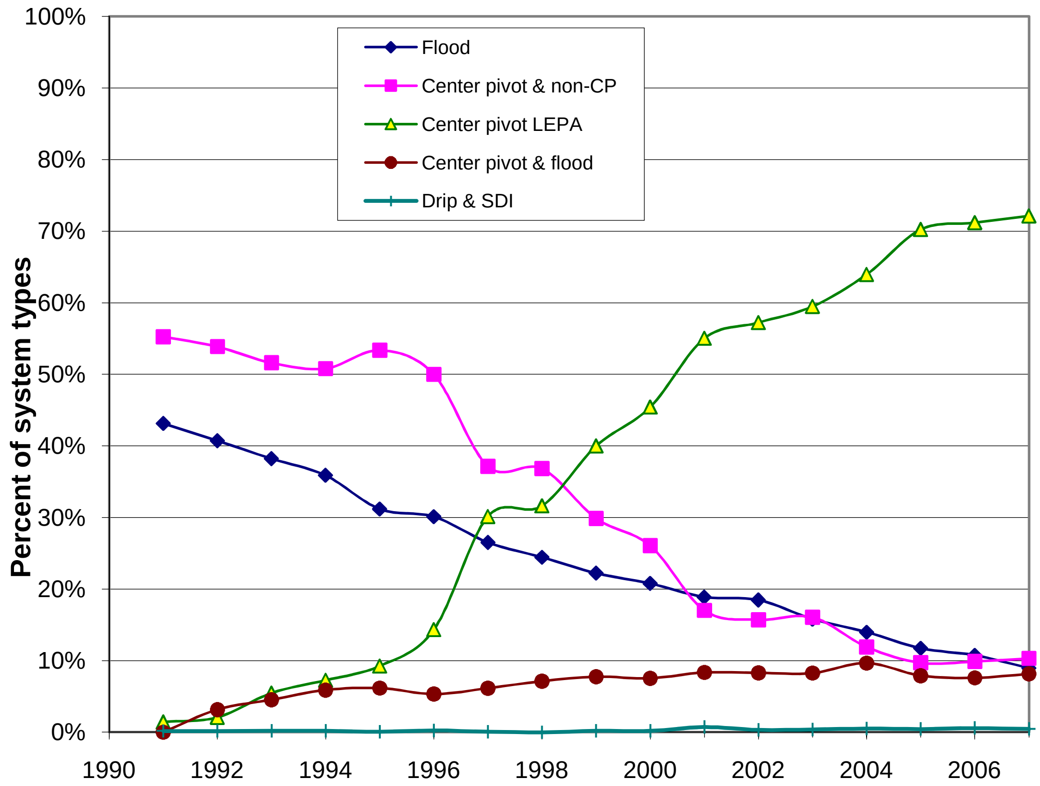


Figure 35. Reported Irrigation System Types, Finney County, Kansas 1990 to 2006.

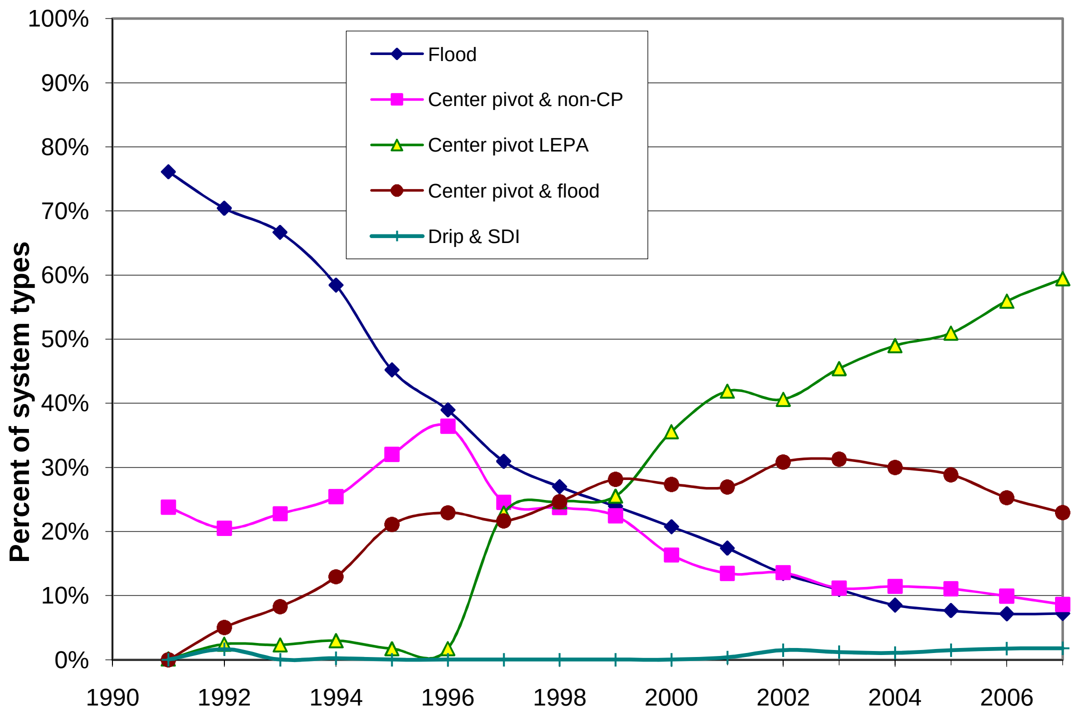


Figure 36. Reported Irrigation System Types, Haskell County, Kansas 1990 to 2006.

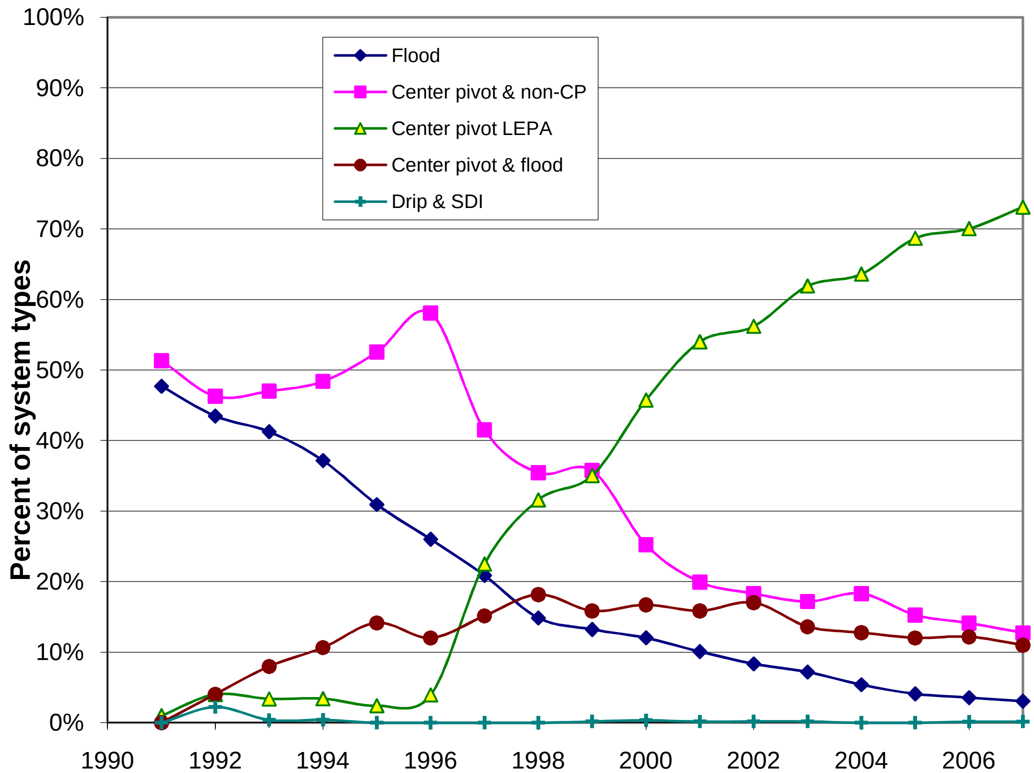


Figure 37. Reported Irrigation System Types, Seward County, Kansas 1990 to 2006.

To simulate irrigation return recharge in the model, return recharge values from the Middle Arkansas River subbasin model (Whittemore et al., 2006) were reviewed in relation to the irrigation system types reported each year from water use reports in the GMD3 area. Each designation of system type listed in the KDA-DWR water use reports was assigned a particular fraction of return recharge as follows in the order of decreasing percentages: flood irrigation 25%, center pivot and flood 17%, center pivot 9%, sprinkler other than center pivot 9%, center pivot LEPA (low energy precise application) 7%, and subsurface drip (SDI) in combination with other type 4%.

Based on the reported water use by county, the average return recharge percentage was computed for each year of 1991-2006 based on the count of each type of irrigation system and the percentages of return recharge assigned for each type. This general approach was also used to estimate the average return percentage by county for predevelopment to 1990. The irrigation system type before 1955 was assumed to be only flood irrigation, similar to what was used in the Middle Arkansas model. The values between 1955 and 1991 were estimated assuming a smooth linear transition between the average return percentage for 1955 (flood irrigation only) and that for 1991, along with manual adjustment for small fluctuations in return recharge fraction determined for the Middle Arkansas model, for which some data on irrigation systems were available before 1991.

The average return recharge percentage by year for each county (Figure 38) was then multiplied by the irrigation-based water use to determine the volume of water that returns to the underlying aquifer. Unlike the Middle Arkansas River and Smoky Hill River models where return recharge was subtracted from the overall ground-water pumping leaving a “net” pumping volume, the GMD3 model treats return recharge as a separate recharge function. The treatment of irrigation return flow as separate recharge is necessary if a more sophisticated approach is adopted to improve recharge simulation in the future (for example, a “delayed” recharge approach in which the recharge takes many years to actually reach the water table several hundred feet deep). For counties outside the GMD3 boundary (e.g., Scott, Pawnee, and Oklahoma and Colorado counties), the return flow values from the closest GMD3 county were used.

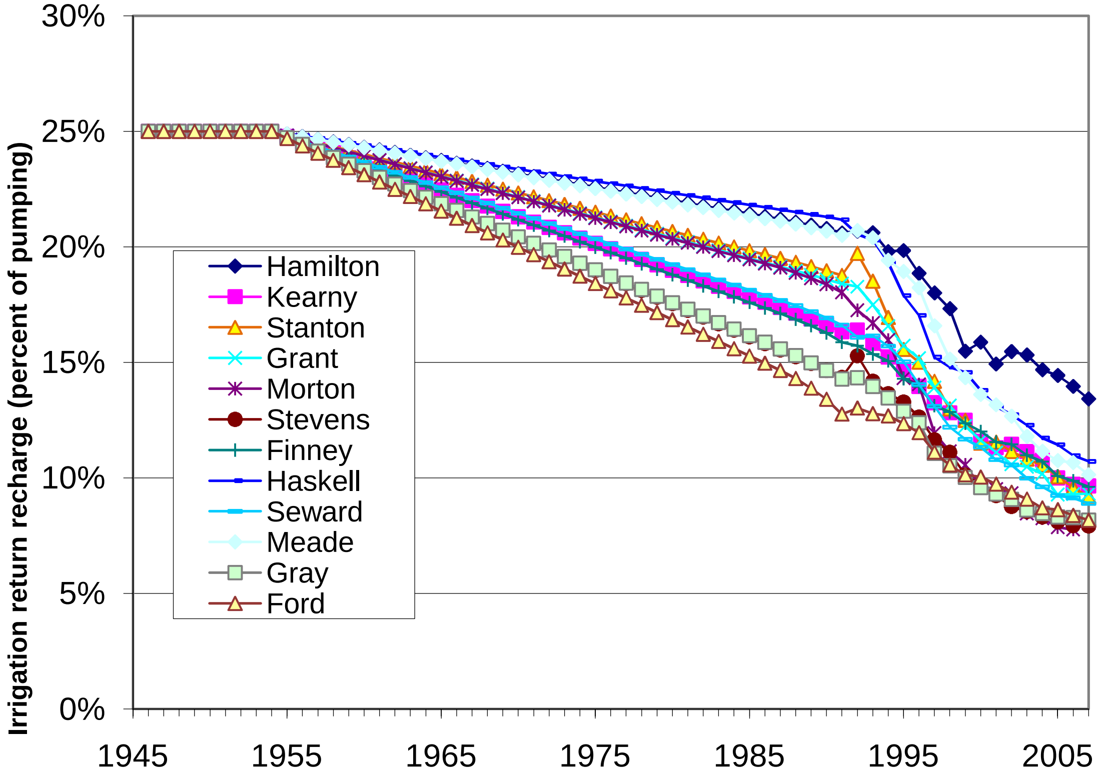


Figure 38. Average percentages of irrigation water returning to the aquifer as recharge by county, 1945 to 2006, used in the GMD3 model.

MODEL CALIBRATION AND SIMULATION

The model developed in this project is temporally divided into two major simulation periods, the steady-state predevelopment period during which there was no large-scale, intensive pumping and, as a result, water levels remained relatively constant, and the transient period during which ground-water development activities began to increase and water levels changed with time. The predevelopment simulation establishes the initial conditions for the subsequent transient simulation. The major data sources for predevelopment simulation are compiled for the period between 1944 and 1946. The predevelopment climatic conditions, including precipitation and temperature, were similar to their historic mean values between 1944 and 2007. The mean annual PDSI values for 1944, 1945, and 1946 were 3.57, 2.12, and 0.25, respectively, for climatic division 7 (southwest Kansas), which indicate very wet, to moderately wet, to near normal conditions for this climatic index during that period.

The transient period simulates the historic evolution of ground-water systems and stream-aquifer interactions from predevelopment to 2007, during which ground-water pumping activities became intensive and produced noticeable declines in ground-water levels. The declining water levels also produced significant decreases in streamflow in the Arkansas River, Cimarron River, and Crooked Creek. Transient simulation is based on an annual stress period (i.e. the major aquifer stresses such as pumping and recharge are updated once every year).

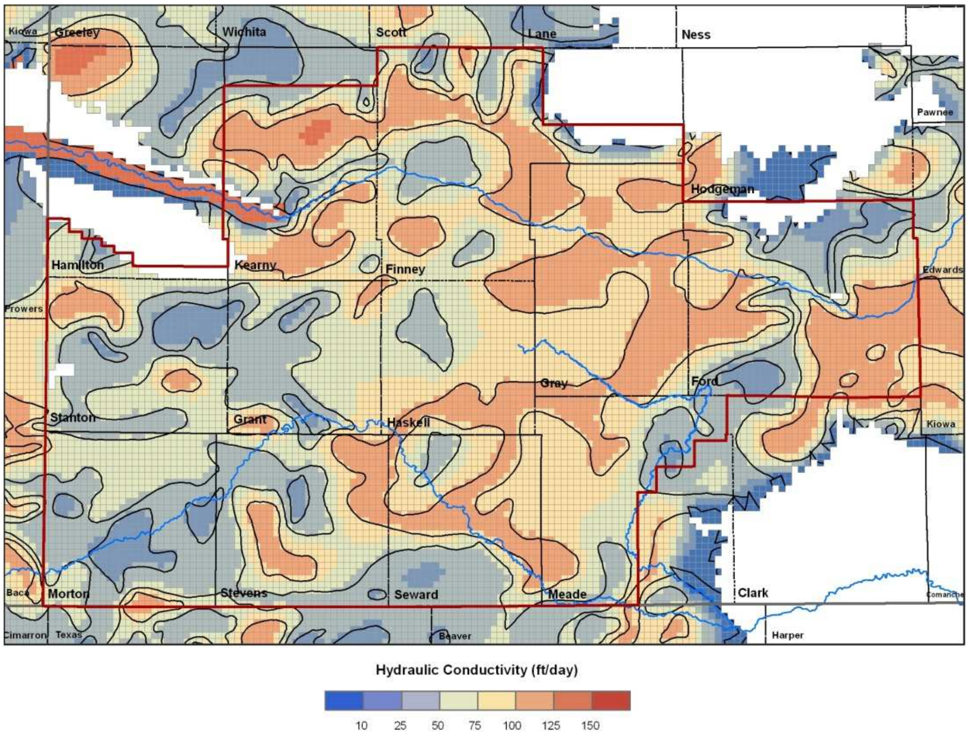
The hydraulic conductivity (K) and specific yield (Sy) are calculated based on the detailed lithology information that became available from the KGS PST+ program, which was not competed until late 2009. The estimated values of both K and Sy within each model cell are dependent on the water-level position relative to the depth intervals of lithologic layers recorded in the drillers' logs. In order to account for the impact of declining water levels on the calculation of K and Sy during the transient period, the calibrated model is broken into six step models: 1) predevelopment, 2) predevelopment to 1966, 3) 1967 to 1976, 4) 1977 to 1986, 5) 1987 to 1996 and 6) 1997 to 2007. In each step model, both K and Sy are dynamically calculated using the observed water levels for the corresponding time period. For K, all lithologic layers between the water table and underlying bedrock are considered using a thickness-weighted average. For Sy, however, calculation only involves the layers through which the water-level decline occurs. By dividing into step models and dynamically calculating K and Sy, the model allows for an effective representation of the vertical lithology variations without explicitly employing multiple layers in the simulation grid.

Model Characteristics

Hydraulic Conductivity and Specific Yield

As the detailed lithology information was not available prior to completion of the KGS PST+ program, initial modeling efforts focused on the use of existing K and Sy coverage from previous USGS studies (Cederstrand and Becker, 1998a, 1998b). Figure 39 shows the K and Sy distribution mapped by the USGS. The USGS studies provide coverage for the HPA only. For the alluvium in the paleovalley of the Arkansas River from Colorado through Hamilton and central Kearny counties, K and Sy are assumed to be 200 ft/day and 20%, respectively.

(a) K



(b) Sy

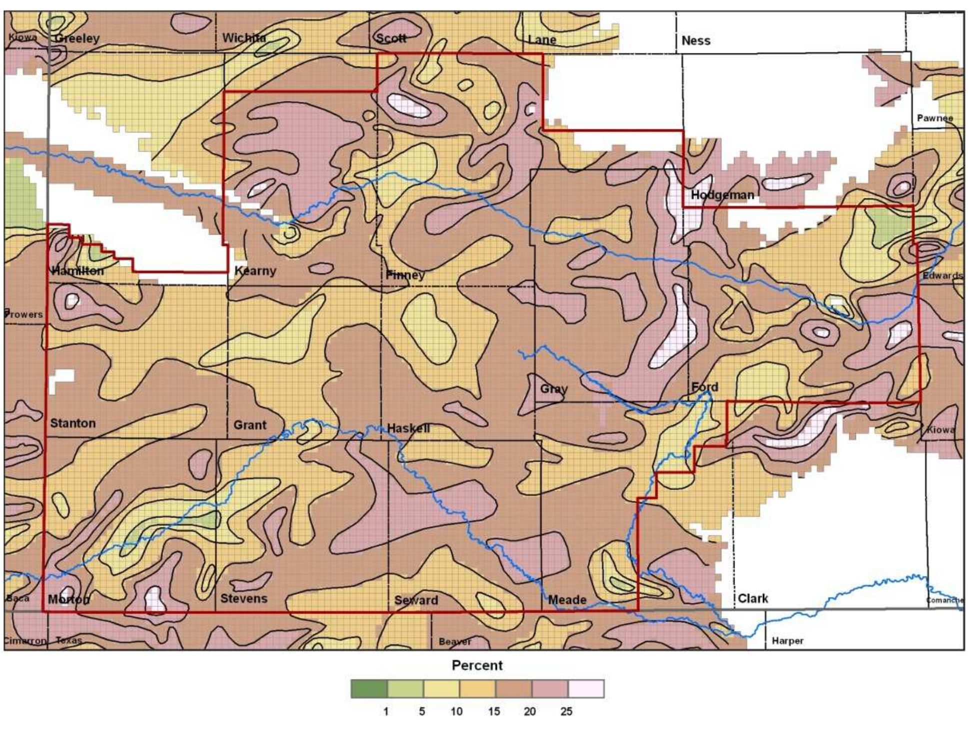


Figure 39. The (a) hydraulic conductivity and (b) specific yield distributions for the GMD3 model area based on previous USGS studies. The USGS studies are for the HPA only. For the alluvium in the paleo Arkansas River valley, K and Sy are assigned constants of 200 ft/day and 20%, respectively.

As mentioned earlier, to improve model accuracy, the USGS hydraulic conductivity and specific yield were subsequently updated with the values calculated from the detailed lithologic log information that became available from the KGS PST+ program in late 2009. The procedure of K and Sy calculation with PST+ lithology data is summarized as follows:

1) For each of the 62 PST+ synonymies, assign a representative value for K and Sy. Table 4 lists the initial values used in model construction. These values were adjusted during model calibration.
2) For K calculation, the K for each wellbore is the thickness-weighted average of different lithology layers from the water table to bedrock. If multiple synonymies exist for a specific depth interval, the K for that interval is computed as the arithmetic mean of K of different synonymies regardless of the order in which different synonymies appear in the well log.
3) For Sy calculation, the Sy for each wellbore is the thickness-weighted average of different lithology layers between the start and end water levels over a transient time period. No specific yield information is needed for the steady-state predevelopment simulation because water levels remain relatively unchanged (i.e. no storage change).
4) The average K and Sy values computed from steps 3 and 4 are for each wellbore. To estimate model cell K and Sy from wellbore K and Sy, a two-dimensional kriging program from GSLIB (KB2D) is used (Deutsch and Journel, 1998).

Table 4. Initial K and Sy values for each PST+ synonymy lithology code. The detailed lithologic descriptions for each synonymy code are in Table 1.

Synonymy	K	SY	Synonymy	K	SY	Synonymy	K	SY
sh	0.0002	0.03	sc	0.2	0.05	fsnd	20	0.22
c	0.0002	0.03	fds	0.2	0.05	fmgsnd	20	0.22
coal	0.0002	0.03	fmds	0.2	0.05	fmsnd	20	0.22
br	0.0002	0.03	fcrsds	0.2	0.05	snd	100	0.22
rb	0.0002	0.03	ds	0.2	0.05	fcrssnd	100	0.22
r	0.0002	0.03	mds	0.2	0.05	msnd	100	0.22
sst	0.0002	0.03	gc	0.2	0.05	mcrssnd	100	0.22
ca	0.02	0.05	mcrsds	0.2	0.05	cg	100	0.22
o	0.02	0.05	crsds	0.2	0.05	crssnd	100	0.25
ts	0.02	0.05	cesd-cg	2	0.2	sg	100	0.25
fs	0.02	0.05	fss	2	0.2	fsdg	200	0.25
fsc	0.02	0.05	fmss	2	0.2	fmsdg	200	0.25
fmsc	0.02	0.05	ss	2	0.2	msdg	200	0.25
m	0.02	0.05	mss	2	0.2	sdg	200	0.25
msc	0.02	0.05	fcrsss	2	0.2	fcrssdg	200	0.25
s	0.02	0.05	mcrsss	2	0.2	mcrssdg	200	0.25
crssc	0.02	0.05	crsss	2	0.2	crssdg	200	0.25
fcrssc	0.02	0.05	u	2	0.2	fg	300	0.25
mcrssc	0.02	0.05				fmg	300	0.25
						fcrsg	300	0.25
						fcrssg	300	0.25
						g	300	0.25
						mg	300	0.25
						mcrsg	300	0.25
						crsg	300	0.25

Figure 40 illustrates the calculation of PST+ K in two different situations: predevelopment and a transient step. Predevelopment involves a single water level and K is computed as the depth averaged value from the predevelopment water level to bedrock. As mentioned earlier, when more than one synonymy code exists for a lithology layer, the K for that layer is computed as the arithmetic mean, although different percentages can be assigned to different synonymies if necessary. In a transient step such as Figure 40b, two water levels are associated with each wellbore, the start and end water levels for the period. K is computed for the depth intervals from the average water level to bedrock.

Figure 41 illustrates the calculation of PST+ Sy under two different conditions: water-level change within one lithologic layer or across different layers. When the water-level change occurs within a single layer, the Sy for that wellbore is simply the Sy for that layer (Figure 41a). When the water level change crosses different layers, Sy is computed as the thickness-weighted value over that change interval (Figure 41b). Similar to K, when multiple synonymy codes exist for a single layer, the Sy for that layer is computed as the arithmetic mean of the multiple synonymies.

The two-dimensional kriging program from GSLIB (KB2D) is used to estimate model cell K and Sy from the wellbore values (Deutsch and Journel, 1998). As the K is thought to be log-normally distributed in nature, a log transform is applied to the wellbore K prior to the kriging interpolation. After the kriging is done, the kriged K values are back-transformed to regular K values for use in the model. For Sy, no log transform is necessary. In the KB2D setup, ordinary kriging is selected, the variogram model is specified as linear, the maximum number of data points for the kriging calculation at each model cell is 16, and the maximum search radius is 40 miles. In areas where the distribution of PST+ wellbores is sparse, the maximum radius is the primary constraint on which wellbores will be included in the kriging calculation of model cell K and Sy values. In areas of good wellbore coverage, on the other hand, a maximum number of 16 nearest wellbores are used in the calculation.

Figure 42 shows the spatial distribution of K initially computed from PST+ lithology. To generate the initial K map, the predevelopment water level was used and K was computed for all layers between the predevelopment level and bedrock. As the PST+ lithology information is only available for the Kansas model area, the K for the Colorado and Oklahoma model areas was based on the previous USGS values in those locations. Compared to the USGS data coverage, the PST+ K is much more detailed due to the substantially greater number of lithologic logs used in the calculation procedure.

As mentioned earlier, in order to account for the impact of declining water levels on the calculation of K and Sy during the transient period, the calibrated model is broken into six step models: 1) predevelopment, 2) predevelopment to 1966, 3) 1967 to 1976, 4) 1977 to 1986, 5) 1987 to 1996, and 6) 1997 to 2007. In each step model, both K and Sy are dynamically updated using the observed water levels for the corresponding time period. During model calibration, the PST+ synonymy K and Sy values (i.e. Table 4) are adjusted by matching observed water levels and streamflows to simulated values.

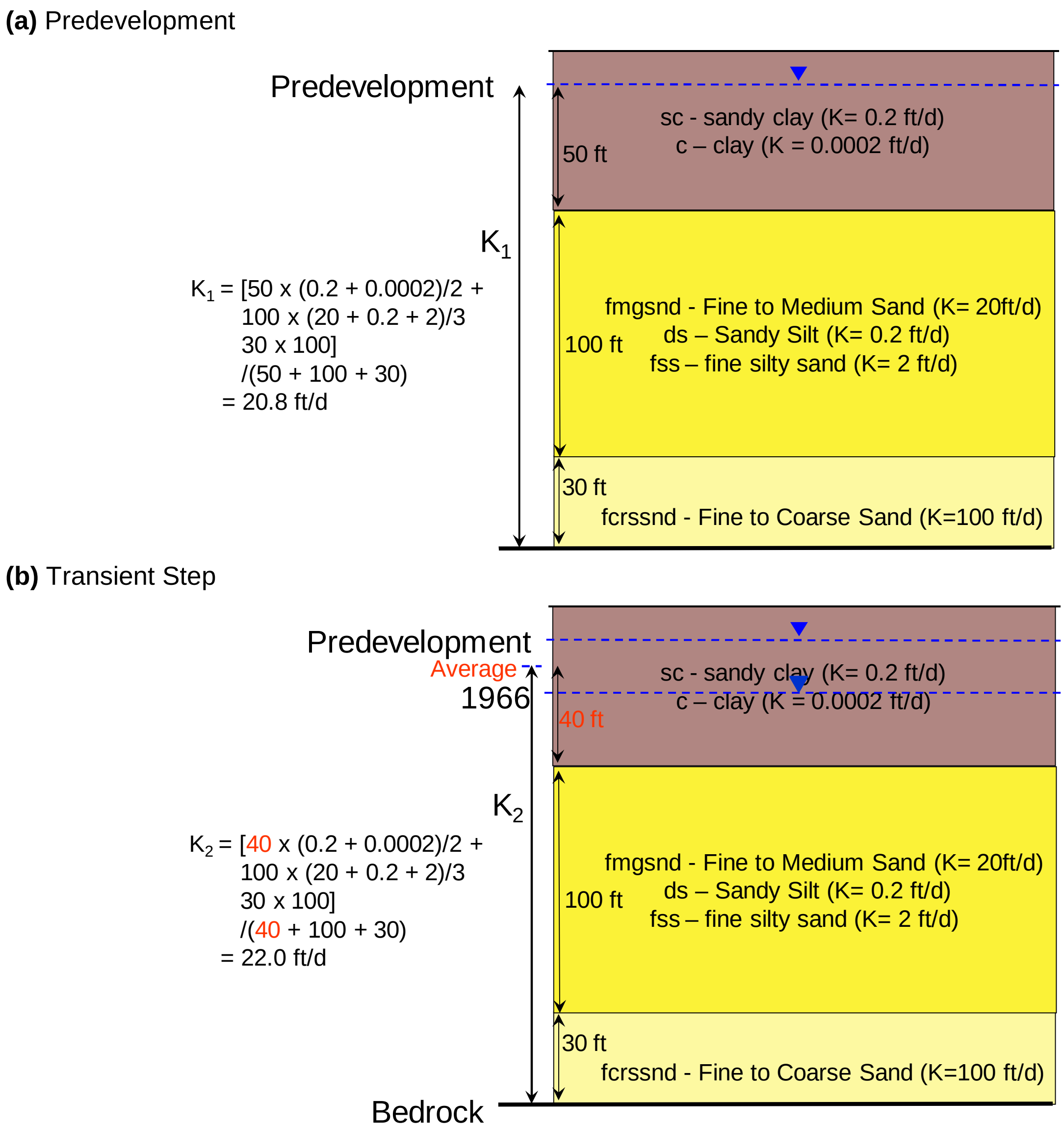
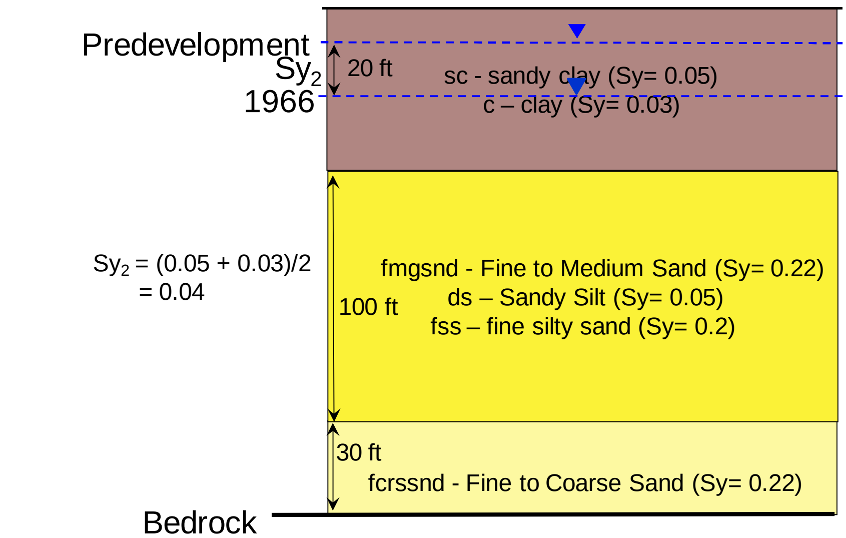


Figure 40. Illustration of PST+ K calculation: (a) predevelopment, and (b) transient step. In predevelopment, there is a single water level and K is averaged from the water table to bedrock. The transient step (b) includes two water levels (predevelopment and 1966), and K is calculated from the average water level during the time step period to bedrock.

(a) Water-level change within one layer



(b) Water-level change across layers

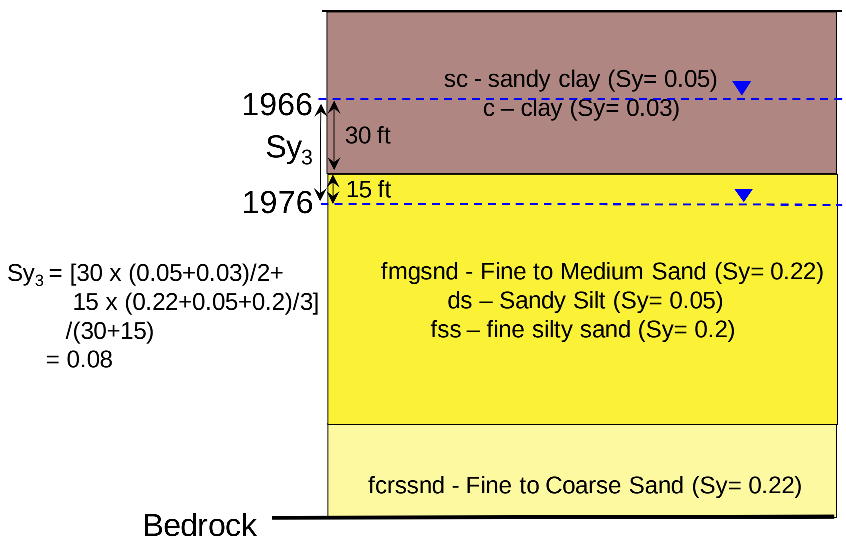


Figure 41. Illustration of PST+ Sy calculation for water-level change: (a) within one lithologic layer, and (b) across layers.

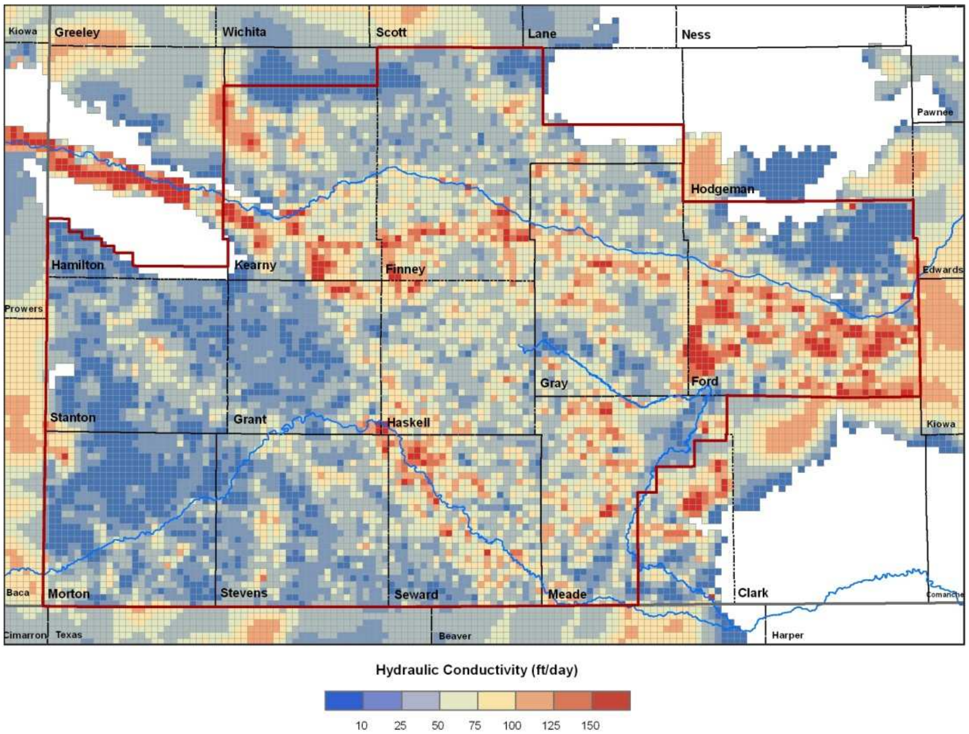


Figure 42. Initial map of hydraulic conductivity based on PST+ lithology information. The K for the Colorado and Oklahoma model areas was based on the USGS values in those locations.

Precipitation Recharge

Precipitation recharge was calculated based on a power-function relationship to precipitation,

$$R = \begin{cases} 0, & P < P_0 \\ a(P - P_0)^b, & P \geq P_0 \end{cases}, \qquad (1)$$

where R is precipitation recharge to ground water, P is precipitation for a given model cell and year, P_0 is threshold precipitation after which ground-water recharge occurs, and a and b are the coefficients of the power function.

The model incorporates zones for the recharge-precipitation power function. Figure 43 shows the distribution of recharge zones in the model. The four major recharge zones include the main aquifer (tan), sand dunes and terraces (brown), alluvial aquifer (light blue) and focused recharge along major tributary streams (dark blue). For each major recharge zone, the power-function parameters P_0, a, and b are calibrated by matching observed water levels and streamflows to simulated values.

In addition to these four major recharge zones, two special recharge zones are included for areas where the predevelopment water table is either below or near the bedrock surface (Figure 43). In special recharge zone I (light green), the water table is often below or at the bedrock surface. Wells obtain water from the bedrock in part of this area. For special recharge zone I, the power function is similar to that of the main aquifer except that the coefficient a is reduced to 1% of the value determined for the main aquifer, as virtually all of the precipitation seepage is assumed to enter the bedrock instead of being retained in the overlying HP aquifer. In special recharge zone II (dark green), the HPA saturated thickness is small and a substantial fraction of the recharge is expected to enter the bedrock. For special recharge zone II, the power function is also similar to that of the main aquifer, but the coefficient a is reduced to 20% of that for the main aquifer.

When land is irrigated, the soil is wetter than in nonirrigated land and thus allows for more seepage of precipitation into the underlying aquifer. The enhancement of precipitation recharge by agricultural irrigation is included by multiplying the recharge determined from the above power function by a constant factor (greater than 1) for the irrigated land across the entire model. The recharge enhancement factor for irrigation is determined through model calibration. To obtain a rough estimate on the irrigated acreage through different years in the transient period, an average water application rate of 2 ft/acre/year is assumed. For a given year, the irrigated acreage for each model cell is then calculated by dividing the total ground-water pumping in that cell by the assumed water application rate.

Despite the use of a single precipitation-recharge relation for each recharge zone, the actual precipitation recharge rate varies across each recharge zone as a function of precipitation. This is different from previous KGS modeling efforts for the Middle Arkansas River and Smoky Hill River (Whittemore et al., 2006; and Wilson et al., 2008), where a spatially averaged precipitation rate was used for each recharge zone, resulting in a single precipitation recharge rate for the entire zone in a given year.

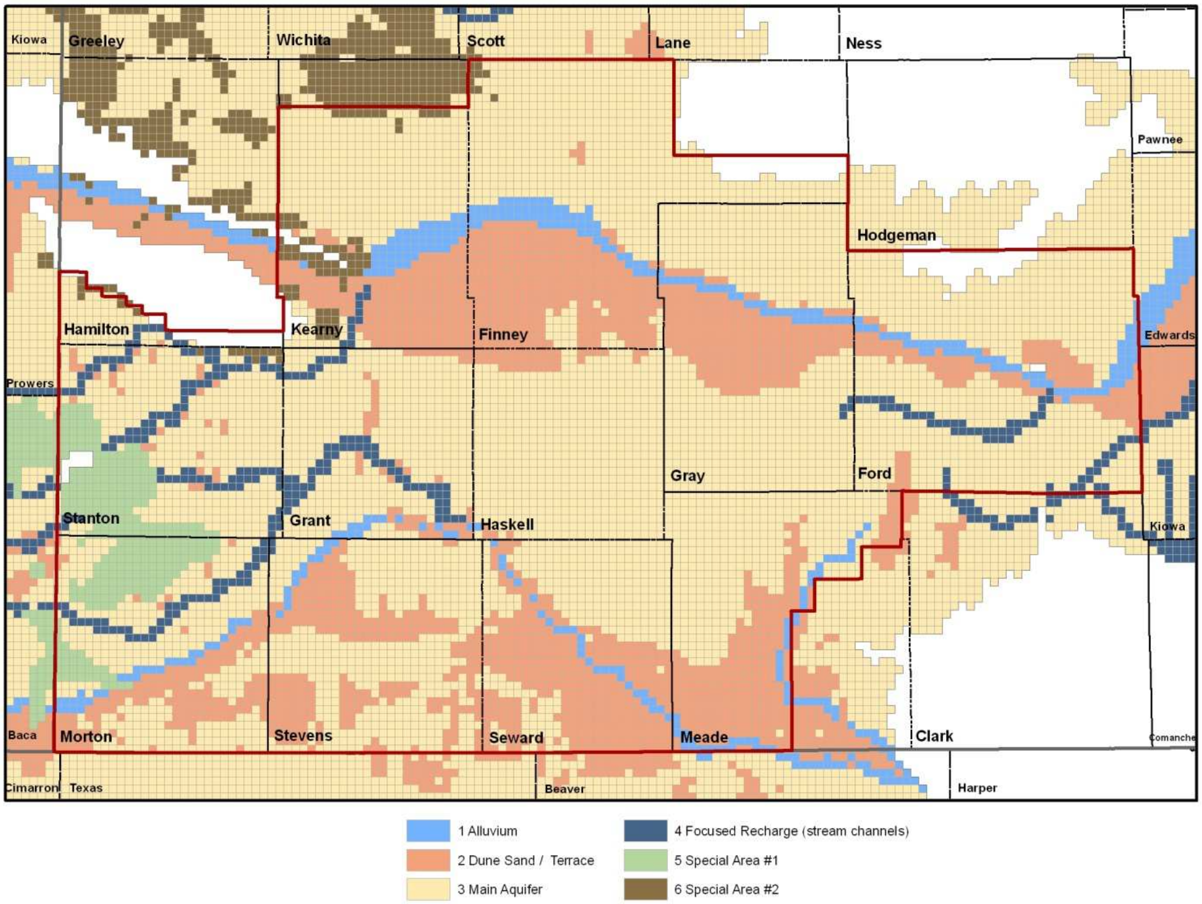


Figure 43. Zonation for recharge-precipitation function.

Ground-water Pumping and Irrigation Return Recharge

The earlier section in this report, "Water Right Development," describes the procedure for separately determining the ground-water pumping data for the Kansas, Oklahoma, and Colorado portions of the model area. The pumping data are for an annual basis. Irrigation return recharge is computed by assigning a particular fraction of total pumping as the return recharge to the aquifer as described in the above section "Irrigation Return Recharge." The return recharge is accounted for by adding it to the overall recharge input file in the model. Ditch return recharge, which is described earlier, is also added to the overall recharge input file.

Stream Characteristics

Three major streams are explicitly simulated in this model, the Arkansas River, Cimarron River, and Crooked Creek (Figure 44). A total of 18 segments and 764 reaches are used to represent all three streams incorporated in the model. In the model setup, additional one-reach segments were also used to represent the surface ditch diversions along the Arkansas River. The streams are simulated as rectangular channels with an underlying streambed. The streambed widths assigned for the Arkansas River are 220 ft upstream of the South Side Ditch diversion and 180 ft downstream to reflect that the river flows are smaller below the major diversions.

The streambed widths for the Cimarron River and Crooked Creek are 100 ft and 50 ft, respectively. The streambed thicknesses assigned to the Arkansas and Cimarron Rivers are 3.28 ft and 5 ft, respectively. The streambed thickness for Crooked Creek is 10 ft for the reach above 30.4 miles upstream of its confluence with the Cimarron River, and 50 ft downstream of that point, which is where the creek valley is generally underlain by a confining zone in the HPA. The thicker streambed thickness for the creek than for the rivers represents the confined nature of the HPA underlying portions of the creek valley, especially the section that trends in the north-northeast direction.

Streambed conductivity is estimated to be 1.0 ft/day for the Cimarron River and the portion of the Arkansas River upstream of Garden City. For the Arkansas River downstream of Garden City, streambed conductivity is 0.1 ft/day. The streambed conductivity for Crooked Creek is lower (0.05 ft/day) than for the rivers because it represents the relatively low permeability estimated for the HPA confining sediments underlying the creek. The estimates for streambed conductivity were obtained during trial-and-error runs for the predevelopment simulation in earlier modeling efforts, and were not changed during the subsequent transient model calibration. The streamflow data from USGS gages at Syracuse, Kendall, Deerfield, Garden City, and Dodge City on the Arkansas River, the gage near Forgan, Oklahoma, on the Cimarron River, and the gage near Englewood in southeast Meade County on Crooked Creek were used in calibrating the simulated stream-aquifer interactions (Figure 44).

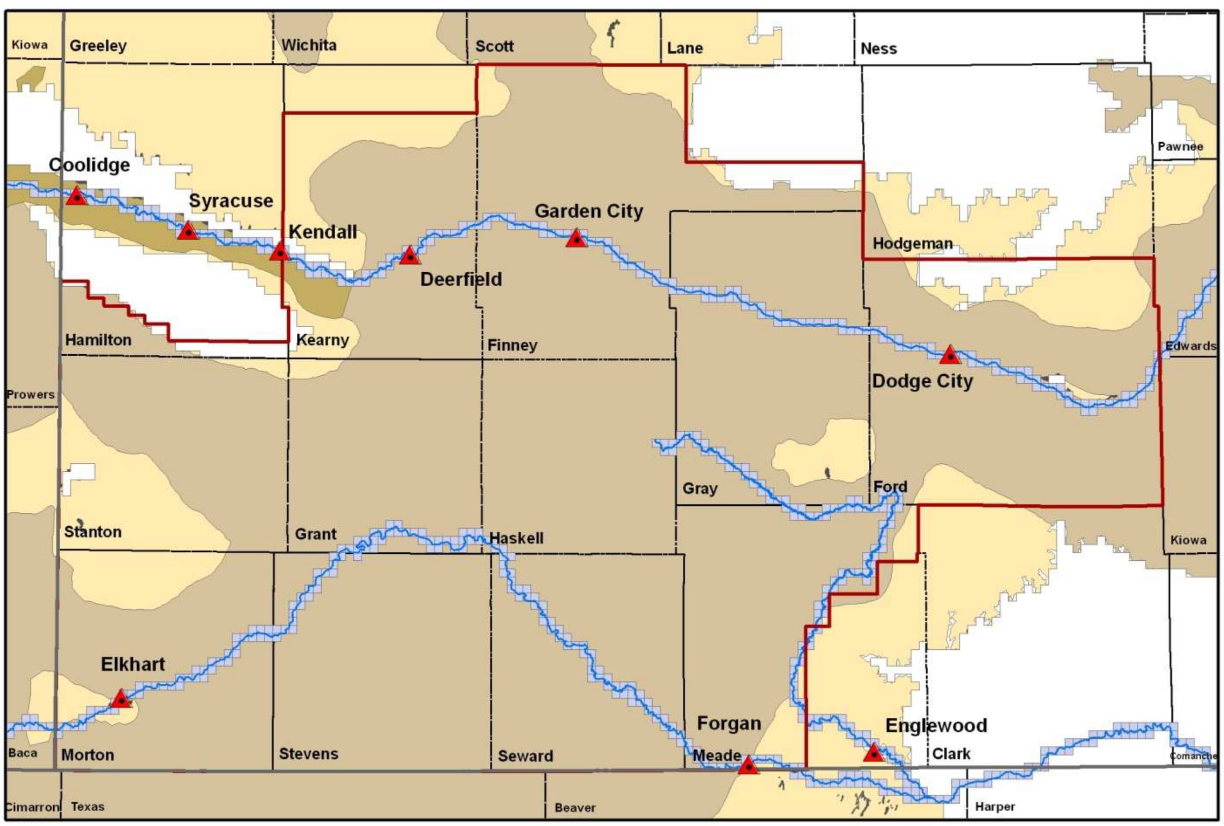


Figure 44. Streams simulated in the model (blue lines) and the location of streamflow gages (red triangles) used for inflow to the model and as target data in model calibration. The gage names are those associated with the USGS gaging station.

Time-varying Specified-head and Specified-flux Boundaries

Time-varying specified-head boundaries are used for active model cells on the northern and southern boundaries, as well as for some of the edges surrounding the inactive bedrock area within the model. Starting with the interpolated predevelopment water levels, each time-varying head cell was reviewed in relation to well measurements taken over the transient period. As described earlier, the lack of long-term, continuous water-level measurements in the model area made specifying boundary heads a challenge. Only 125 out of 2,400 wells contain long histories of consistent measurements taken in the winter months (Figure 21). Wherever these types of wells are located near the head-boundary cells, the water-level trends shown in the measurement histories were applied to the head-boundary cells. The measurements from wells without long-term, winter-based measurements were still used when possible.

On the eastern and western borders, time-varying fluxes are specified. These fluxes are computed based on Darcy's law as the product of head gradient and transmissivity. To evaluate the head gradient at the western boundary, the water levels at the western edge and at a column that is 6 miles east to the western edge are used. The gradient is computed as the water-level difference between the two columns over a distance of 6 miles. Similarly, the head gradient at the eastern edge is evaluated based on the water levels at the eastern edge and at a column that is 6 miles west of the eastern edge. The transmissivity is computed as the product of hydraulic conductivity and saturated thickness. For simplicity, the transmissivity values at the internal columns are used for the flux calculation across the eastern and western borders. The specified fluxes are treated as two lines of artificial wells in the model input file.

Evapotranspiration

Evapotranspiration (ET) was only considered in the main riparian zones (the alluvium zone in Figure 42). The maximum ET rate at the land surface and the extinction depth were estimated to be 4 in/yr and 5 ft, respectively. When the depth to water is between the land surface and extinction depth, the ET rate is linearly interpolated based on the depth to water relative to the extinction depth.

Model Calibration

The key to successful development of a model for prediction and management purposes is to calibrate the model so that it can simulate adequately the historic hydrologic conditions. The calibrated values of model parameters must be consistent with hydrogeologic conditions in the area. The general process of model calibration involves adjusting the values of selected input parameters within plausible ranges in order to improve the match between field-observed data and model-simulated values. Data used in the process include ground-water levels throughout the area and streamflows at the gaging stations. Recharge, hydraulic conductivity, and specific yield are considered as the parameters to calibrate in this model due to their relatively large uncertainties and high impacts on the results. There were a total of 26 calibrated parameters: the eight groups of synonymy K values (see the different text colors in Table 4 indicating the eight groups), five groups of Sy values (see the different fill colors in Table 4 indicating the five groups), precipitation-recharge power-function parameters P_0, a and b for recharge zones 1 through 4, and the precipitation recharge enhancement factor for irrigated land. To facilitate the calibration process, the parameter estimation program PEST (Doherty, 2004) was employed. Each PEST run generally takes 15 to 25 hours on a DELL computer equipped with a 3.2 GHz CPU and 3 GB of RAM.

The values of the calibrated parameters are adjusted to improve the match between model simulations and observed target data. The first category of target data for model calibration is the water levels at selected wells in the predevelopment period. Figure 45 shows the locations of the 114 wells used in the calibration. The second category of target data is the water-level differences over the transient period for these wells. Water-level differences were based on a 1-yr interval in earlier calibration efforts, but later changed to a 5-yr interval to improve the signal-to-noise ratio (i.e. the water level difference calculated for the 5-yr interval is larger, thereby suppressing the water level measurement noise more significantly). The third category of target data is the streamflow from the gaging stations (Figures 45 and 46). As the ground-water levels and streamflows are very different in terms of their units, data accuracies, and practical relevance, the streamflow data were log-transformed and multiplied by a factor of 10 before they were used in the calibration. The log transformation of streamflow is necessary so that high and low streamflows are equally weighted in calibrating the model. The total number of observation data points from all three categories is 1,573.

Due to the complexity of the model, a single PEST run could not produce the most desirable calibration results. As a result, a series of PEST runs were performed in which the calibration settings were adjusted incrementally. Table 5 summarizes the root mean of squared residuals (RMS) (a residual is defined as observation – simulation) of the predevelopment heads, transient water-level differences, and gaged streamflows for each major PEST run. Run A produced a set of linear recharge curves that were not physically plausible. Runs B through D were based on the water-level differences at a 1-yr interval, which were thought to contain too much noise. To improve the signal-to-noise ratio, a 5-yr interval was used in the transient water-level difference data for the remainder of PEST runs E through AA.

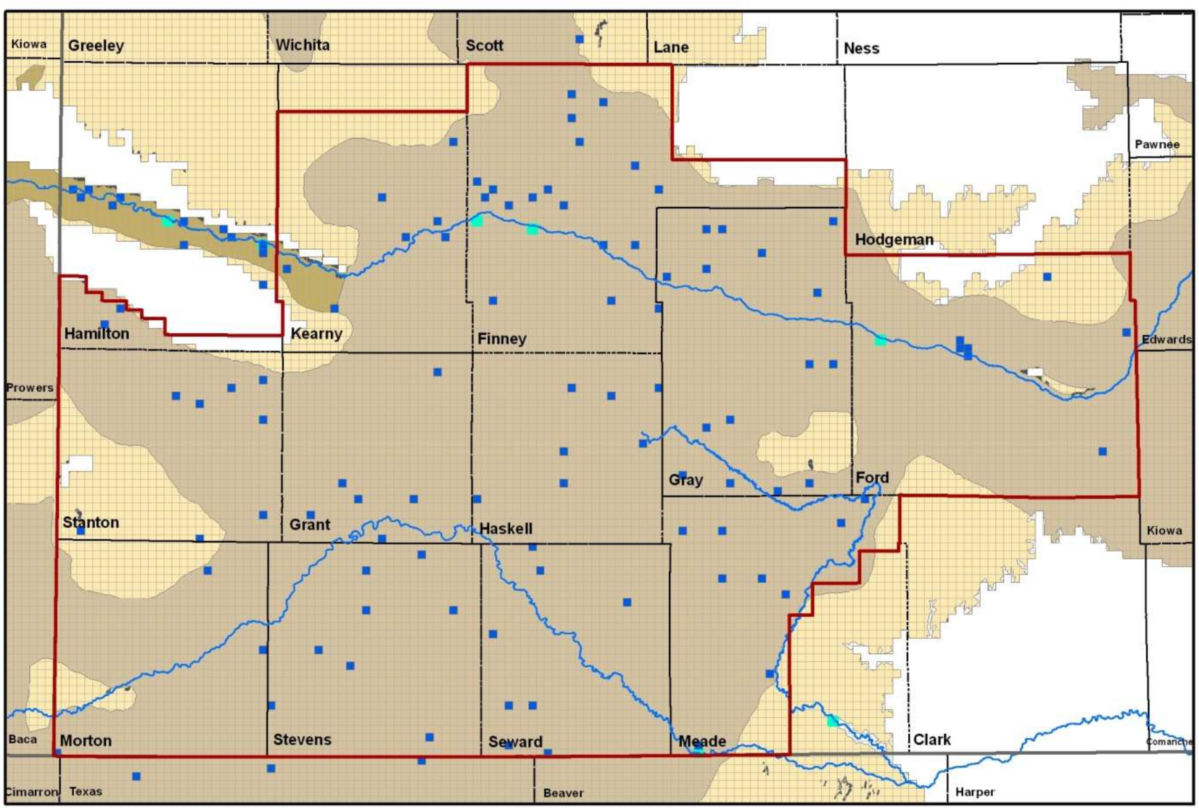


Figure 45. Locations of the 114 long-term water-level wells (blue cells) and seven streamflow gages (cyan cells) from which data were used as targets in model calibration.

Table 5. Root mean squared residual (RMS) summary for each major PEST run. The model from run R is deemed to be the best calibrated model.				
PEST Run	**Overall**	**Predevelopment Heads (ft)**	**Water Level Difference (ft)**	**Streamflows $\log(ft^3/sec)$**
A	26.88	21.01	4.84	1.03
B	26.76	21.10	4.80	0.85
C	26.85	21.14	4.82	0.90
D	27.56	21.70	4.85	1.01
E	36.98	26.29	9.40	1.29
F	32.26	21.69	9.37	1.20
G	31.32	21.08	9.31	0.94
H	31.28	21.08	9.27	0.93
I	31.21	21.14	9.22	0.84
J	31.31	21.24	9.22	0.85
K	31.28	21.18	9.25	0.84
L	31.06	20.99	9.22	0.85
M	31.09	21.03	9.22	0.84
N	30.80	20.78	9.18	0.85
O	30.99	20.94	9.20	0.85
P	30.81	20.81	9.16	0.84
Q	31.38	21.13	9.32	0.93
R	31.21	21.19	9.20	0.82
S	32.53	22.53	9.16	0.83
T	31.24	21.19	9.22	0.83
U	32.00	21.21	9.82	0.98
V	32.33	21.78	9.68	0.86
W	32.43	21.93	9.67	0.84
X	32.31	21.82	9.66	0.84
Y	32.35	21.81	9.69	0.86
Z	31.73	21.55	9.32	0.86
AA	33.54	22.36	10.02	1.15

Calibration setups were changed for different PEST runs E through AA, including the initial parameter values, fixing values of a subset of the calibrated parameters, adjustment of the lower and upper bounds of parameter values, log transformation of the hydraulic conductivity, and adjustment of weighting factors for different observation data. Based on the RMS statistics and the plausibility of recharge rates and PST+ synonymy K and Sy values, the model from PEST run R is deemed to be the best calibrated model (Table 5).

Figure 46 shows the calibrated precipitation-recharge power-function curves for each of the four major recharge zones (see Figure 43). Given the same precipitation rate, recharge is much higher in the alluvial and terrace/sand dune zones than in the main aquifer. These recharge curves are for the non-irrigated land only. For the average annual rates of precipitation (Figure 5), which generally range from less than 17 to over 24 inches in the model domain, Figure 46 indicates that annual recharge can range from less than 0.1 in/yr for the main aquifer to about 1.5 in/yr for the alluvium and terrace and sand dune zones. The actual precipitation recharge for irrigated areas is the amount determined from the calibrated power function multiplied by an enhancement factor, which was determined to be 2.0 from model calibration. Thus, precipitation recharge in irrigated areas in the alluvium and terrace and sand dune zones in the eastern model area could average as much as 3 in/yr. Figure 47 shows the simulated precipitation recharge for the predevelopment period and 2007, and the average recharge from predevelopment to 2007. The figure indicates that precipitation recharge is primarily controlled by the distribution of the different recharge zones, with the alluvial and sand dune and terrace zones receiving the highest rates of recharge.

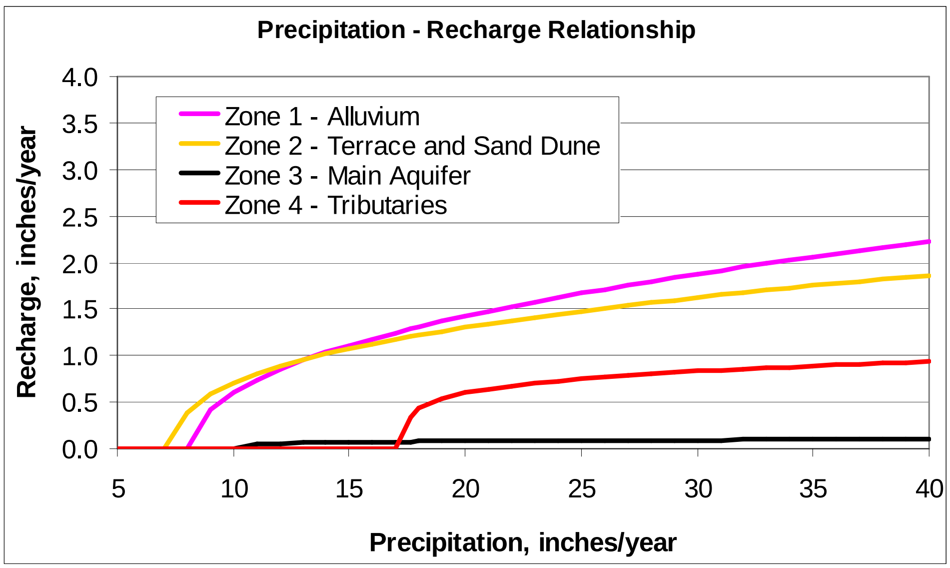


Figure 46. Calibrated precipitation-recharge curves for the four major recharge zones.

Table 6 lists the calibrated K and Sy values for each PST+ synonymy group. The synonymy grouping is different between K and Sy. The K for the last two synonymy groups is essentially identical. The calibrated Sy values for the last two synonymy groups appear to be a little larger than the values found from a well test in this region, as the Sy from a well test is typically a spatial average of both the low- and high-Sy layers. Figure 48 shows the K, transmissivity ($T = K \times b$, where b is the saturated thickness) and Sy for the entire model domain computed based on the calibrated synonymy for different model steps. The water-level decline has a major impact on the effective values of K, T, and Sy. In general, as the water levels drop from predevelopment time to 2007, the effective values for both T and Sy become smaller.

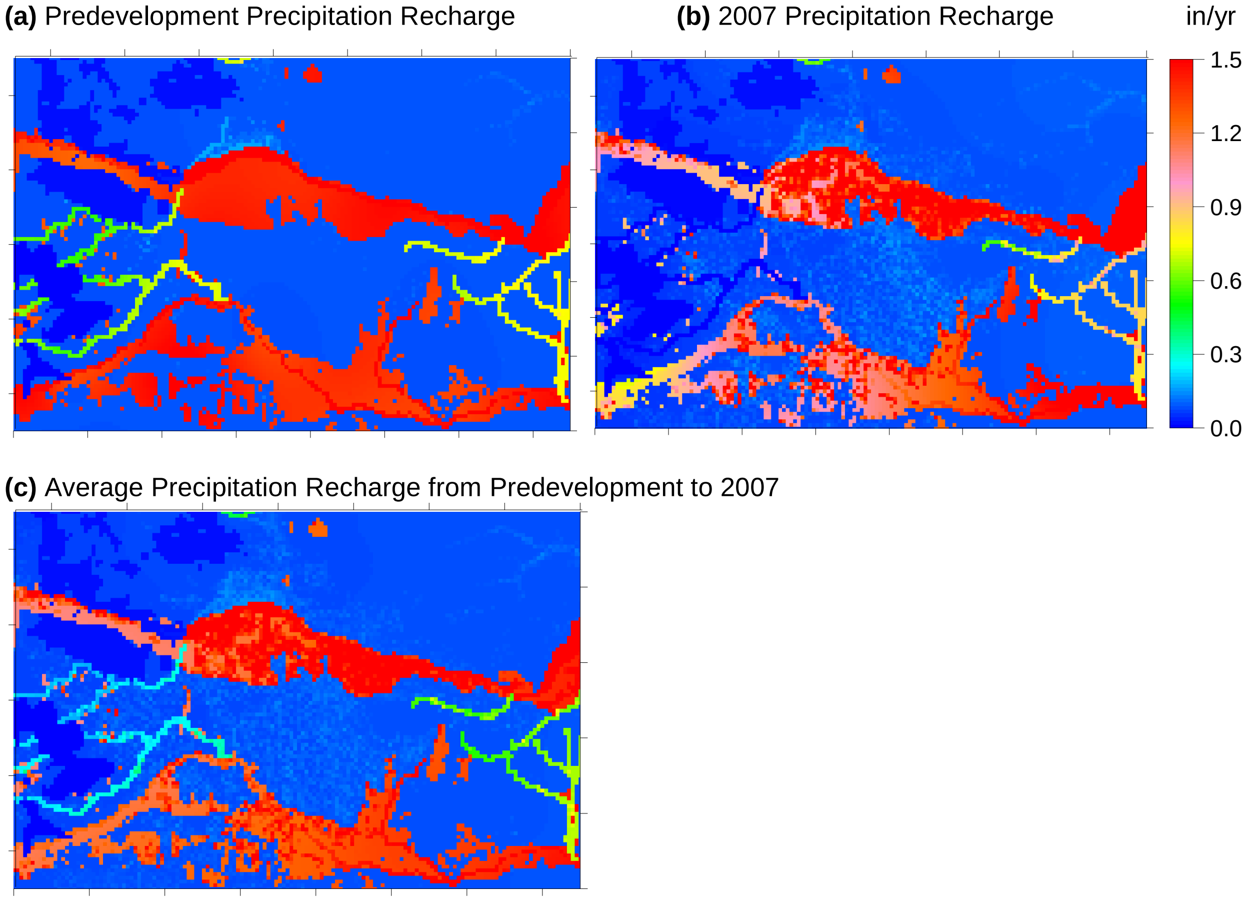


Figure 47. Calibrated precipitation recharge for different simulation times.

Table 7 lists the mean residual, mean absolute residual, and the RMS residual for all three categories of target data used for calibration. The mean residual is given as the mean of measured minus simulated values, whereas the mean absolute residual is the mean of the absolute values of measured minus simulated values. The mean residual for the predevelopment water levels is -0.59 feet, indicating that overall the simulated water levels are slightly higher than observed values in the predevelopment period. The mean residual for transient water-level differences is -1.12 feet, indicating that the simulated water-level changes are slightly greater than the observed values in the transient period (from predevelopment to 2007). The mean absolute residuals are 14.80 and 5.60 feet for predevelopment water levels and transient water-level differences, respectively. The relative mean absolute error for predevelopment water levels, which is the mean absolute residual divided by the maximum difference in observed predevelopment water levels across the active model area (1,299 ft) times 100, is 1.1%. The mean residual for streamflow targets is 6.28 ft^3/sec, indicating the simulated streamflows are overall smaller than observed values. The explanation for this is the model is geared toward simulating the baseflow conditions. Temporary tributary inflows or surface runoff resulting from individual precipitation events cannot be simulated by the model. As a result, the model underpredicts when streamflow is increased by precipitation events, shifting the mean residual statistics to the positive side.

Table 6. The calibrated values for PST+ synonymy lithologies.

Synonymy	K	SY	Synonymy	K (ft/d)	Sy	Synonymy	K (ft/d)	Sy
sh	0.00004	0.05	sc	4.4	0.08	fsnd	15	0.24
c	0.00004	0.05	fds	4.4	0.08	fmgsnd	15	0.24
coal	0.00004	0.05	fmds	4.4	0.08	fmsnd	15	0.24
br	0.00004	0.05	fcrsds	4.4	0.08	snd	63	0.24
rb	0.00004	0.05	ds	4.4	0.08	fcrssnd	63	0.24
r	0.00004	0.05	mds	4.4	0.08	msnd	63	0.24
sst	0.00004	0.05	gc	4.4	0.08	mcrssnd	63	0.24
ca	0.0001	0.08	mcrsds	4.4	0.08	cg	63	0.24
o	0.0001	0.08	crsds	4.4	0.08	crssnd	63	0.29
ts	0.0001	0.08	cesd-cg	14.5	0.16	sg	63	0.29
fs	0.0001	0.08	fss	14.5	0.16	fsdg	299	0.29
fsc	0.0001	0.08	fmss	14.5	0.16	fmsdg	299	0.29
fmsc	0.0001	0.08	ss	14.5	0.16	msdg	299	0.29
m	0.0001	0.08	mss	14.5	0.16	sdg	299	0.29
msc	0.0001	0.08	fcrsss	14.5	0.16	fcrssdg	299	0.29
s	0.0001	0.08	mcrsss	14.5	0.16	mcrssdg	299	0.29
crssc	0.0001	0.08	crsss	14.5	0.16	crssdg	299	0.29
fcrssc	0.0001	0.08	u	14.5	0.16	fg	299	0.29
mcrssc	0.0001	0.08				fmg	299	0.29
						fcrsg	299	0.29
						fcrssg	299	0.29
						g	299	0.29
						mg	299	0.29
						mcrsg	299	0.29
						crsg	299	0.29

The statistics in Table 7 for the transient water-level differences are for the 5-yr interval used in the calibration. If the water-level change for the 114 wells is computed for the entire simulation period of predevelopment to 2007, the RMS is 33.6 ft. The observed values for this calculation were either the measured water levels or levels estimated for the cells in which the wells are located based on contoured water-level surfaces for predevelopment and 2007. The average water-level change simulated by the model is -76.38 ft in comparison with an observed change of -63.04 ft. The changes for a few wells contribute substantially to the differences and RMS. These could be related both to changes difficult to simulate because of local variations within the 1-square-mile model cell as well as unknown problems with monitoring wells (such as possible for well 372550101333801, R64C33). The overprediction of water-level decline is an average change of -0.219 ft/yr.

If the average water-level changes from predevelopment to 2007 are computed for all of the active cells (except specified head cells, and assuming the bedrock surface elevation for cells where the simulated water level is below the bedrock surface) based on contoured surfaces, the changes are 54.23 ft and 53.17 ft for simulated and observed data, respectively. A similar calculation for only the model cells within the GMD3 area yields changes of 69.89 ft and 67.01 ft for the simulated and observed values, respectively. The RMS values for the simulated change are 28.63 ft for the entire model and 26.18 ft for the GMD3 area. The simulated and observed changes agree much better for all of the active cells than for the changes for only the 114 target wells, and the RMS values are smaller. The contoured water-level surfaces for predevelopment and 2007 conditions are based on many more well observations than the 114 target wells. This indicates that the model simulates the overall surface of the water levels better than at the selected 114 wells, and supports the idea that peculiarities associated with some of the 114 wells contribute to a larger RMS.

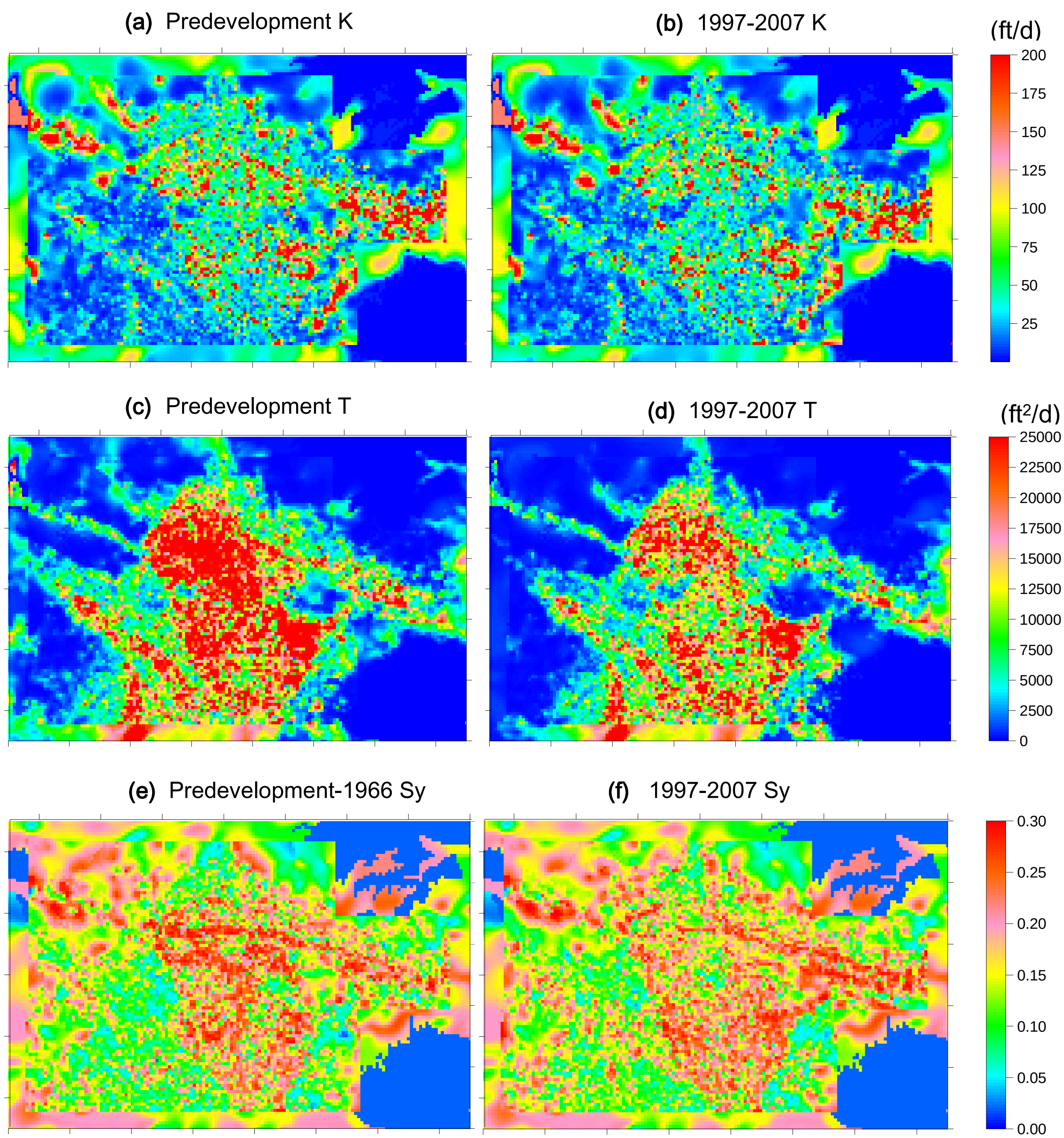


Figure 48. Calibrated K, T, and Sy for different model steps: (a) predevelopment K, (b) 1997-2007 K, (c) predevelopment T, (d) 1997-2007 T, (e) predevelopment-1966 Sy, and (f) 1997-2007 Sy. The water levels in the separate model steps are different. The effective values for both T and Sy decrease when the water levels decline from predevelopment to 2007.

Table 7. Mean residual, mean absolute residual, and root mean squared residual for model calibration targets.				
	Number of data	Mean residual	Mean absolute residual	Root Mean Squared residuals (RMS)
Predevelopment water levels (ft)	114	-0.59	14.80	21.19
Transient water-level differences (ft)	1176	-1.12	5.60	9.20
Streamflow (ft^3/sec)	283	6.28	18.93	32.24

Model Verification

Model verification is a means of demonstrating that the calibrated model is an adequate representation of the physical system by comparing the simulated results to historical data that were not involved in the calibration process (Anderson and Woessner, 1992). Given that model calibration was typically performed with relatively limited data, the set of calibrated parameter values may not be appropriate for representing the system under all other possible conditions. Therefore, model verification allows independent assessment of the performance of the calibrated model before applying it as a prediction and management tool. As the precipitation was lower than average in 2002 and an appreciable number of water-level measurements exist around January 2003, the calibrated model is verified against the observed water levels of January 2003. Figure 49 shows the simulated water levels from the calibrated model as compared to the observed data in January 2003. The overall agreement between the simulated and observed water levels is deemed reasonable, although there are a few local areas where mismatches are noticeable.

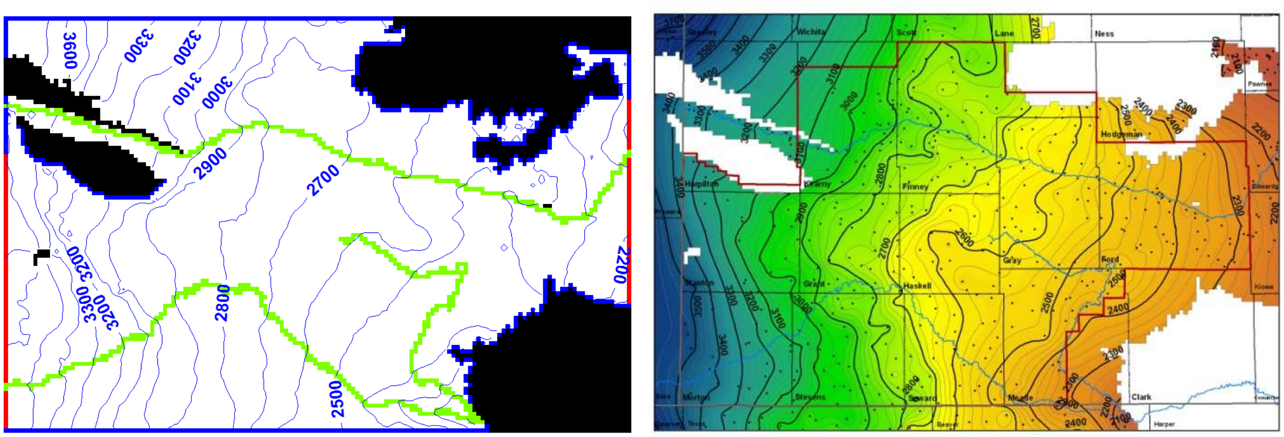


Figure 49. Simulated (left) versus observed (right) water levels for January 2003.

Sensitivity Analysis

Sensitivity analysis is an approach for assessing the impact of parameter uncertainty on model 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 highly sensitive to a parameter perturbation, that parameter needs to be characterized as reliably as possible. As sensitivity results will change when any aspect of the model conditions is changed, their statistics are only meaningful after the model is calibrated. The sensitivity of a calibrated model with respect to each parameter *p* is computed as,

$$RS_p = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\partial d_i}{\partial p / \hat{p}}\right)^2} \qquad (2)$$

where ∂p is the small perturbation around the calibrated parameter value $\hat{p}$, ∂d_i is the change in the model-simulated ground-water level or streamflow at a particular observation time and location *i,* and *N* is the total number of observation data points in the modeling period used for the PEST calibration (i.e. the total number of model calibration targets, 1573). Scaling the sensitivity by the corresponding base value $\hat{p}$ gives results that are more indicative of the actual influence of p and allows more appropriate comparison of the values computed for different parameters.

Table 8 lists the values and sensitivities of the calibrated parameters from PEST. The letter “a” in the parameter names indicates association with precipitation recharge – a00 is the enhancement factor due to irrigation, a11 is the threshold precipitation for recharge zone 1, a21 is the coefficient a in the power function (see equation 1) for recharge zone 1, a31 is the coefficient b in the power function for recharge zone 1, a12 is the threshold precipitation for recharge zone 2, and so on. The parameters “hy” and “sy” represent the hydraulic conductivity and specific yield, respectively, for each PST+ synonymy group. In general, the synonymy K is the most sensitive parameter for improving the model match for observed water levels and streamflows.

Table 8. The calibrated values and sensitivities of different model parameters.

Parameter	value	R Sens		Parameter	value	R Sens
a00	2.00	0.1322		hy1	0.00004	0.0014
a11	8.21	0.2240		hy2	0.00014	0.0007
a12	7.50	0.1807		hy3	4.4	0.3782
a13	10.17	0.0286		hy4	14.5	0.5231
a14	17.50	0.0233		hy5	15	0.116
a21	0.47	0.6889		hy6	63	1.488
a22	0.50	0.7471		hy7	299	0.523
a23	0.05	0.1001		hy8	299	10.540
a24	0.50	0.0331		sy1	0.05	0.107
a31	0.45	0.2332		sy2	0.08	0.126
a32	0.38	0.4009		sy3	0.16	0.159
a33	0.20	0.0439		sy4	0.24	0.229
a34	0.20	0.0042		sy5	0.29	0.153

Model Results

Water Levels

Figure 50a shows the simulated versus observed water levels at all of the long-term calibration wells for both the predevelopment and transient periods. The straight line is the reference for perfect agreement between the model values and the data. Most of the points fall close to the reference line, indicating that overall the simulated values agrees well with the observed data in both the predevelopment and transient periods. The RMS and mean absolute residual are 33.3 ft and 23.5 ft, respectively. The relative mean absolute error is 1.8%, higher than that calculated for predevelopment water levels only (1.1%). This indicates the model produces a slightly bigger mismatch for the declining water levels during the transient period than for the steady-state levels in the predevelopment period.

Figure 50b displays the simulated versus observed 5-yr water-level changes from predevelopment to 2007. The majority of 5-yr water-level declines are between 0 and 20 ft. When the water-level declines are large, the model generally appears to underpredict the observed values. On the other hand, when the water level rises, the model generally produces overpredictions. The explanation is that the model is a simplified representation of the actual ground-water system and does not provide an effective simulation for the extreme conditions where the water-level declines are extremely large or the water level rises. Large water-level declines could, in some cases, be related to a semi-confined portion of the HPA in which leakage through the confining layer is very slow. Water-level rises could result from recovery of water levels due to slow drainage from units above the water table during a wet period with little pumping. Complicated mechanisms such as these are not simulated in a single-layer model.

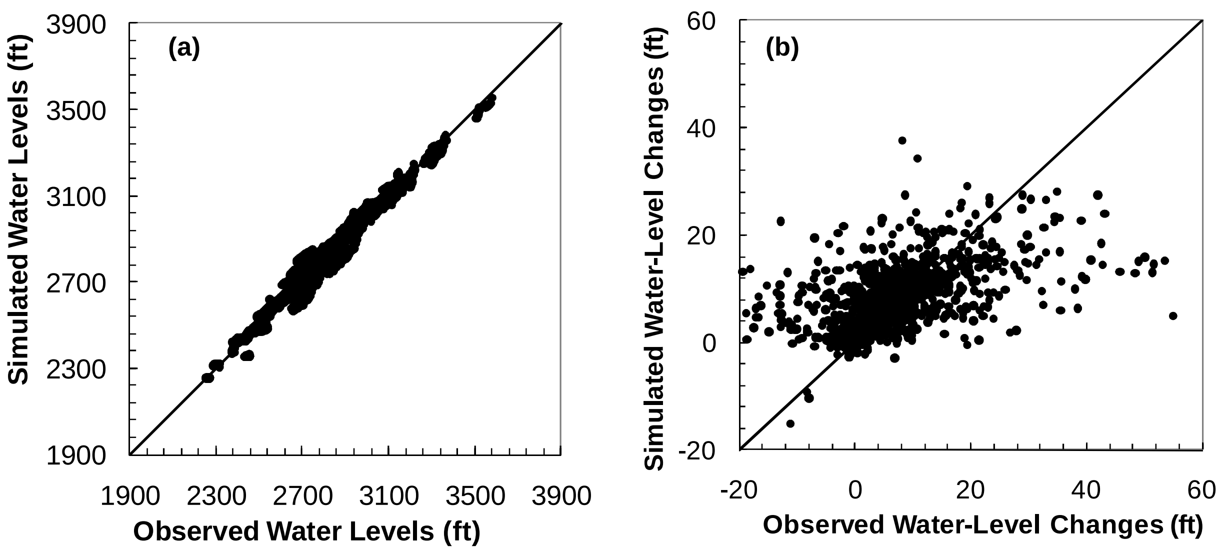


Figure 50. Scatter diagrams of (a) simulated versus observed water levels and (b) simulated versus observed water-level changes for 5-yr intervals for all calibration well hydrographs.

Figure 51 shows contours of simulated ground-water levels from the calibrated model compared to the interpolated observed data for different time periods. Despite the local mismatch in certain areas, simulated ground-water levels generally agree well with the observed data. In the predevelopment period, the water-table gradient in the HPA follows the general topography of the model area (i.e. gently sloping from west to east). As the water levels decline, especially in recent years such as 2007, well pumping significantly alters the patterns of water-level contours, creating some local cones of depression or mounds produced by surrounding declines.

Figure 52 presents the simulated versus observed water-level changes over different time spans (approximately 10-yr intervals for most maps). Similar to that for the water levels, the overall agreement between simulated and observed changes is very good despite some local areas where the match is poor. An example of the good regional agreement is the split of the areas of greater than 20-ft declines into two general zones for 1997-2007 along northwest to southeast Grant, southwest Haskell, northeast Stevens, and northwest Seward counties. It is currently not known whether this split is due to economic and land-use factors or characteristics of the aquifer.

To facilitate visual assessment, the locations of the 114 wells with long-term hydrographs used for calibration were grouped based on their geographic areas (Figure 53). Figure 54 shows simulated versus observed hydrographs for 81 of the wells that are representative of all the different groups. Each hydrograph includes the USGS well identification number. The calculated model recharge, including precipitation recharge and irrigation return flow, is plotted on the secondary axis. Overall, the agreement between simulated and observed hydrographs is good. The most significant mismatch occurs in Grant and Haskell counties north of the Cimarron River (Figure 54g). The simulated water levels for most of the wells in this group are significantly higher than observed values for predevelopment, and that mismatch remains through the transient period. Previous USGS modeling studies used a seepage term to improve the match in this region, causing ground water to flow out of the HPA into the underlying Dakota bedrock thereby producing lower HPA water levels. However, based on an investigation of the subsurface hydrogeology during the current KGS study, the direction of such an inter-aquifer exchange does not appear to be likely. Additional characterization of hydrogeological conditions will be needed to further improve the model match in this area.

Figure 55 shows the RMS of residuals between the simulated and observed hydrographs for each calibration well. Similar to the group hydrographs, the RMS is relatively large in Grant and Haskell counties north of the Cimarron River, as well as for a few wells to the south of the Cimarron River near the Kansas-Oklahoma border.

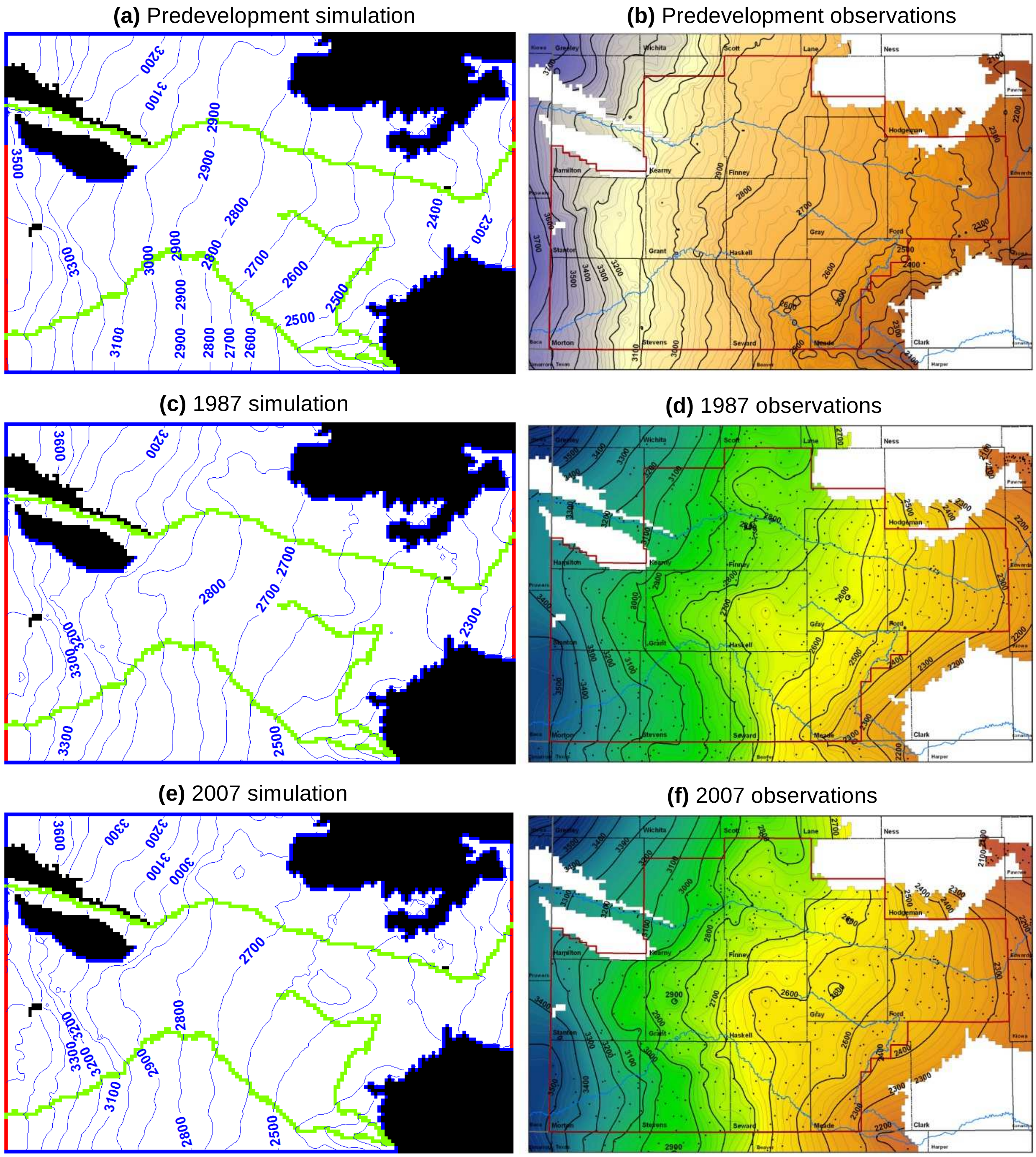
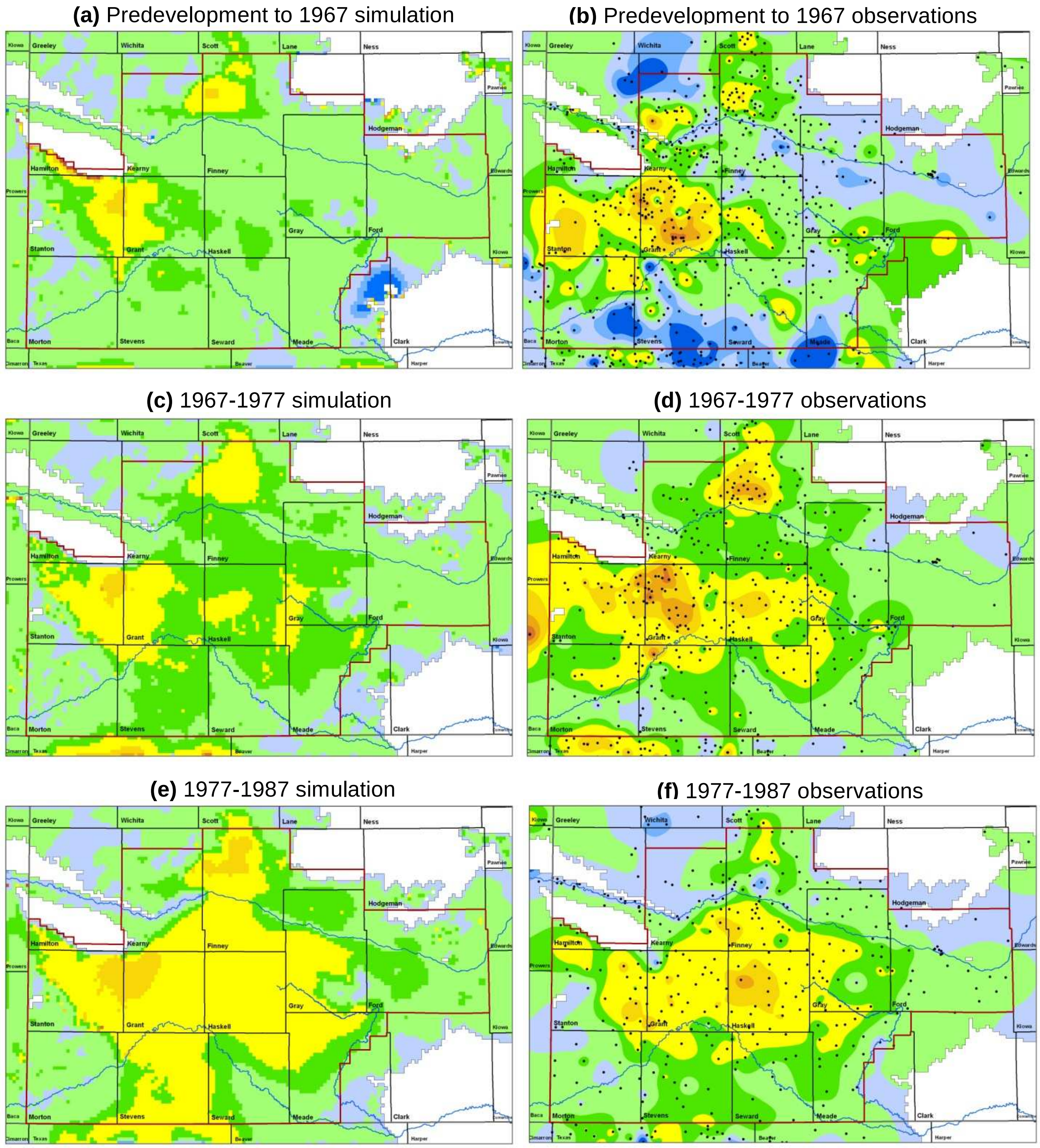


Figure 51. Comparison of simulated and observed water-level contours for different time periods.



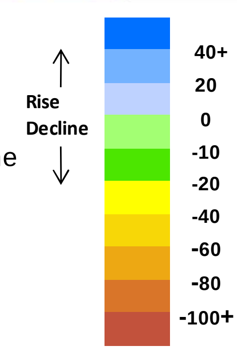
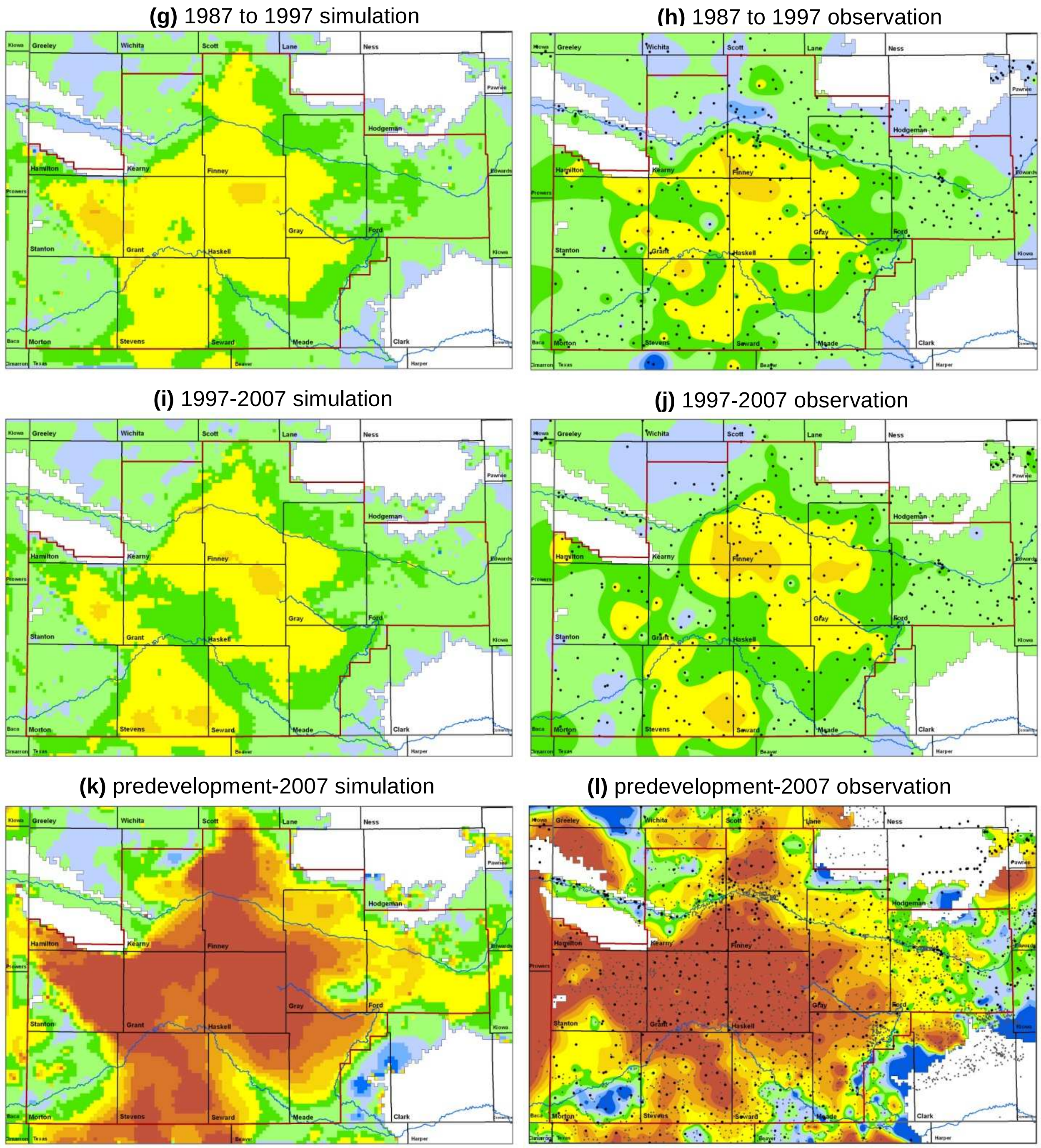


Figure 52. Simulated versus observed water-level changes for different time intervals.



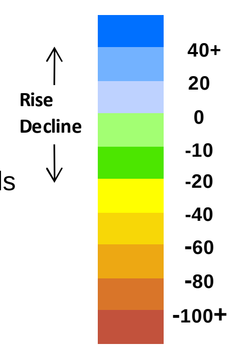


Figure 52. Simulated versus observed water level changes for different time intervals (continued).

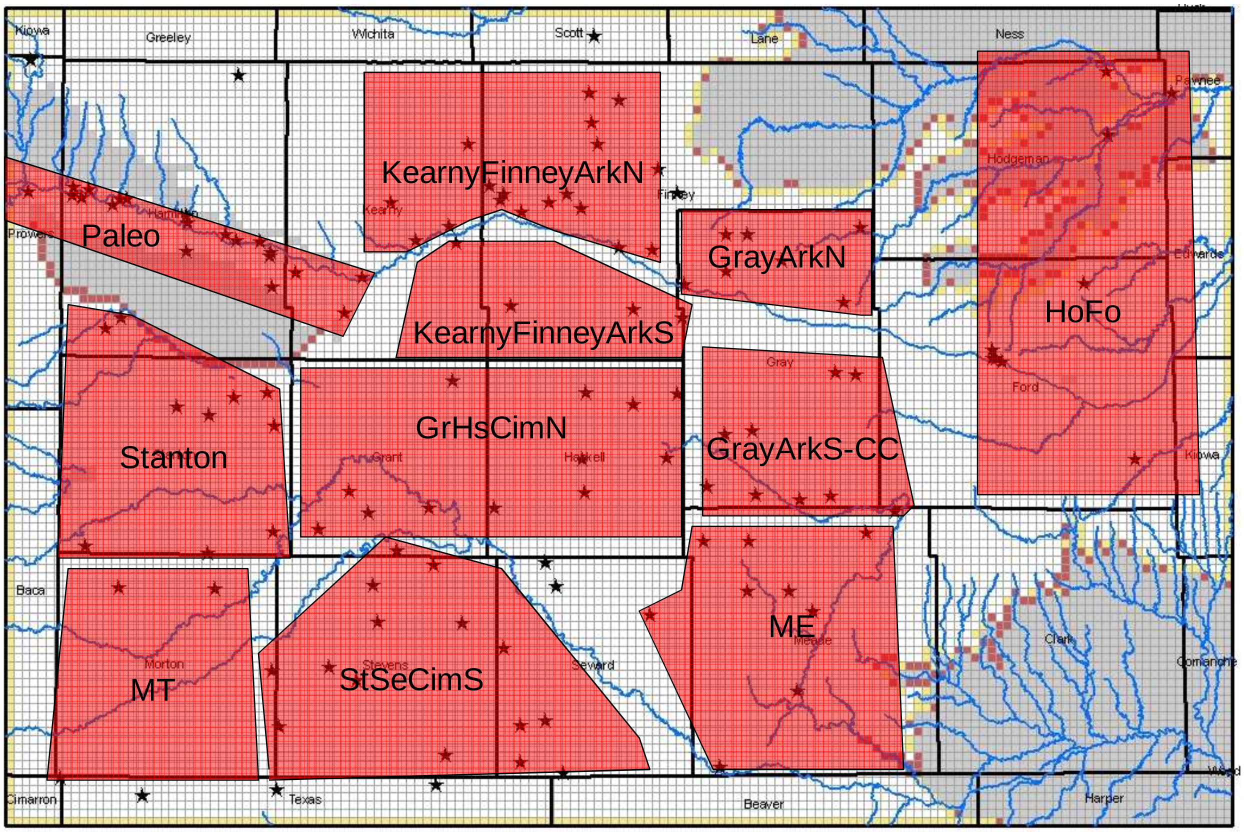


Figure 53. Different geographic groups of wells with long-term hydrographs used for calibration.

(a) Paleo Arkansas River Valley

(b) Kearny & Finney Counties North of Arkansas River

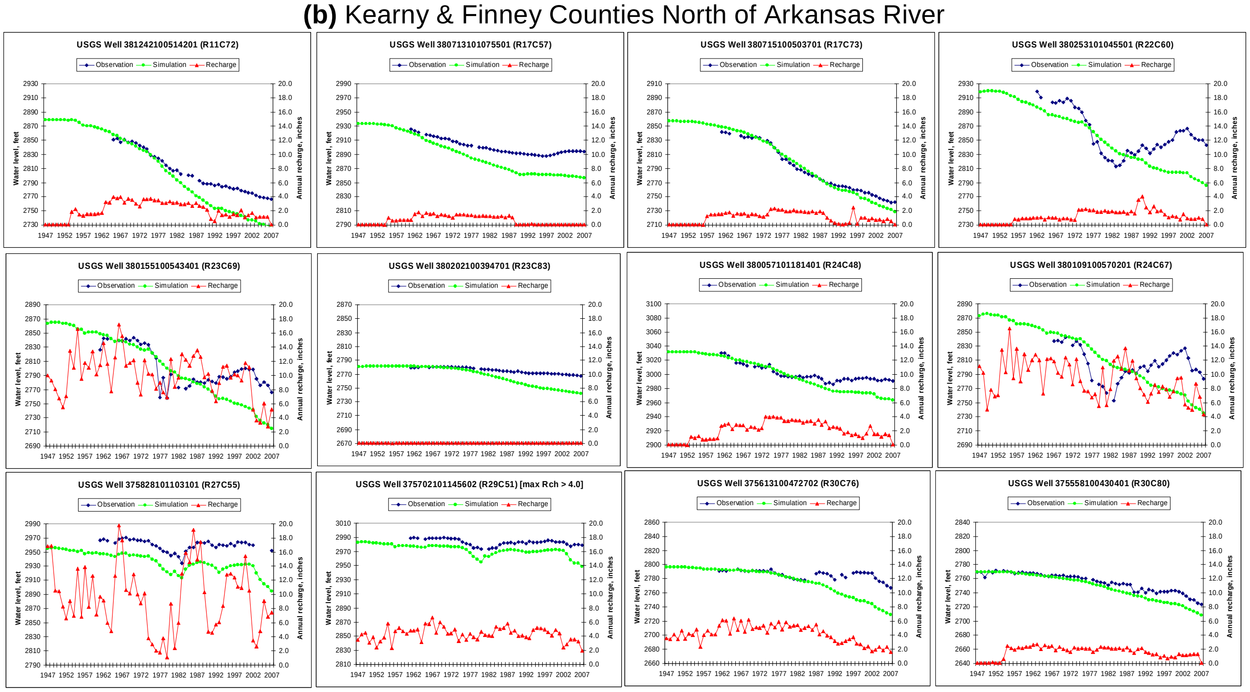
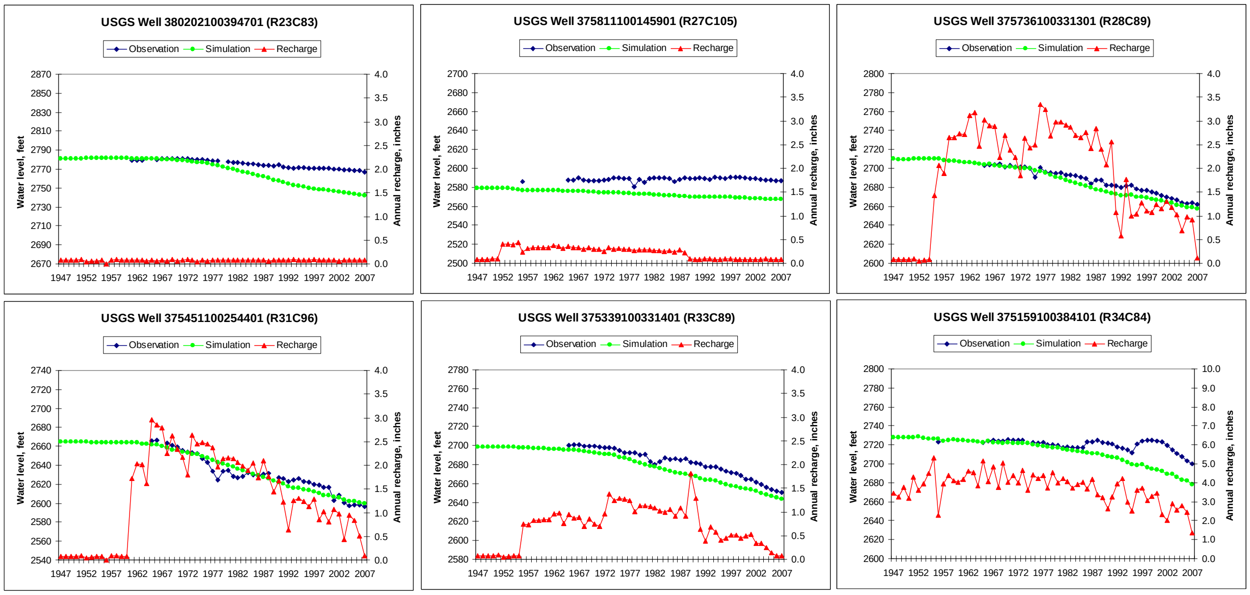


Figure 54. Simulated (green) vs. observed (dark blue) well hydrographs for each geographic group displayed in Figure 53. The model recharge (red), which includes precipitation recharge and irrigation return recharge, is plotted on the secondary (left) y-axis.

(c) Gray County North of Arkansas River



(d) Kearny & Finney Counties South of Arkansas River

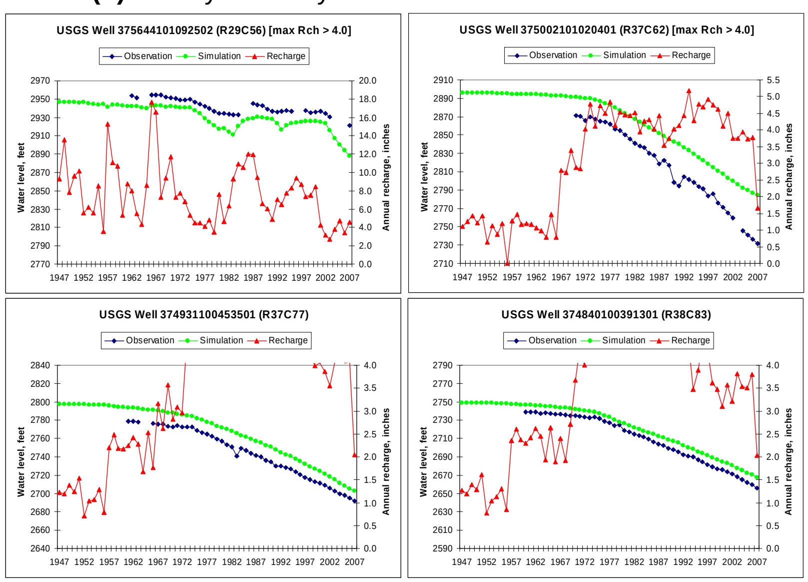
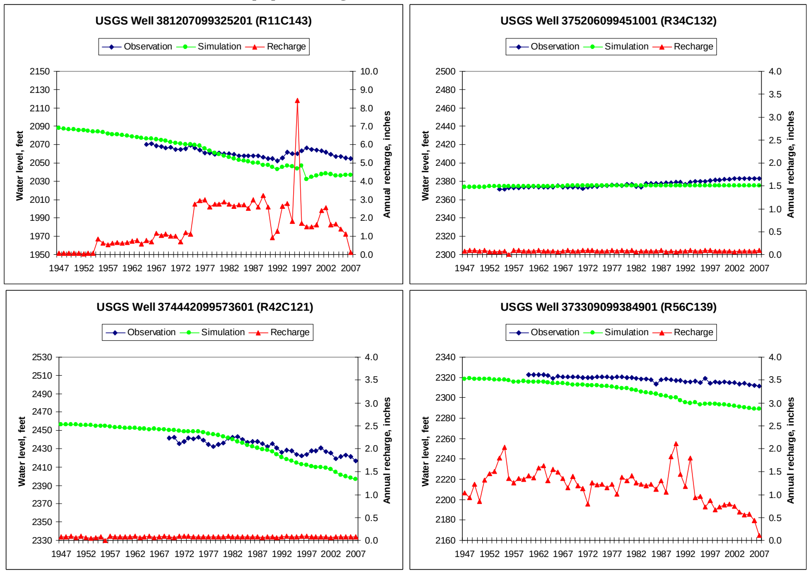


Figure 54. Simulated vs. observed well hydrographs for each geographic group (continued).

(e) Hodgeman & Ford Counties



(f) Stanton County

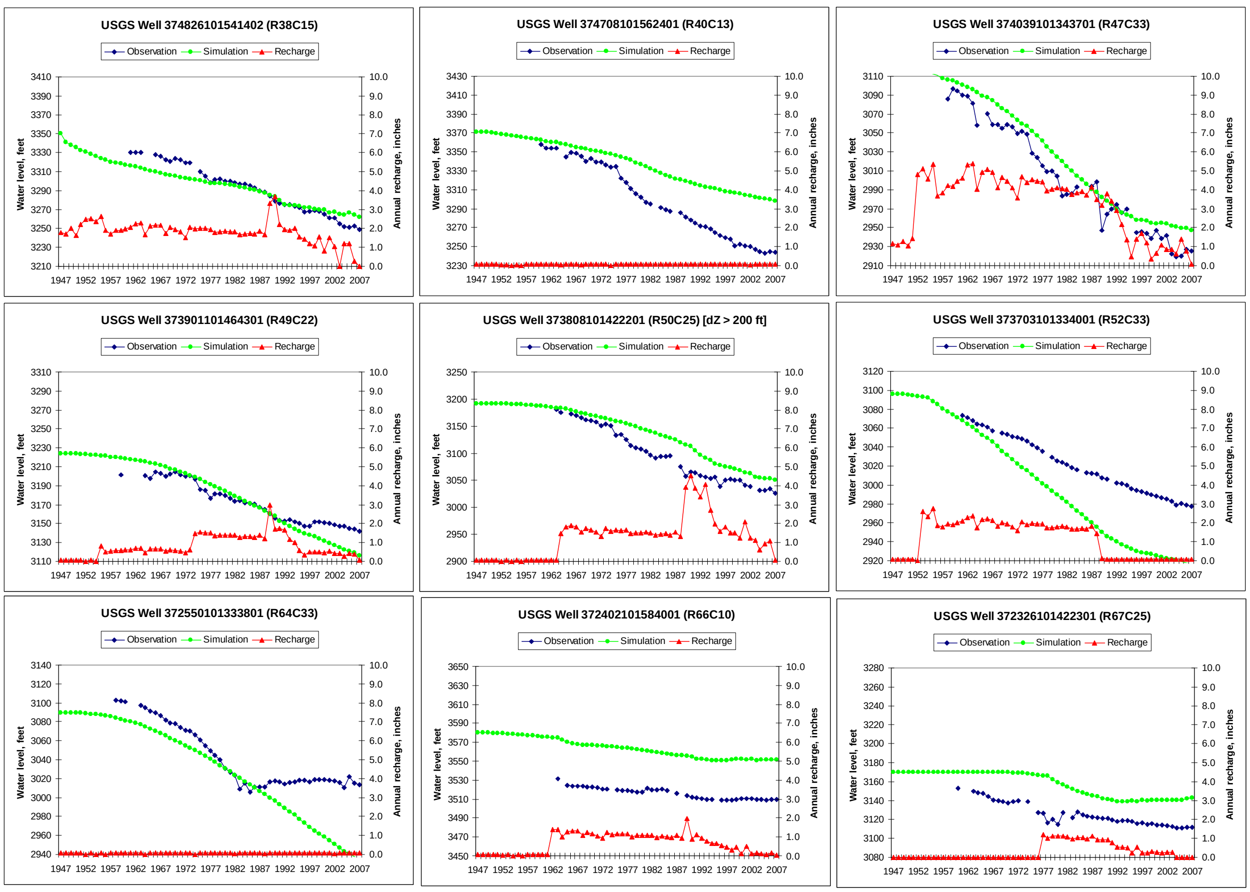
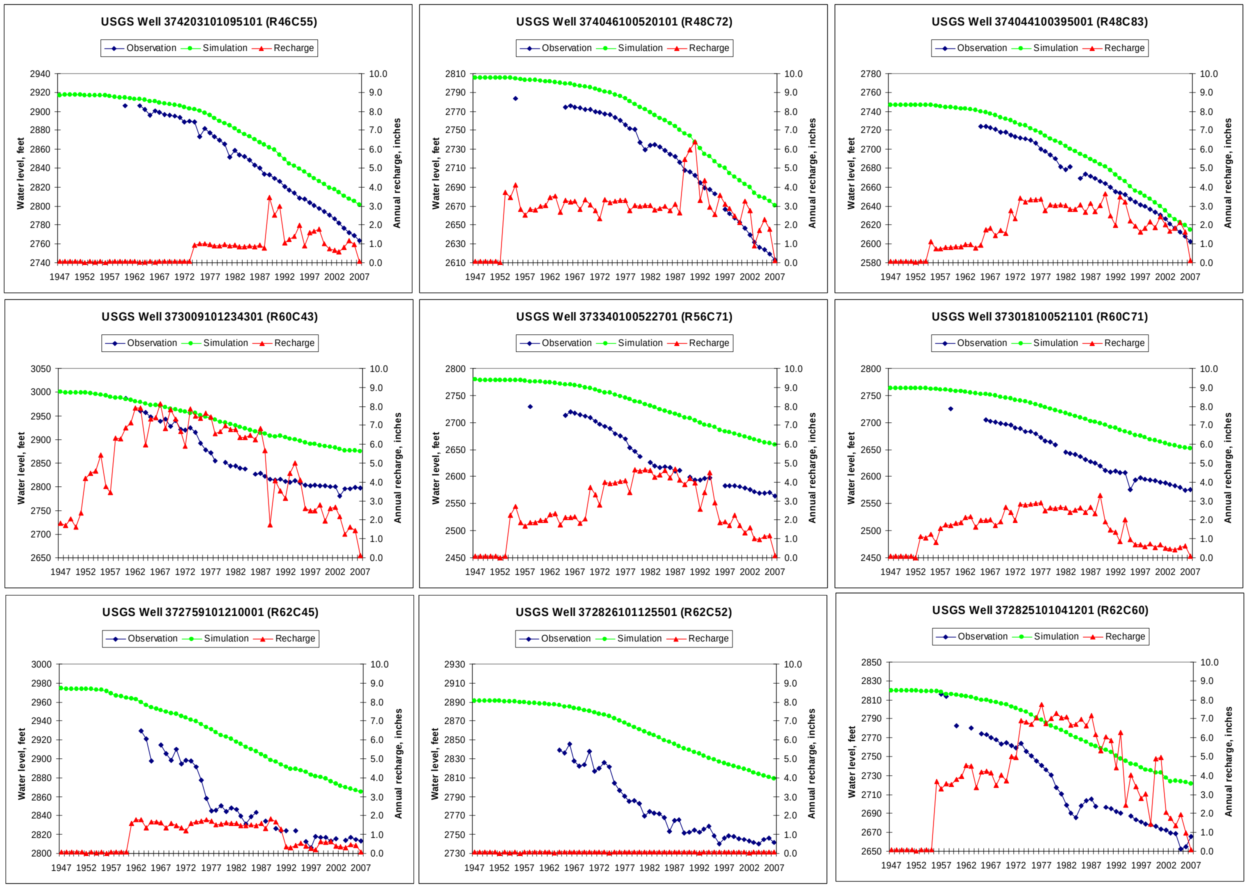


Figure 54. Simulated vs. observed well hydrographs for each geographic group (continued).

(g) Grant & Haskell Counties North of Cimarron River



(h) Gray County South of Arkansas River to Crooked Creek

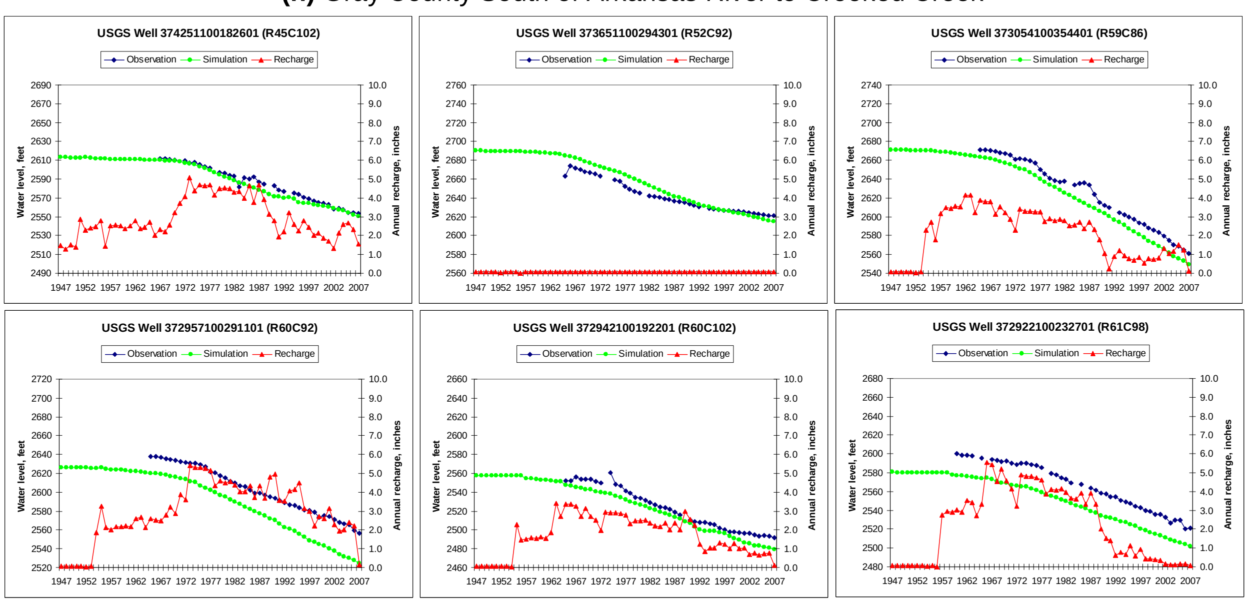
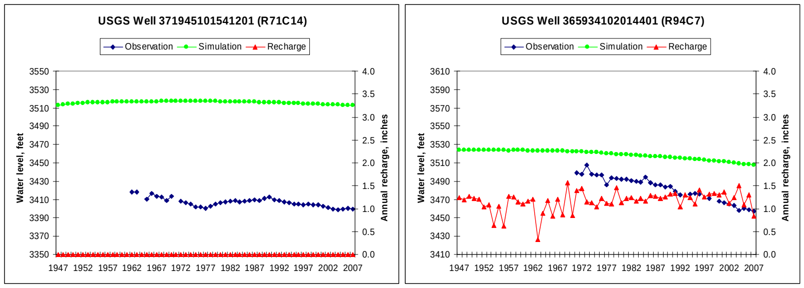


Figure 54. Simulated vs. observed well hydrographs for each geographic group (continued).

(i) Morton County



(j) Stevens & Seward Counties South of Cimarron River

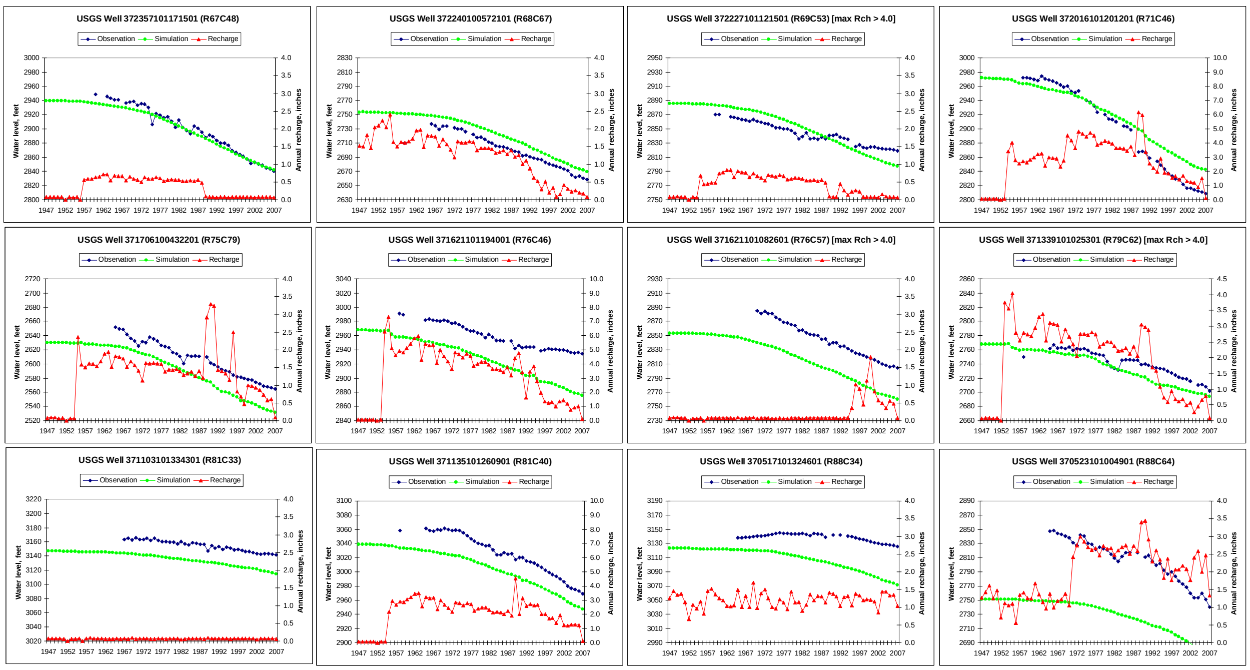


Figure 54. Simulated vs. observed well hydrographs for each geographic group (continued).

(i) Meade County

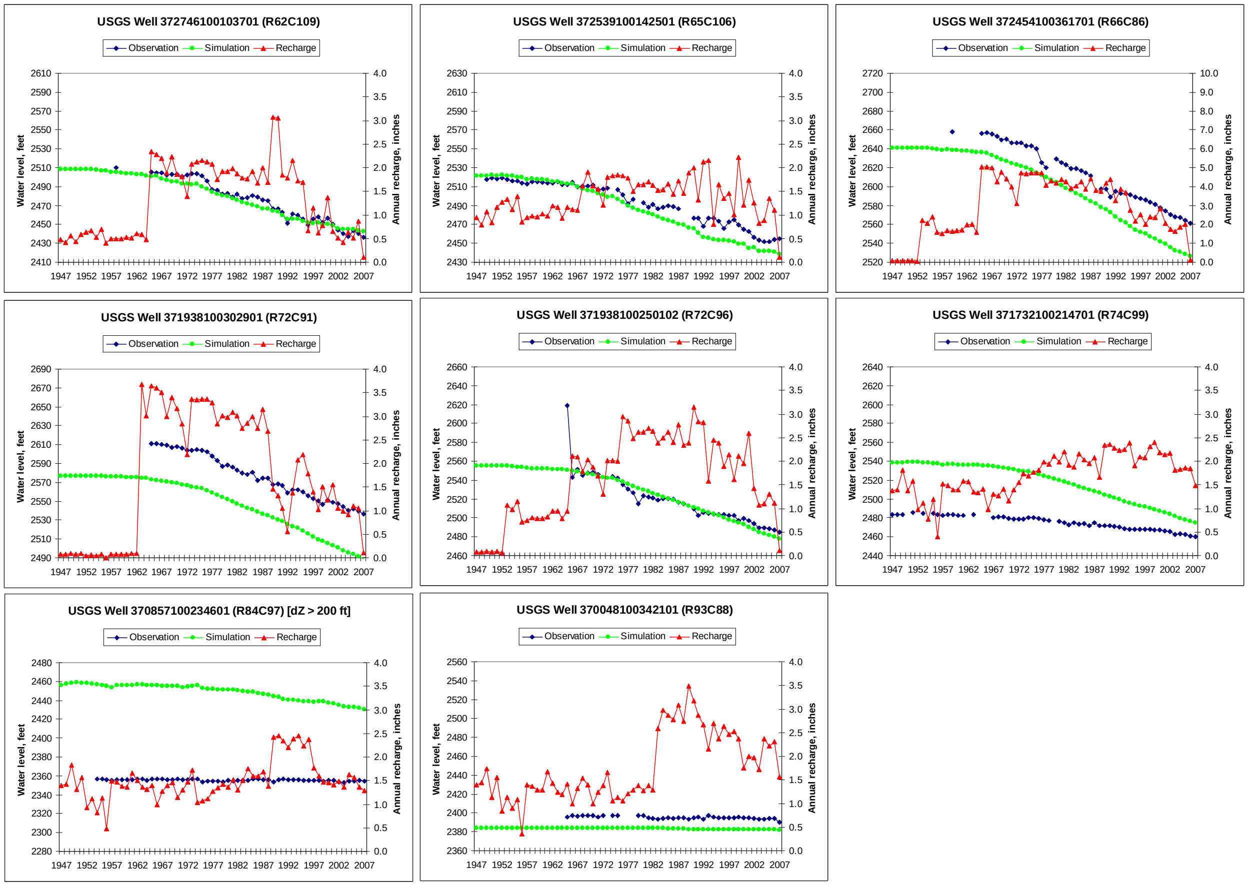


Figure 54. Simulated vs. observed well hydrographs for each geographic group (continued).

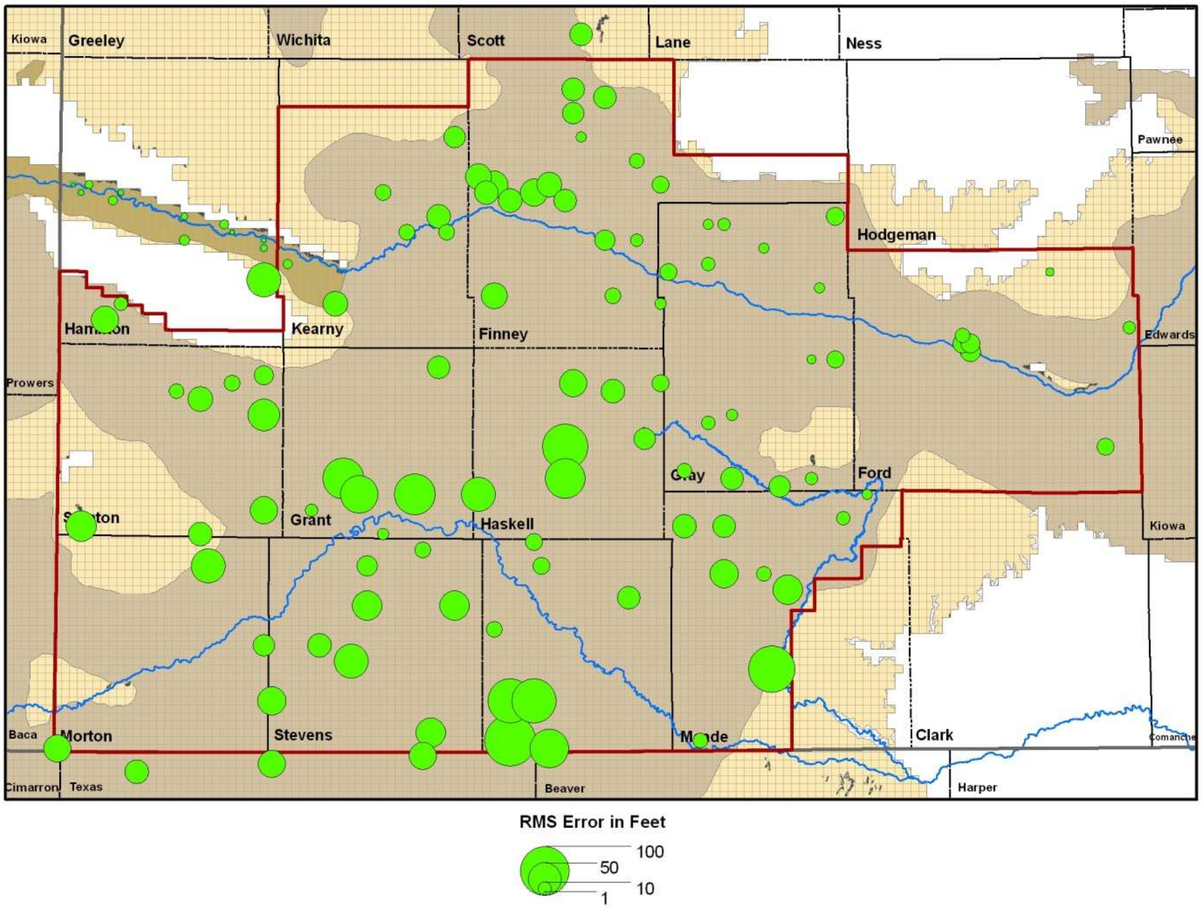


Figure 55. Spatial distribution of RMS for each calibration well. The circle size indicates the magnitude of the RMS error. The unit is ft.

Streamflows

Figure 56 plots the simulated versus observed streamflows at different gages on the Arkansas River, Cimarron River, and Crooked Creek (see Figure 44 for the location of each gage). Overall, the simulated and observed streamflows agree well. The model only simulates stream-aquifer interactions and does not take into account the surface runoff from precipitation events. Thus, the simulated streamflows are often less than the observed values. This is particularly true for Crooked Creek where the model simulation is an excellent match with the stream baseflow but includes no high-flow peaks. As indicated earlier, no inflow is included in the model for Crooked Creek because the creek originates within the model domain. Moreover, the agreement between simulated and observed flows for the Cimarron River and Crooked Creek improves with time because the high flow events decrease from greater infiltration of runoff to the aquifer as ground-water levels decline. High flows entering the southwest part of the model area in the Cimarron River are no longer transmitted downstream to the Forgan gage location in the southeast model area because the river is now dry for too long a stretch and the high-flow events are not large enough to saturate the aquifer in the river corridor. For the Arkansas River, however, although recent short-term high-flow events may not reach either the Garden City or Dodge City gages, extended large flows can reach these stations when the alluvial aquifer becomes saturated enough to transmit the flows farther downstream.

Figure 57 displays the residual streamflows (simulated minus observed values) for different gages. Similar to Figure 56, the majority of the residual streamflows are negative, indicating the model underestimates streamflow (especially during high-flow events) more times than it overestimates flow.

Figure 58 shows the streamflows, stream-aquifer interactions, and irrigation ditch diversions along the Arkansas River in the predevelopment period. No perennial tributary inflows exist for the Arkansas River. Starting with the input flow from the most upstream reach, streamflow undergoes continuous modification from stream-aquifer interactions and irrigation ditch diversions as water moves downstream. Figure 58a indicates that the accumulative stream-aquifer interaction is insignificant between the upstream river entry to the model and Garden City (approximately 80 miles in stream length from the upstream end). After Garden City, the Arkansas River becomes a predominantly gaining stream. Between the upstream model entry and downstream exit, the Arkansas River gains about 98 ft^3/sec overall from the aquifer. Figure 58b shows the stream-aquifer interaction (i.e. ground-water discharge into stream) for each stream reach along the river. Positive values mean the stream is gaining water from the aquifer. Between the upstream river entry and Garden City, the stream-aquifer interactions are relatively large. However, the positive and negative values generally balance each other and, as a result, the net ground-water discharge into the river is small. This is because annual ground-water levels and stream stages during predevelopment time are approximately similar to each other between the upstream river entry and Garden City (so that water moves both ways between the stream and the aquifer). Downstream of Garden City, stream-aquifer interactions become predominantly positive as the ground-water levels are typically higher than the stream stages so water moves mostly from the aquifer to the river.

Figure 59 shows the streamflows and stream-aquifer interactions along the Cimarron River in the predevelopment period. Crooked Creek joins the Cimarron River about 185 miles downstream from the upstream model entry of the river, creating a small step increase in streamflow at that location. Figure 59b indicates that for the first 100 miles of the Cimarron River, the net stream-aquifer interaction is nearly zero due to the similar elevations of annual ground-water levels and stream stages. After the first 100 miles, ground-water levels become higher than the stream stages and the Cimarron River becomes a predominantly gaining stream. When the river reaches the bedrock area in the northeastern corner of Beaver County in Oklahoma, stream-aquifer interaction becomes zero. Where the Cimarron River reaches the bedrock area, the cumulative rate of ground-water discharge to the river totals ~205 ft^3/sec.

Figure 60 illustrates the streamflows and stream-aquifer interactions along the Crooked Creek in the predevelopment period. As no upstream inflow exists in the model for this stream, the simulated streamflow all comes from stream-aquifer interaction. The minor separation of curves in Figure 60a is due to rounding to different significant digits in the streamflow and stream-aquifer interaction results in the model output files. The figure indicates that the Crooked Creek is primarily a gaining stream because the ground-water levels are higher than streambed elevations. The total ground-water discharge rate for the creek is about 13 ft^3/sec in the predevelopment period.

Figures 61-63 display the streamflows and stream-aquifer interactions for the Arkansas River, Cimarron River, and Crooked Creek in 2007. The water-level declines in the HPA have a significant impact on the stream-aquifer interactions in all three streams. For the Arkansas River, stream-aquifer interaction remains similar to that in the predevelopment period in the paleovalley from the western model boundary to central Kearny County, because ground-water levels change little in this area. Downstream of the paleovalley, ground-water levels are below streambed elevations and the Arkansas River starts to substantially lose water to the underlying aquifer. To the east of Garden City, the Arkansas River is dry so there is little interaction between the stream and the aquifer for the remainder of the river course (Figure 61). For the Cimarron River, ground-water levels are below the streambed for much of the first 130 miles of stream length. Essentially no stream-aquifer interaction occurs in this part of the river due to the dry streambed. About 130 miles downstream, ground-water levels are again higher than the streambed and the Cimarron River gains water from the underlying aquifer. The cumulative rate of ground-water discharge into the Cimarron River totals ~100 ft^3/sec at the point the river reaches the bedrock area (Figure 62). For Crooked Creek, ground-water level declines have shifted the perennial start of the stream approximately 30 miles downstream from its predevelopment position. The cumulative rate of ground-water discharge into Crooked Creek is reduced from ~13 ft^3/sec in the predevelopment period to ~8 ft^3/sec in 2007 (Figure 63).

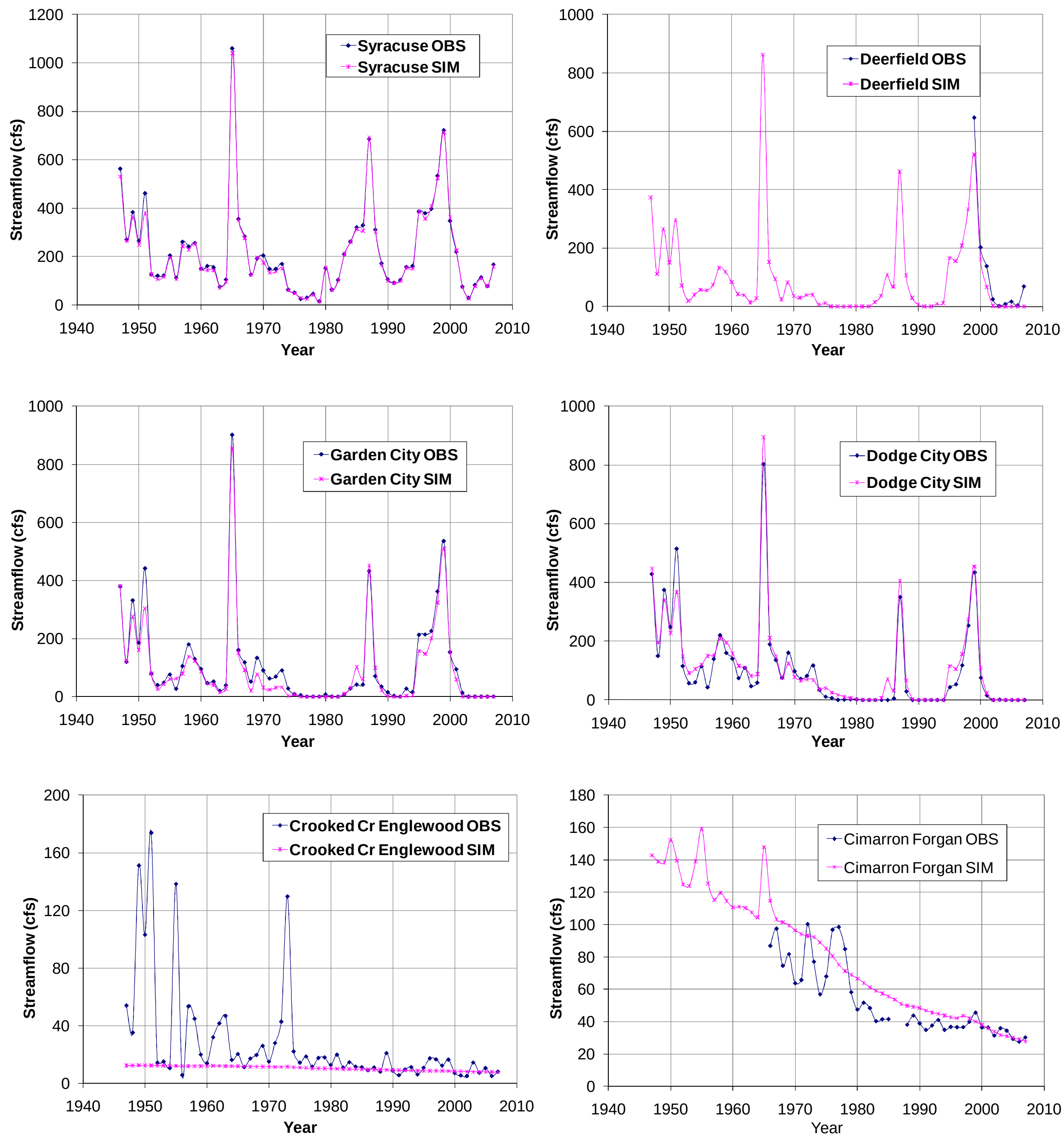
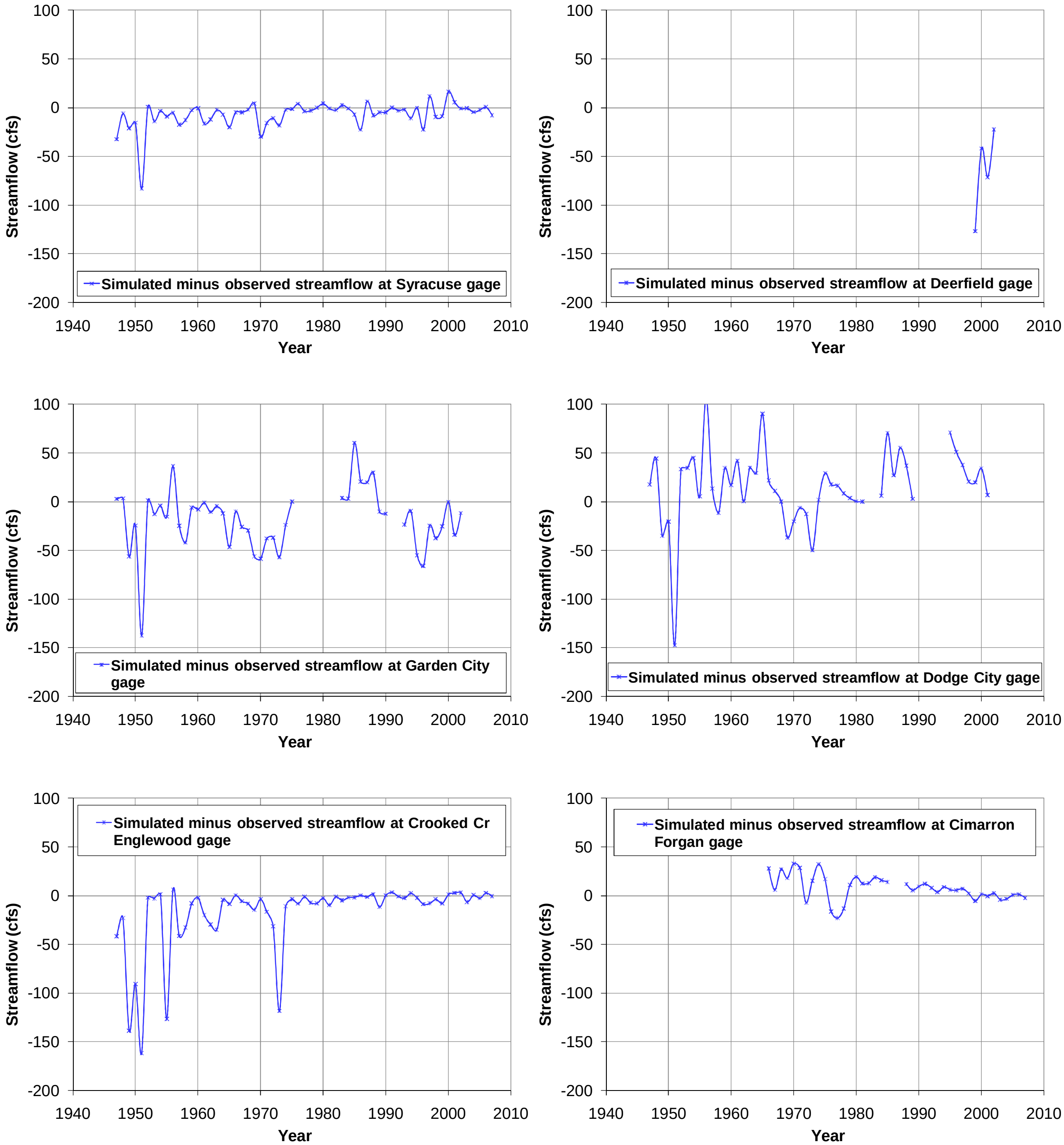
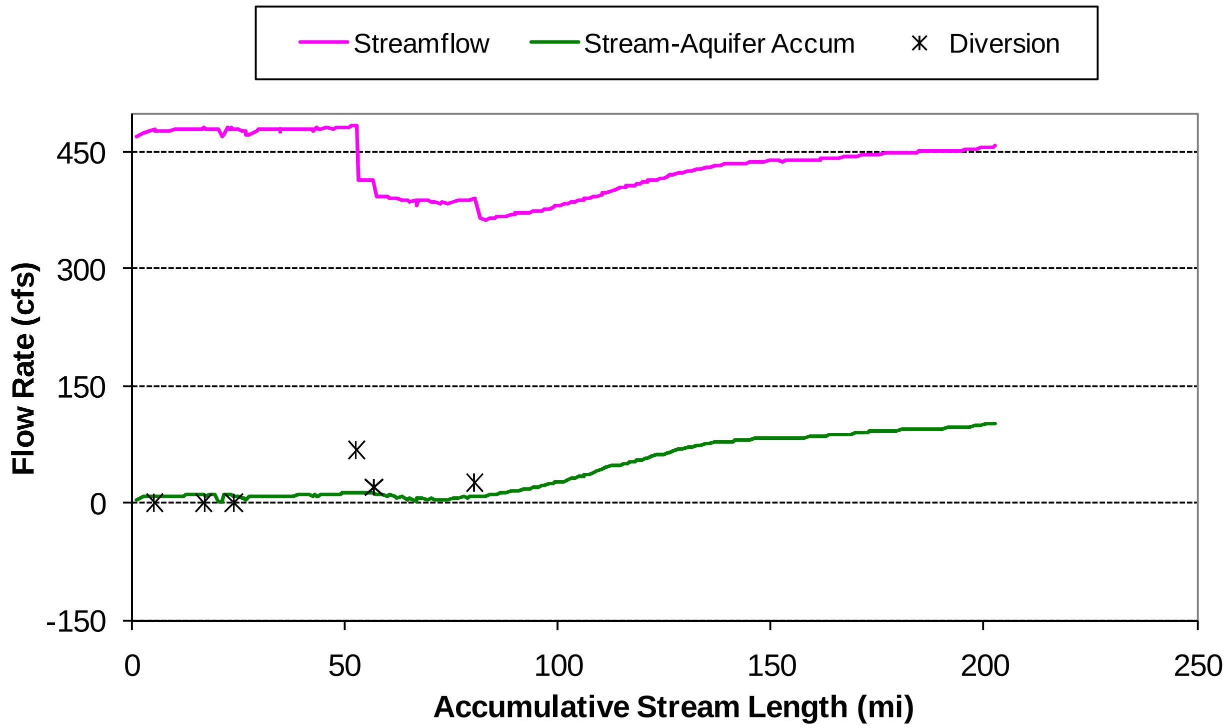


Figure 56. Simulated versus observed streamflows at different gages on the Arkansas River, Cimarron River, and Crooked Creek.



Figures 57. Simulated minus observed streamflow for different gages on the Arkansas River, Cimarron River, and Crooked Creek. The breaks in the curves are due to lack of streamflow observations for those years.

(a) Streamflow, accumulative stream-aquifer interaction, and ditch diversions



(b) Stream-aquifer interaction for each river reach

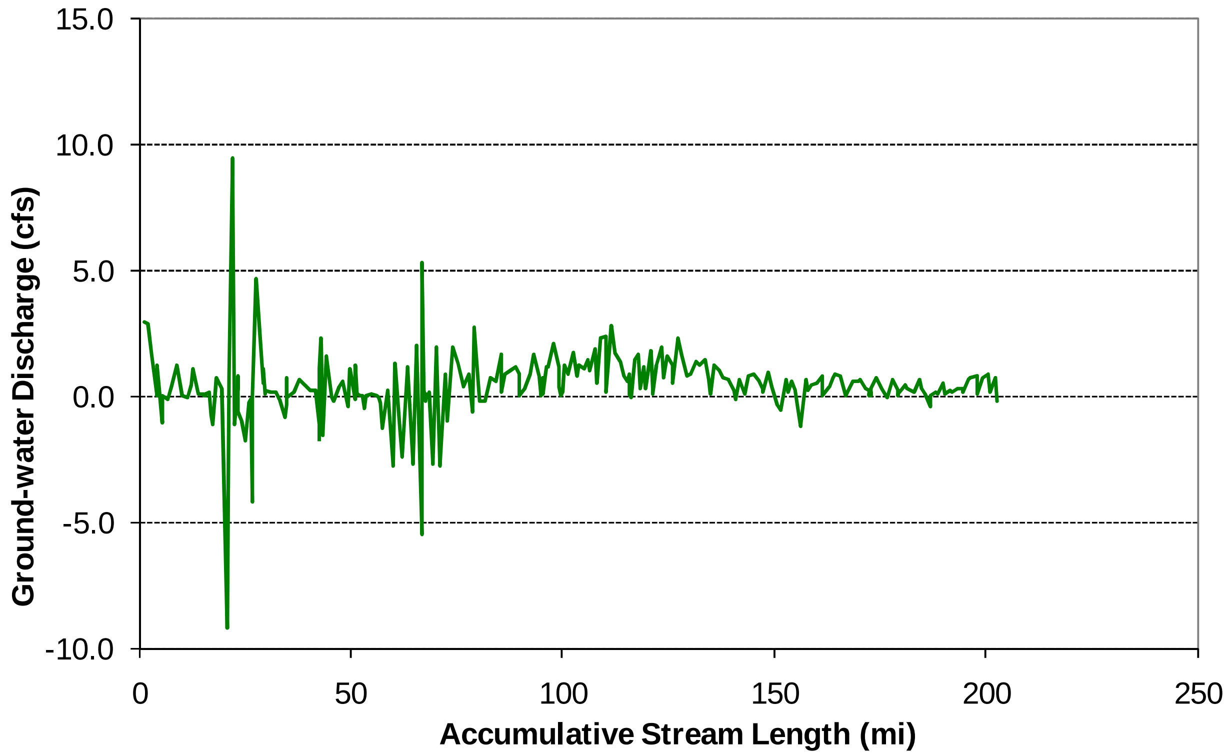
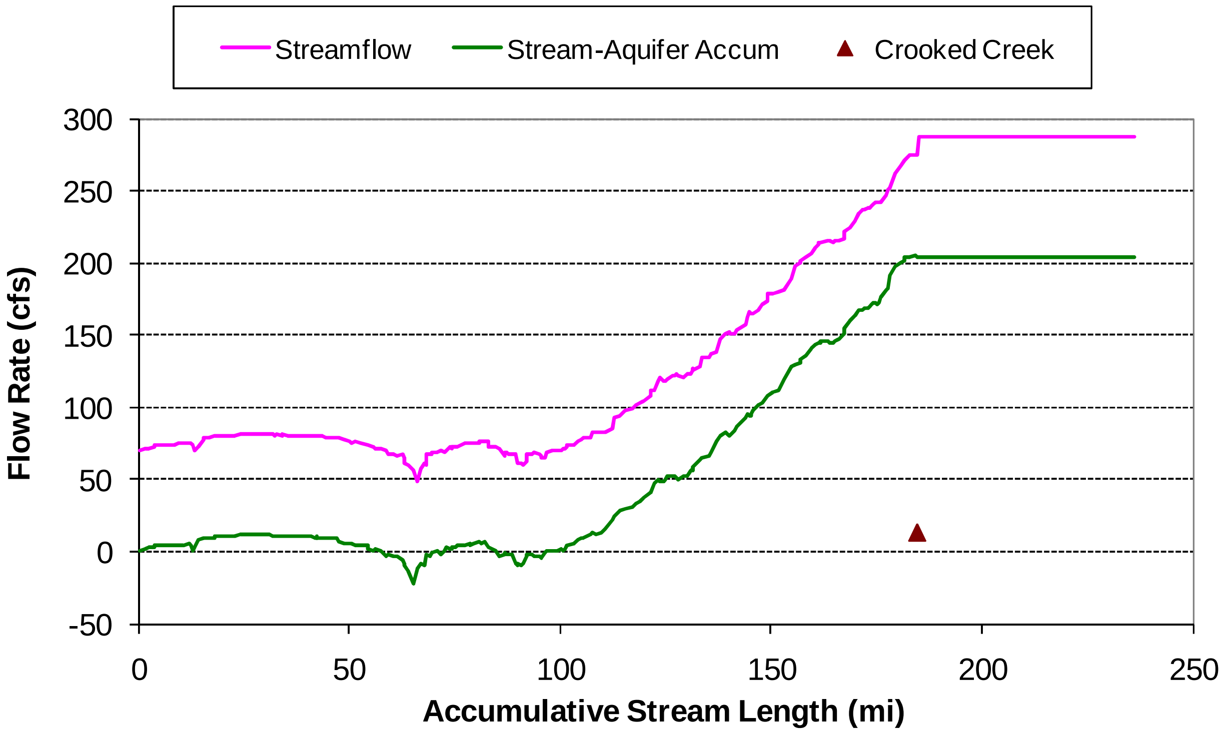


Figure 58. Simulated streamflow and stream-aquifer interaction along the Arkansas River in the predevelopment period.

(a) Streamflow and accumulative stream-aquifer interaction



(b) Stream-aquifer interaction for each river reach

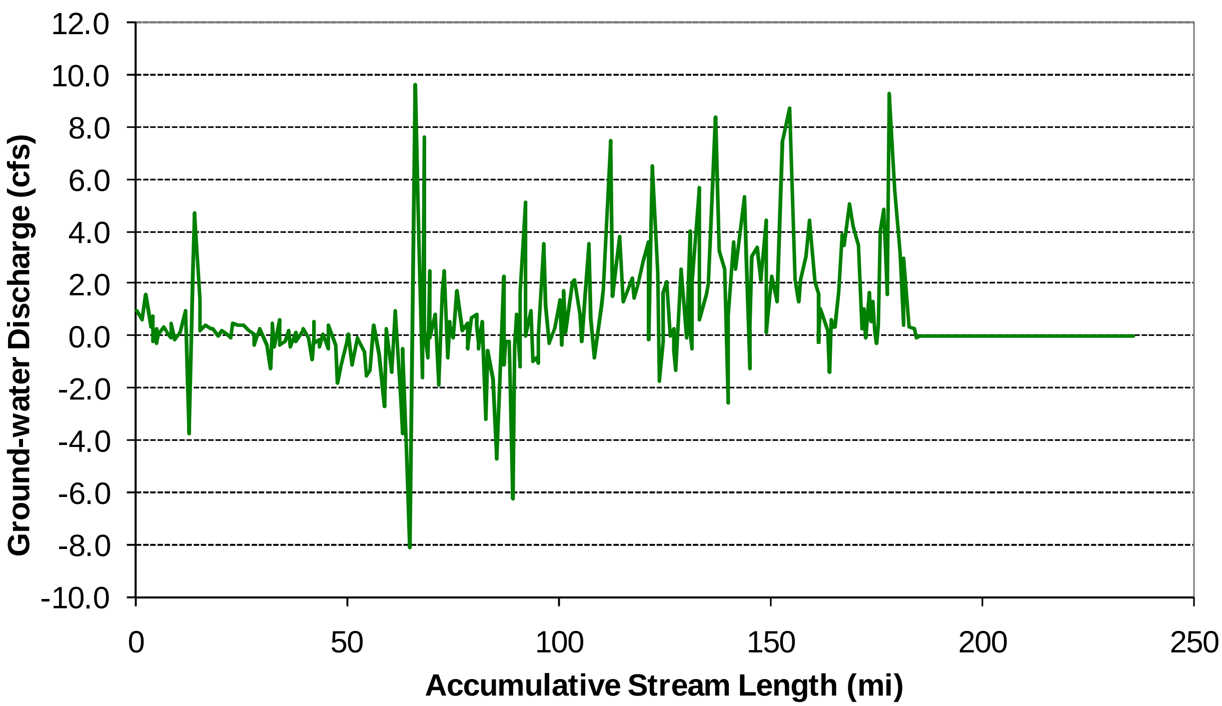
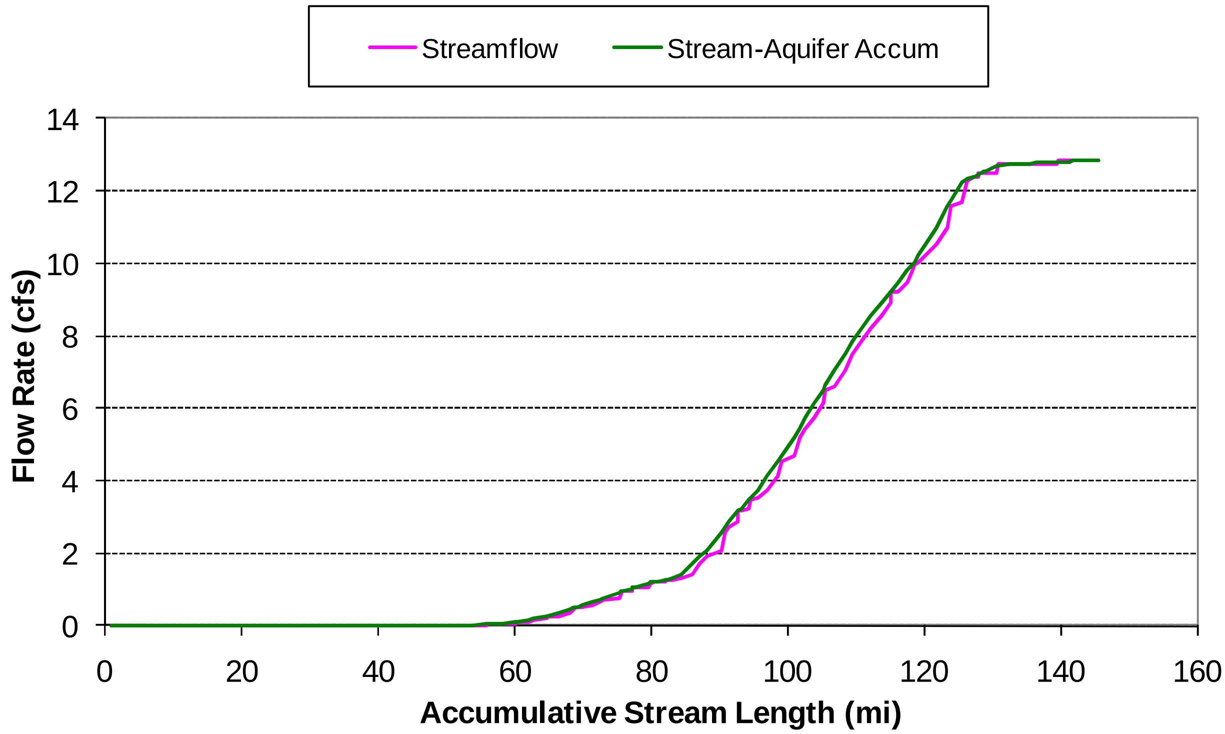


Figure 59. Simulated streamflow and stream-aquifer interaction along the Cimarron River in the predevelopment period.

(a) Streamflow and accumulative stream-aquifer interaction



(b) Stream-aquifer interaction for each stream reach

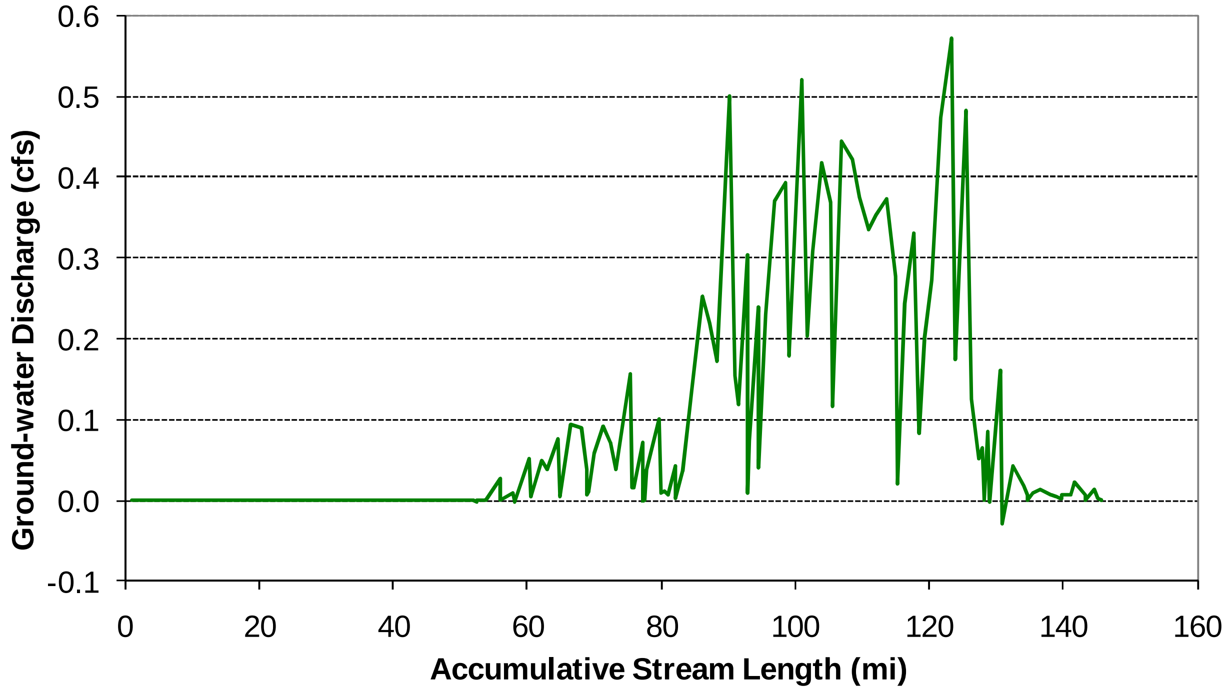
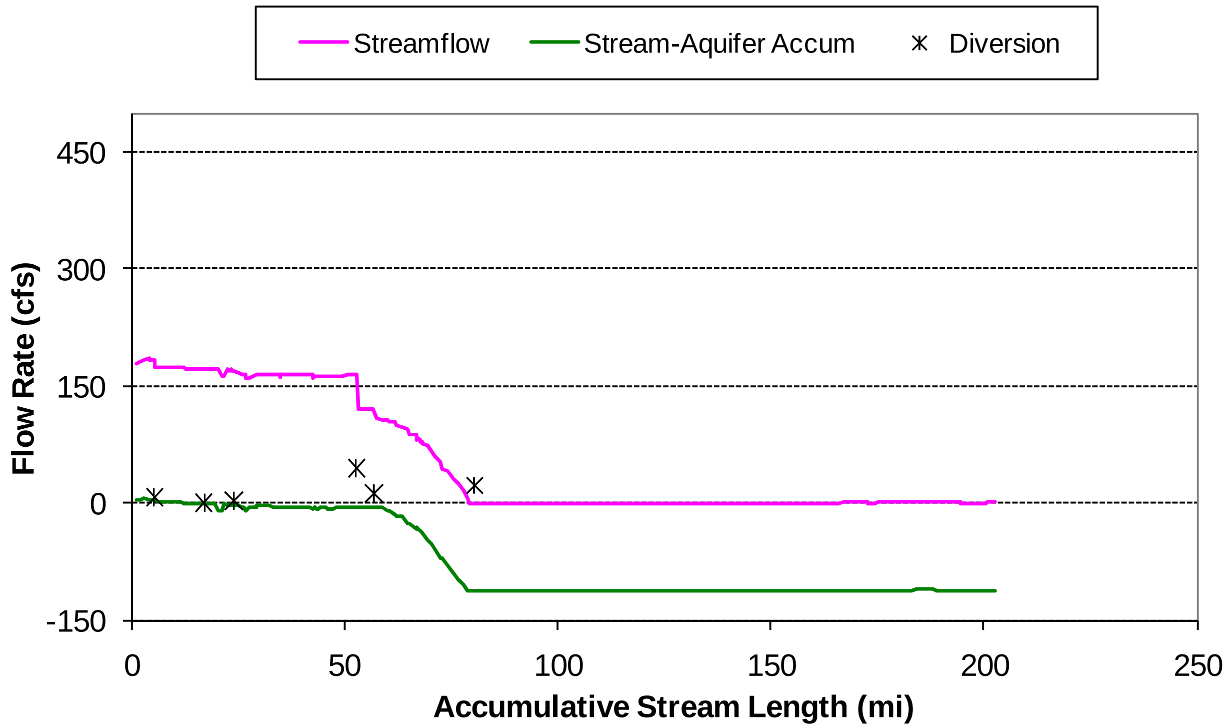


Figure 60. Simulated streamflow and stream-aquifer interaction along Crooked Creek in the predevelopment period.

(a) Streamflow, accumulative stream-aquifer interaction, and ditch diversions



(b) Stream-aquifer interaction for each river reach

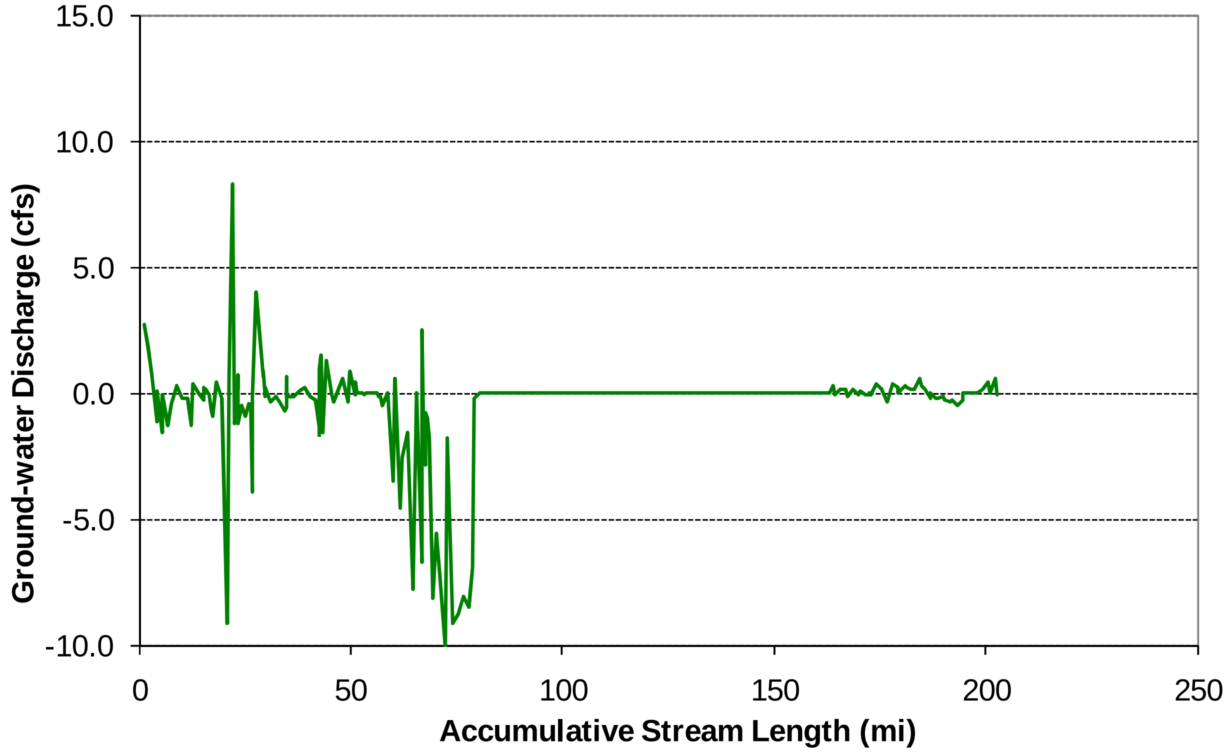


Figure 61. Simulated streamflow and stream-aquifer interaction along the Arkansas River in 2007.

(a) Streamflow and accumulative stream-aquifer interaction.

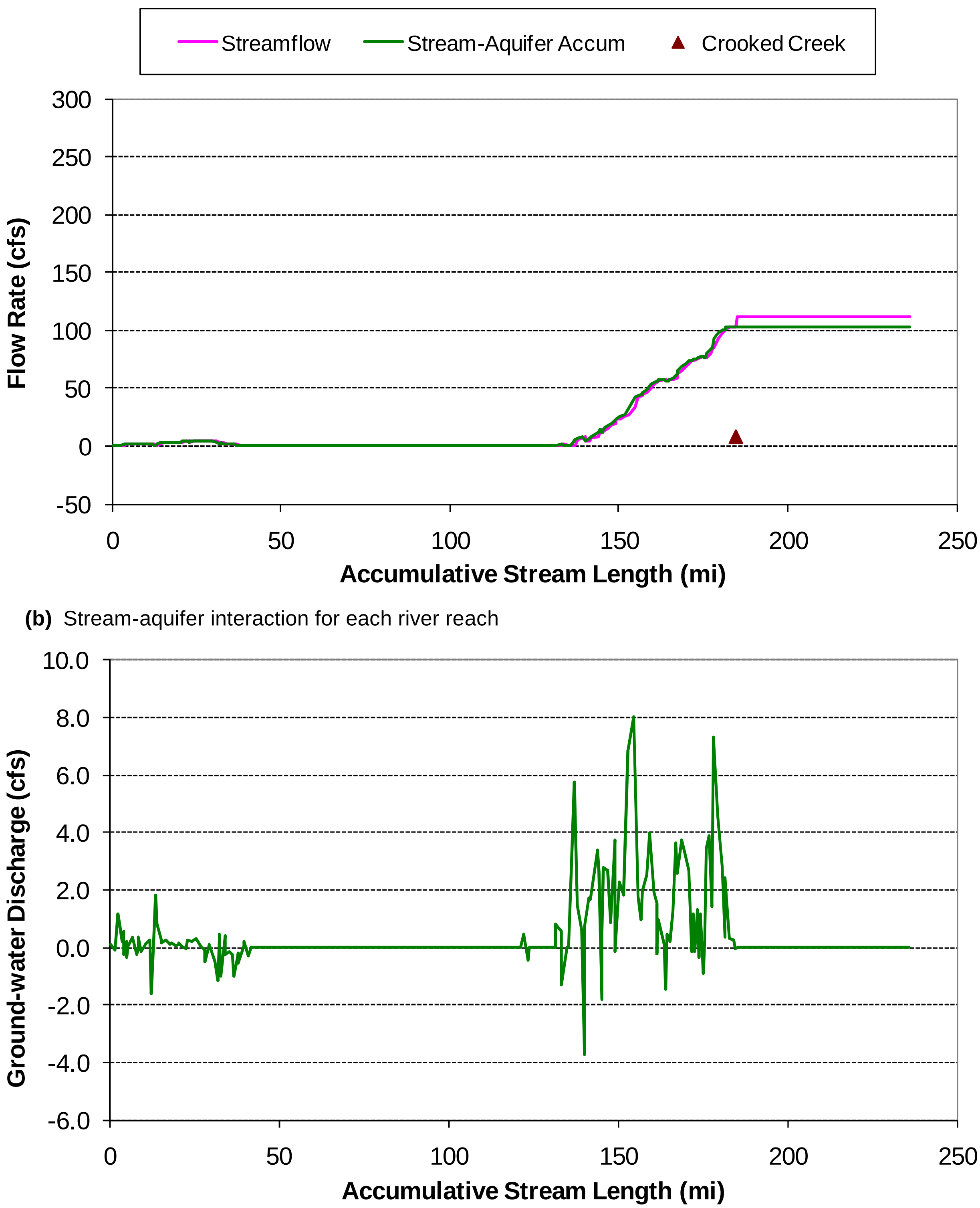
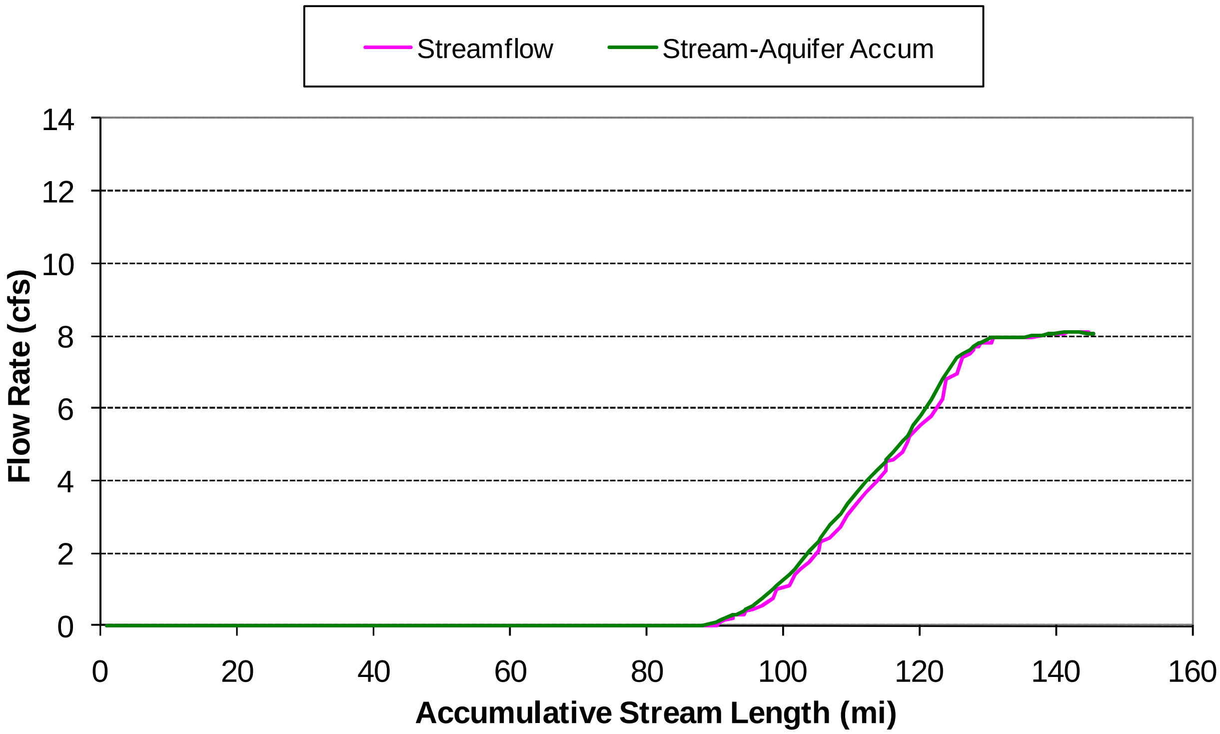


Figure 62. Simulated streamflow and stream-aquifer interaction along the Cimarron River in 2007.

(a) Streamflow and accumulative stream-aquifer interaction



(b) Stream-aquifer interaction for each stream reach

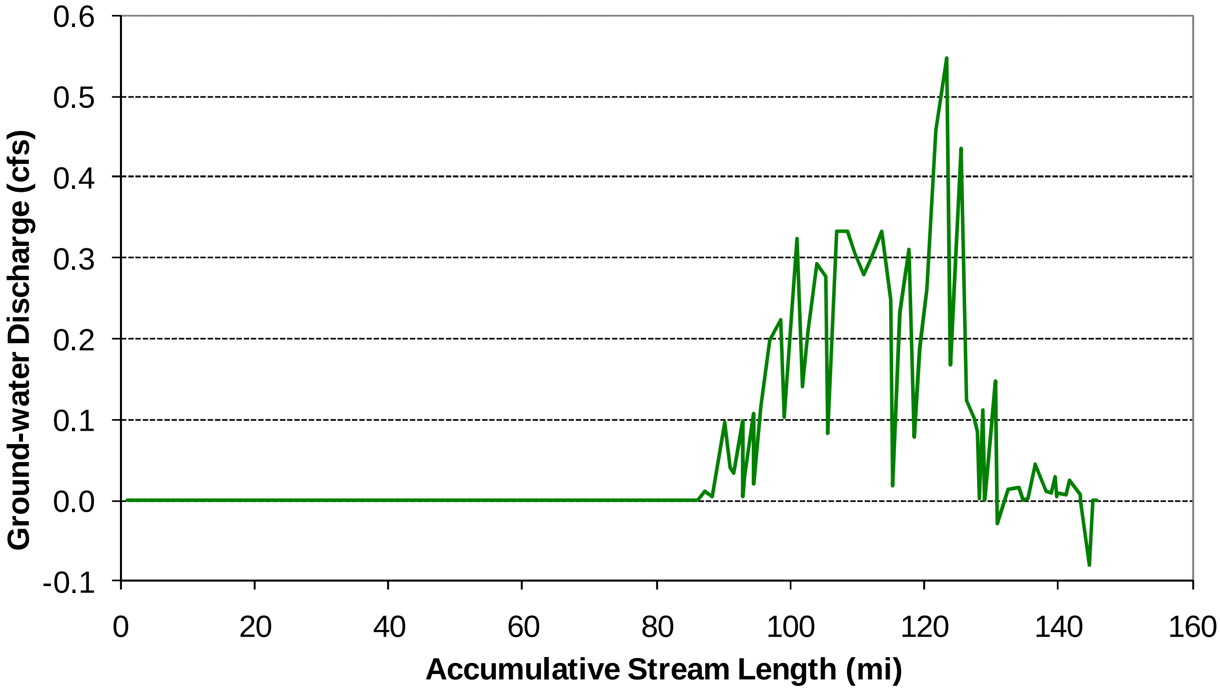


Figure 63. Simulated streamflow and stream-aquifer interaction along Crooked Creek in 2007.

Ground-water Budgets

Model boundary budgets

Figure 64 shows ground-water budgets across the northern, eastern, southern, and western borders of the model, as well as across the Kansas/Oklahoma state border. Figure 64a displays the annual rate of ground-water movement, whereas Figure 64b shows the cumulative volume of ground water that has moved across these different borders since predevelopment. Positive values mean that the overall movement of ground water is into the HPA aquifer within the model domain (i.e. the aquifer is gaining water across that border). For both the western and northern model borders, the aquifer gains water throughout the transient period. For the western border, the annual rate of ground water flowing into the aquifer is nearly constant until the early 1980s, then declines through 2007. The total amount of ground water gained is 1,180,000 acre-ft between predevelopment and 2007. For the northern border, the annual rate of ground water flowing into the aquifer remains relatively steady between predevelopment and the middle 1970s, then gradually increases until the middle 1980s, and then remains steady for the rest of the modeled period. The total amount of gain is 30,000 acre-ft at the end of the simulation. For the eastern model border, the aquifer discharges ground water throughout the transient period. The annual rate of ground-water loss is relatively constant until the mid-1960s, then decreases slowly through 2007. The total amount of water that discharges across the eastern border is 1,070,000 acre-ft by the end of the simulation.

The ground-water budget is more complicated across the southern model border. Between predevelopment and the middle 1960s, the aquifer gains water across the southern model boundary at a rate that decreases from 28,000 to about 15,000 acre-ft/year. During the middle to late 1960s, the annual rate of ground-water movement across the border abruptly changes from positive to negative, indicating that the aquifer starts to lose water out of the southern border. The loss rate peaks around 1976-1977 and then varies while generally decreasing until it becomes essentially zero in the late 1990s. During the last several years, the annual rate becomes positive again, indicating that instead of losing water as occurred previously, the model begins to gain water from the southern border. Between predevelopment and 1965, the aquifer gains 379,000 acre-ft of water across the southern border. From 1965 to 1996, the aquifer loses an cumulative volume of 710,000 acre-ft. The amount of gain between 1996 and 2007 is comparatively very small (~40,000 acre-ft). Between predevelopment and 2007, the overall loss of water across the southern model border is 291,000 acre-ft.

The ground-water budget across the Kansas/Oklahoma state border is somewhat similar to that across the southern model border. Between predevelopment and 1965, the annual rate of ground-water movement across the state border is essentially zero. After 1965, the rate becomes negative, indicating that the Kansas side of the aquifer begins to lose water to the Oklahoma side. The rate of ground-water loss peaks around the middle 1980s, and then becomes smaller during recent years. Between predevelopment and 2007, the total amount of ground water discharging across the Kansas border into Oklahoma within the model domain is 550,000 acre-ft.

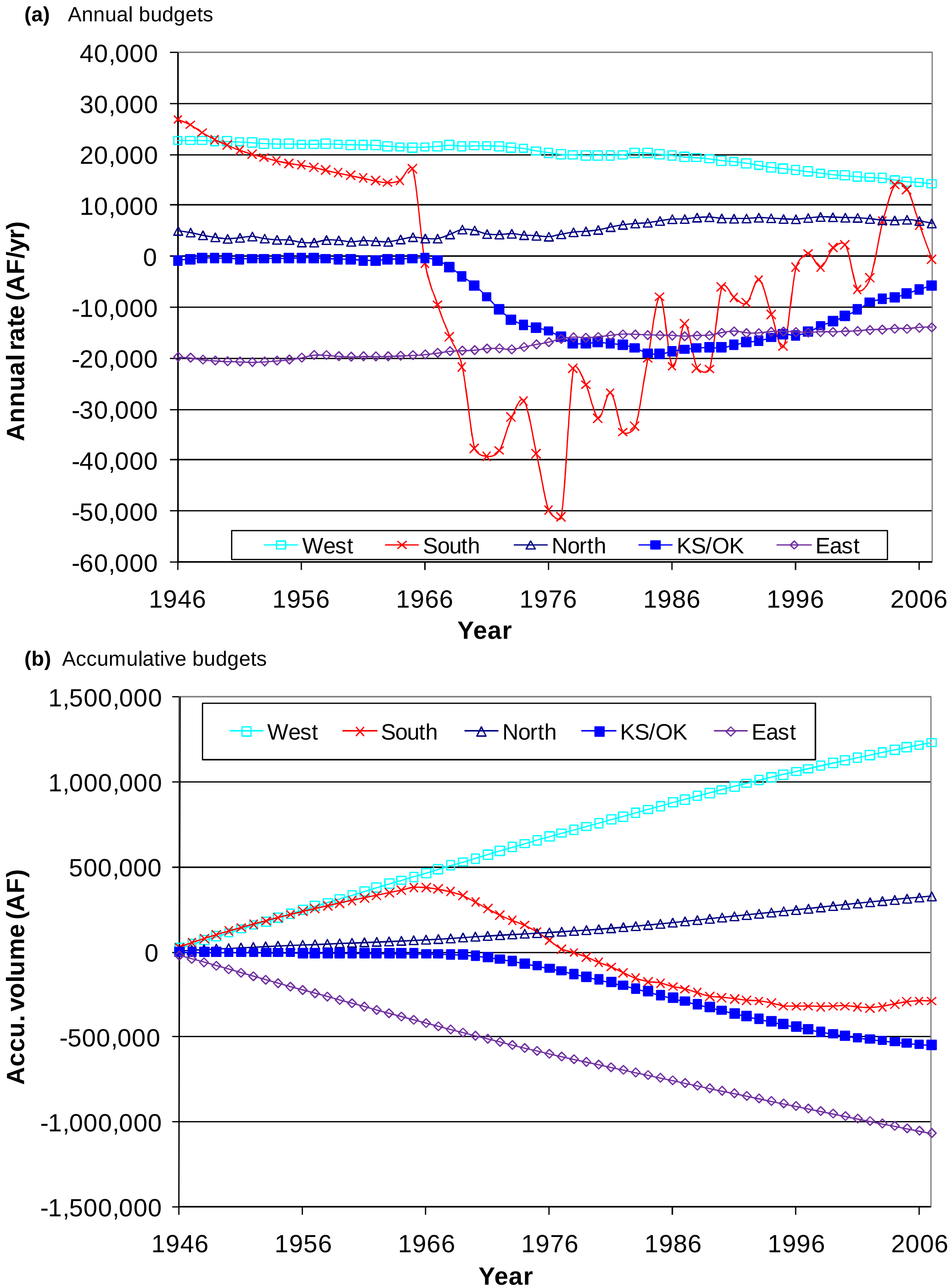


Figure 64. Ground-water budgets across the northern, eastern, southern, and western borders of the model, and the Kansas/Oklahoma state border within the model.

Figure 65 displays the ground-water budgets across the head boundaries specified around the edges of the bedrock area in Hamilton County (including portions in Kearny and Stanton counties, Kansas, and Prowers County, Colorado), Hodgeman County (including portions in Ford and Finney counties) and Clark County (including portions in Meade County). See Figure 44 for the locations of these different head boundaries. As in Figure 64, positive values mean that ground water moves from these specified head boundaries into the HPA. For the bedrock edge in the Hodgeman County area, the annual flow rate is slightly below zero between predevelopment and 1967. After 1967, the rate becomes positive and increases until it becomes nearly constant from the early 1990s through 2007. Between predevelopment and 2007, the cumulative volume of water that flows from the Hodgeman County bedrock area into the aquifer is 240,000 acre-ft. For the bedrock edge in the Hamilton County area, the annual rate of ground-water movement is negative through most of the simulation period, and only becomes positive after 1996. In 2007, the aquifer gains water from the bedrock at a rate of 2,970 acre-ft/year. The overall loss of ground water into the bedrock area between predevelopment and 2007 is 366,000 acre-ft. For both the Hodgeman and Hamilton areas, the change in the average direction of ground-water flow across the bedrock edges is primarily due to the continuous decline of ground-water levels in the HPA. As water levels continue to decrease, the rate of ground-water movement across these edges is expected to continuously increase slowly. For the bedrock edge in the Clark County area, the rate of ground-water movement is consistently negative, indicating that the aquifer is discharging water into the bedrock area throughout the simulation period. Between predevelopment and 2007, a total of 884,000 acre-ft of water flows from the aquifer into the Clark County bedrock area.

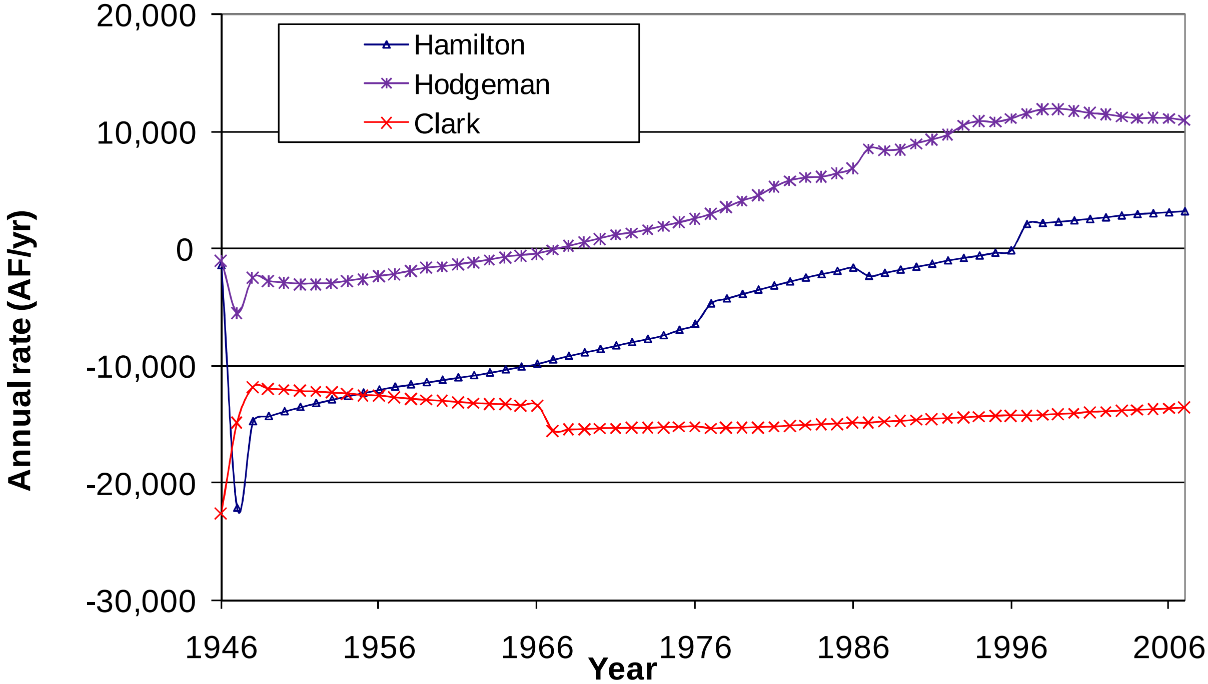
Model component budgets

Figure 66 presents the ground-water budgets for different components, including total recharge (the sum of irrigation-enhanced precipitation recharge and ditch-diversion and ground-water pumping return recharge), evapotranspiration (ET), flow produced by time-varying specified head boundaries, stream-aquifer interactions (i.e. discharge to and leakage from streams), aquifer storage decline, and ground-water pumping. Also included in the figure is the recharge solely from precipitation (without that induced from irrigation return flows). The 62 years shown include predevelopment (represented by 1946) and the transient period 1947-2007.

Precipitation recharge remains relatively constant throughout the transient simulation (Figure 66a). If the mean rate of precipitation recharge (265,000 acre-ft/yr for the active cells) for the 62 years is divided by the active cell area of 12,083 mi^2, the average recharge rate across the model is equivalent to about 0.41 in/yr. This value is similar to the 0.37 in/yr estimated by Sophocleous (2004) for the HPA in western Kansas based on data from KGS, KWO, and USGS publications. If the values from the USGS publication (Hansen, 1991) for the 12 counties covered completely or partially by GMD3 are averaged, the precipitation recharge estimate is 0.70 in/yr.

The line for total recharge in Figure 66a shows a gradual increase between predevelopment and the middle 1960s caused by the additional recharge associated with irrigation. As ground-water pumping activities begin to intensify after the middle 1960s, the induced recharge becomes more substantial until the late 1970s when it plateaus. After the early 1990s, as irrigation efficiency improves, the return recharge, and therefore the total recharge, begins to decline. In 2007, the total recharge rate is about 457,000 acre-ft/yr as compared to the annual rate of precipitation-only recharge of 256,000 acre-ft/yr. The 2007 total and precipitation-only rates are equivalent to 0.71 in/yr and 0.40 in/yr, respectively.

(a) Annual budgets



(b) Accumulative budgets

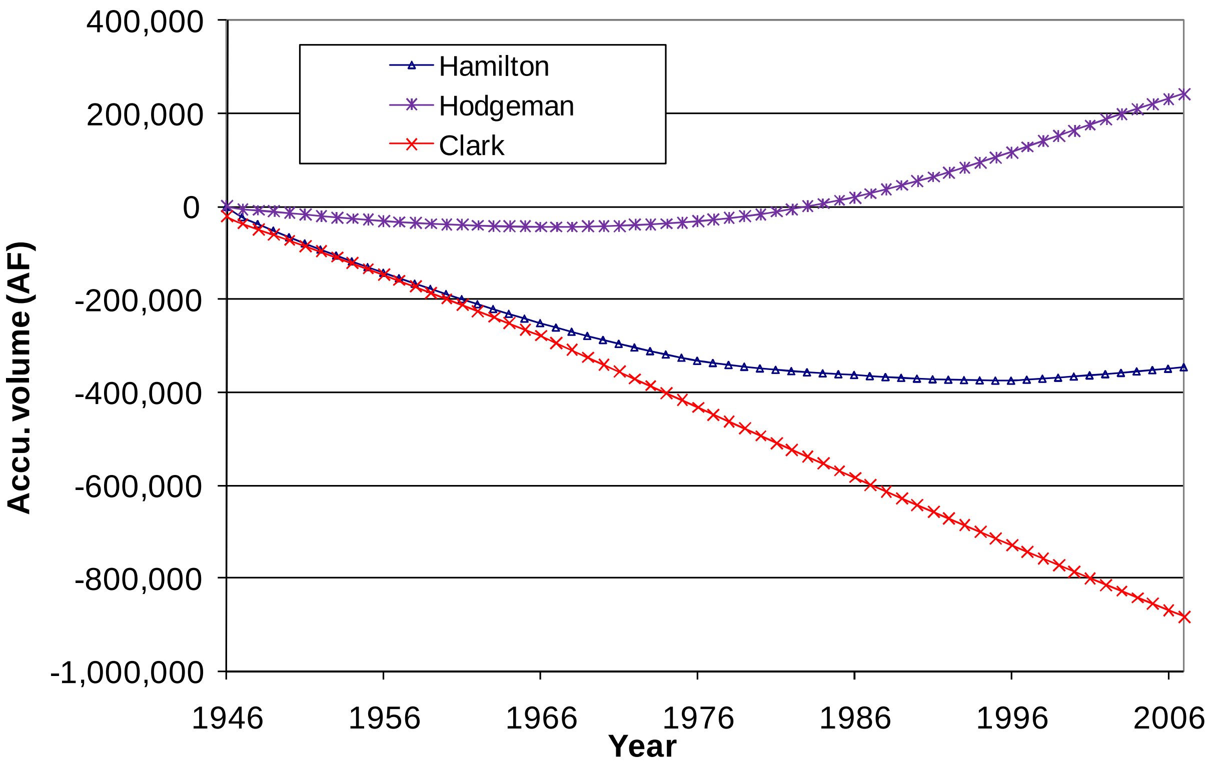


Figure 65. Ground-water budgets across different internal head boundaries.

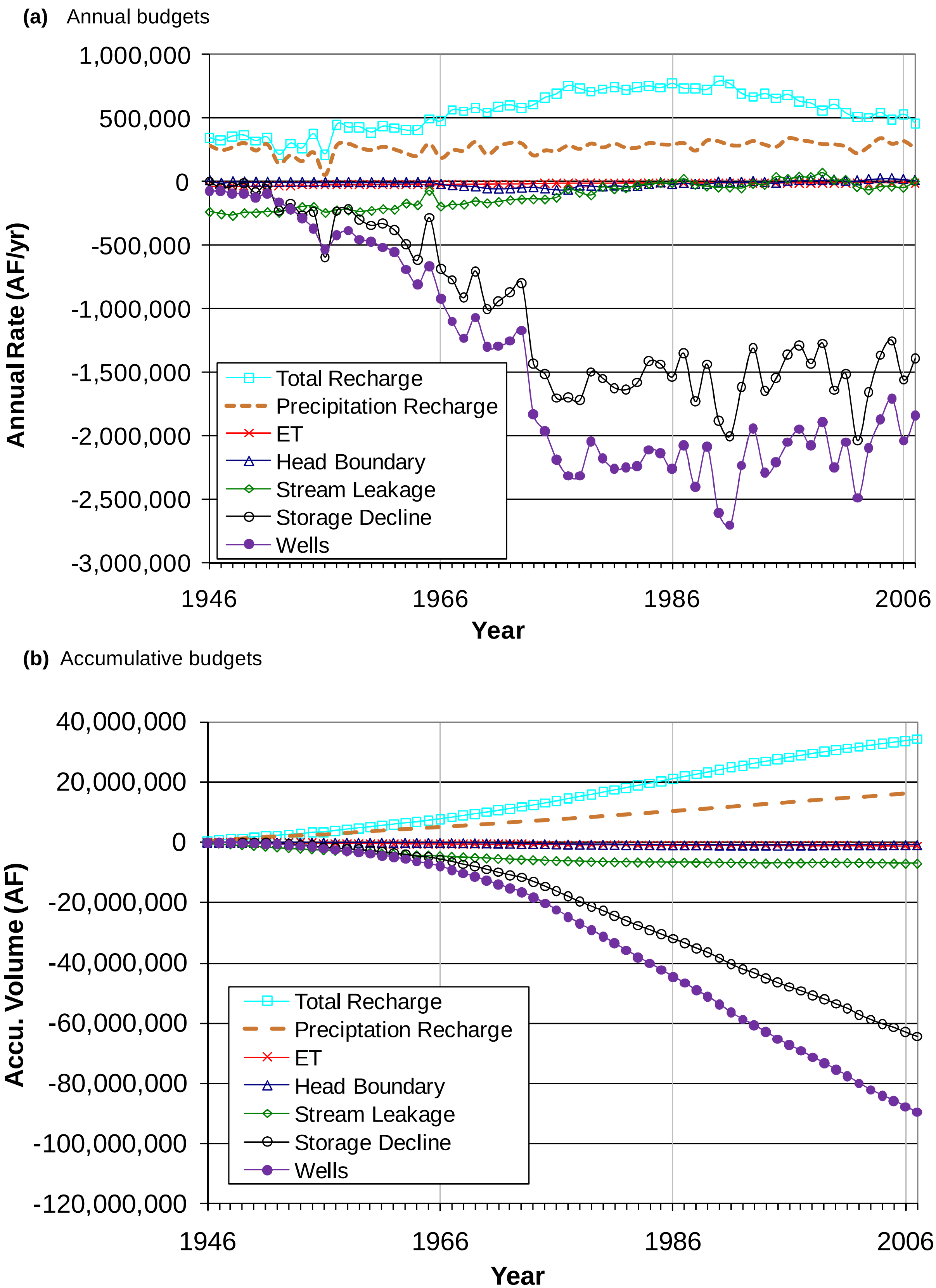


Figure 66. Ground-water budgets for different aquifer components.

The overall budget of ground water flowing across different specified head boundaries is close to zero because the amount of water that moves into the model through the head boundaries is balanced by the water that moves out. However, during the mid-1960s to the mid-1980s, a small net amount of water flows out of the model domain (negative values in Figure 66a). The amount of ground water lost to ET is minimal because the depth to water is below the extinction depth across nearly all of the model area. The model developed in this project only simulates the portion of water that moves from the aquifer to the atmosphere though the ET process. The ET loss of irrigation water at the land surface is not included in this model, although it is indirectly considered in the efficiency values of system types in the irrigation recharge calculation.

The declining ground-water levels have substantially affected stream-aquifer interactions in the model area. In the predevelopment period, ground-water levels are high enough to discharge a relatively large amount of ground water into the streams (negative values in Figure 66a). As ground-water levels decline, the rate of ground-water discharge decreases until it essentially becomes zero in the early 1980s. Between the early 1980s and 2007, the net rate of ground-water discharge is close to zero in the model. During this period, the amount of ground water that flows from the aquifer to the Cimarron River and Crooked Creek is approximately equal to the water that flows from the Arkansas River into the aquifer.

Ground-water pumping (designated as "Wells" in Figure 66) is comparatively small in predevelopment time. Starting in the early 1950s, the annual amount of pumping becomes noticeable and continually increases (Figure 66a). During the early to middle 1970s, the ground-water pumping rate abruptly increases. From the mid-1970s to the mid-1990s, the trend in the annual pumping is generally constant although it varies appreciably. During the last decade of the modeled period, a small decreasing trend occurs in the annual pumping rate. In 2006 and 2007, the annual pumping rates are 2,040,000 and 1,840,000 acre-ft/yr, respectively. For the majority of simulated years, the annual rate of ground-water pumping far exceeds the total recharge rate, resulting in a substantial amount of loss in aquifer storage and, therefore, water-level declines. Between the late 1970s and 2007, the simulated rate of aquifer loss averages about 1,600,000 acre-ft/yr. In 2006 and 2007, the aquifer loses water at annual rates of about 1,570,000 and 1,400,000 acre-ft/yr, respectively.

The cumulative pumping of ground water is 89,600,000 acre-ft at the end (2007) of the simulation period (Figure 66b). This compares with the 2007 cumulative values of 34,100,000 acre-ft for total recharge and 7,080,000 acre-ft for net discharge to streams simulated in the model. The cumulative amounts of net boundary flows and ET are both near zero relative to the other components in Figure 66b. The net effect of the pumping and the other model components is a cumulative storage loss of 64,500,000 acre-ft from the HPA. If the net discharge to streams for predevelopment conditions (1946, 238,000 acre-ft/yr) in the model were constant throughout the model period (1946-2007), the cumulative amount of net discharge to streams would have been 14,760,000 acre-ft (the predevelopment rate multiplied by 62 years). Therefore, the model predicts that water-level declines in the HPA have captured about 7,680,000 acre-ft (which is calculated from 14,760,000 – 7,080,000 acre-ft) of stream discharge that would have left the model domain in the absence of the water-level declines. Without this capture, the aquifer storage loss would have been approximately 12% greater than simulated.

Aquifer storages were calculated for different times and regions based on the simulated water levels and calibrated specific yield values for different PST+ lithology synonymy groups. The total aquifer storage calculated for the predevelopment simulated water levels is 226,780,000 acre-ft based on all of the active model cells (including the specified-head cells). The calculated storage at the end of 2007 for the same model cells is 160,371,000 acre-ft. In these calculations, if the simulated water level was below the bedrock surface in a model cell, the saturated HPA thickness and the aquifer storage are assigned zero for that cell. The decline in ground-water storage, 66,409,000 acre-ft, comprises 29.3% of the simulated predevelopment storage. In comparison, if a contoured water-level surface based on measurements is used to compute storage for the same model cells, the total storage volumes for predevelopment and 2007 are 223,981,000 and 159,917,000 acre-ft, respectively. The decrease in aquifer storage using measured data is 64,064,000 acre-ft, which is a decline of 28.6% from the predevelopment value. The storage volumes from the model and estimated from observations for the entire model domain differ by only 1.2% and 0.3% for predevelopment and 2007 conditions.

The total storage volumes simulated for the GMD3 area within the model domain for predevelopment and the end of 2007 are 193,454,000 and 133,622,000, respectively, giving a storage decline of 59,832,000 acre-ft, which is 30.9% of the predevelopment value. The total storage volumes computed for the GMD3 area from measured water levels are 191,216,000 and 133,726,000 acre-ft for predevelopment and 2007, respectively. These values give a storage decrease of 57,490,000 acre-ft, which is 30.1% of the predevelopment volume. The storage volumes from the model and estimated from observations for the GMD3 area differ by only 1.2% and 0.1% for predevelopment and 2007 conditions. Thus, the model performs well for simulating aquifer storage changes with time.

Acknowledgments

The KGS modeling team acknowledges the cooperative agreement between the U.S. Bureau of Reclamation (USBR) and Kansas Water Office (KWO), which provided funding for the model construction phase of the project (the subject of this report). This funding included Kansas Water Plan funds. The constructed model is now being used to simulate future scenarios to provide information for planning and management of ground-water resources in Southwest Groundwater Management District No. 3 (GMD3). The work on the scenarios is being funded by the KWO and GMD3. The authors of this report acknowledge the contributions of several individuals at the Kansas Geological Survey to this project. Allen Macfarlane gave assistance on the PST+ database. John Woods assisted in selected data processing activities. Mark Schoneweis contributed to one of the graphics. Marios Sophocleous provided advice on HPA recharge.

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