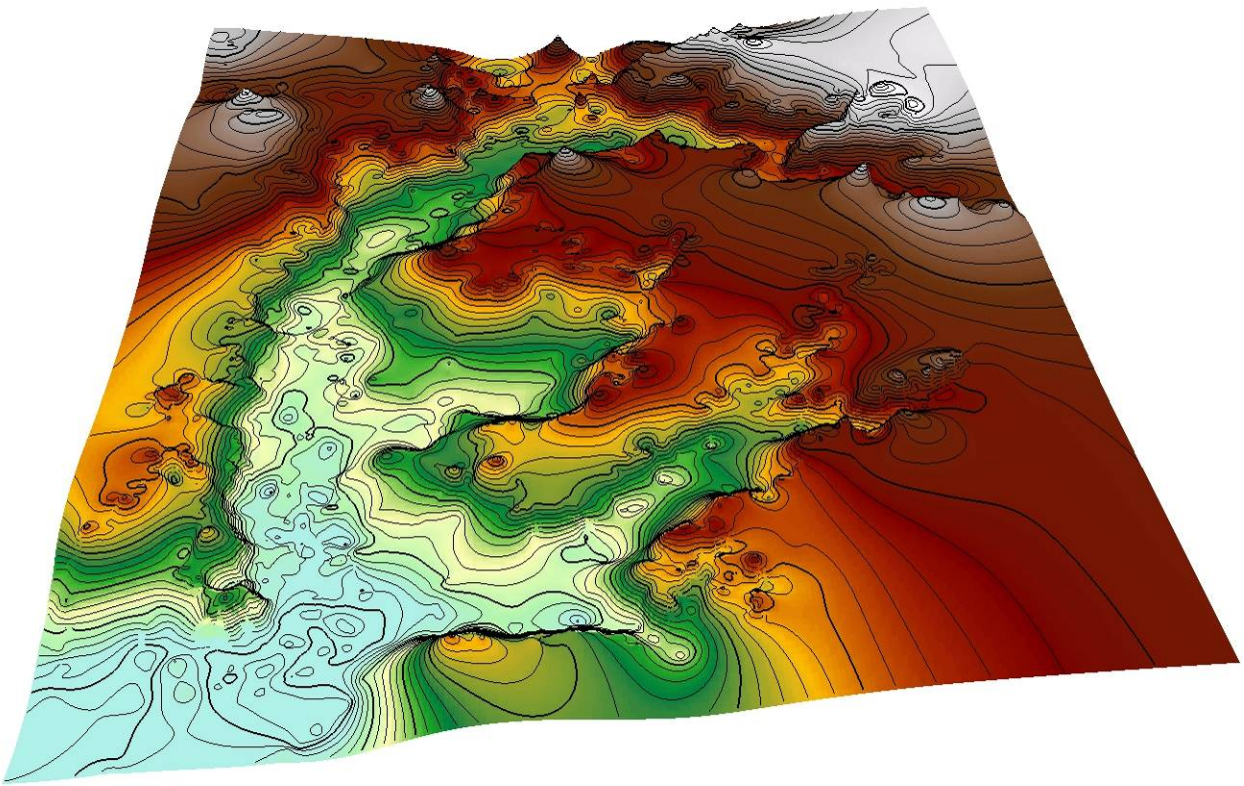
Smoky Hill River Valley Ground-water Model
Kansas Water Office Contract 07-136 (KAN46570)

Open File Report 2008-20

This project was funded by the State of Kansas Water Plan Fund



Brownie Wilson, Gaisheng Liu, Don Whittemore, and James Butler, Jr

GEOHYDROLOGY

KANSAS GEOLOGICAL SURVEY
The University of Kansas

Smoky Hill River Valley Ground-water Model
Kansas Water Office Contract 07-136 (KAN46570)

Open File Report 2008-20

This project was funded by the State of Kansas Water Plan Fund

Kansas Geological Survey, Geohydrology Section
University of Kansas, 1930 Constant Avenue,
Lawrence, KS 66047
http://www.kgs.ku.edu/

Disclaimer

The Kansas Geological Survey does not guarantee this document to be free from errors or inaccuracies and disclaim any responsibility of liability for interpretations based on data used in the production of this document or decisions based thereon.

Table of Contents

ACKNOWLEGMENTS

The authors of this report would like to acknowledge the contributions of several individuals to this project. Nick Schneider spent a considerable amount of time collecting well logs (both on- and off-site), reviewing and decoding the lithology, and preparing numerous fence diagrams. Allen MacFarlane helped guide Nick Schneider in the lithologic work, and he and Marios Sophocleous provided working knowledge and recommendations during the initial creation and structure of the model. Geoff Bohling conducted some preliminary statistical investigations and reviewed the methodology for the regressed pumping files. John Woods spent a significant amount of time identifying stream elevations along the surface drainage courses and provided data processing support. Mark Schoneweis contributed graphics and assisted with the completion of the final report.

The authors would also like to recognize the members of the Technical Advisory Committee, especially Martha Tasker for her oversight and knowledge of channel changes along the river and for providing additional data sources for the model. Brad Shoran provided valuable in-field observations and organized public meetings within the study area for presentation of the model results. We would also like to thank Peterson Drilling Inc. for sharing test-hole information used in our lithologic analysis. We also appreciate the participation of Kansas Water Office staff, especially Nathan Westrup and Chris Gnau, in organizing the TAC meeting, providing suggestions during the modeling process, and reviewing the final report. The KGS appreciates the funding from the Kansas Water Plan for supporting the project.

EXECUTIVE SUMMARY

The Kansas Water Office (KWO) contracted with the Kansas Geological Survey (KGS) in the spring of 2007 to develop a numerical ground-water model as a component of a larger, comprehensive review of the regional water supply in the Smoky Hill River basin. The objective of the model is to better understand the stream-aquifer interactions by simulating streamflow in the Smoky Hill River and ground-water levels in the surrounding alluvial deposits downstream of Kanopolis Reservoir. In addition, the model will be used to simulate climatic, streamflow, and pumping conditions and their effects on the surface- and ground-water supplies. The model was developed with input from a stakeholder advisory committee consisting of individuals from the KWO, the Kansas Department of Agriculture's Division of Water Resources, the City of Salina, water users in the Smoky Hill River valley, and other interest groups.

Since 1948, when construction on Kanopolis Reservoir was completed, the downstream reach of the Smoky Hill River and the hydrologically connected alluvial aquifer have seen extensive surface- and ground-water-right development, primarily for irrigation and municipal demands. The City of Salina, located just west of the confluence of the Smoky Hill and Saline rivers, owns the largest and some of the most senior water rights downstream of the reservoir.

The regional water supply is sensitive to periods of extensive drought and extreme flooding conditions, both of which have taken place in recent years. As recently as July 2006, extended periods of below-normal precipitation and resultant low streamflow in the Smoky Hill River prompted the City of Salina to seek protection of their water rights. The climatic conditions also affected reservoir levels in Kanopolis. Operating levels were far below normal in 2006, only to fill to flood-pool elevations in a matter of months during the spring of 2007.

The KGS model is an adaptation of MODFLOW, a widely-used software program for modeling ground-water flow and stream-aquifer interactions developed by the U.S. Geological Survey (USGS). The study area includes the Smoky Hill River and the hydrologically connected alluvial aquifer from the Kanopolis outlet tubes to the confluence of the Smoky Hill River with the Saline River just east of Salina. The model is subdivided into 11,484 rectangular grid cells, each 0.25-by-0.25-mile in size.

The model was calibrated to represent both a steady-state condition (predevelopment period of 1944 to 1947) and a transient condition (predevelopment period to the end of 2006). The transient portion models flow conditions that change over time and uses six-month time steps centered on the "growing" season (April to September) and "winter" season (October to March).

The ancestral channel of the Smoky Hill River is very different from its present channel location. In geologic history, the river used to flow south between present-day Marquette and Lindsborg into the Arkansas River. Geologic evidence indicates that headward erosion from a tributary to the Kansas River captured or cut off the Smoky Hill River, resulting in its present northward flow towards Salina. Geologic review of well logs indicates that the Arkansas River paleochannel hydrologically connects the Smoky Hill alluvium and the Equus Beds portion of the High Plains aquifer to the south. However, the connection appears to be small and insignificant in terms of water movement between the two aquifer units.

The lithologic review also shows much of the area contains a confining layer of low-permeability material (silts and clays) sitting on top of the permeable alluvial aquifer sediments (sands and gravels). This indicates that stream-aquifer interactions, although present and significant in

practical relevance to this model, may not be as strong as in other typical alluvial systems. In addition, the confining layer causes the aquifer to behave as a confined aquifer in some places.

The model was calibrated to match area-wide water levels, selected well hydrographs, and mean six-month streamflows at the Lindsborg and Mentor gaging stations on the Smoky Hill River. Steady-state or predevelopment results show that the river was primarily a gaining stream throughout the model area. The transient phase of the model indicates on average from 1962 to 2006 the river generally gained water from the aquifer except in the Salina area where the river begins to lose water to the aquifer. The river resumes its gaining state just east of the city extent to its exit from the model area.

No wells in the model area contain long-term depth-to-water records over the entire transient period. To calibrate the model to water-levels, well groups (wells located within proximity to each other and whose combined measurement histories provide an extended timeline) were selected throughout the valley and in the Equus Beds aquifer. The model-simulated water levels compare very favorably with observed water-levels within the core areas of the alluvial aquifer (near the river and relatively higher saturated thicknesses) and less so in areas of little ground-water development near the alluvial aquifer edges or in the upland terrace deposits where the permeable sediments are thin.

Long-term recharge to the aquifer system is estimated to be in the 1 to 1.5 inch range. During the transient phase of the model, recharge is computed based on the total precipitation in each stress period. The transient portion of the model indicates there is an overall slight decline in net storage of the aquifer system from the predevelopment period (1944 to 1947) to 2006 and an increasing trend in ground-water development.

Two scenarios were requested by the KWO and simulated with the calibrated transient model, both of which were based on a non-traditional but innovative management approach. The scenarios were based on a “back calculation” approach of repeating climatic conditions from 1948 to 2006 with present day water demands. Under the first scenario, primary surface-water inflows to the model (e.g., releases from Kanopolis) were systematically adjusted each year until a target low-flow rate (20 ft^3/sec, provided by the KWO) for the Smoky Hill River was achieved near Salina. Out of the 118 six-month time steps in the model, 63 required some amount of flow to be released from Kanopolis Reservoir in order to achieve the target flow near Salina while maintaining the 2006 level of water right development. The second scenario simulated the flow rate near Salina again by repeating climatic conditions from 1948 to 2006 with no surface-water inflows (e.g., no water being released from Kanopolis) and no ground- or surface-water pumping. In the second scenario, the target flow of 20 ft^3/sec near Salina was not achieved in 30 of the 118 model time steps.

INTRODUCTION

The Smoky Hill River enters western Kansas in Wallace County, just south of Goodland, and runs generally due east for approximately 280 miles (over 450 river miles) to its confluence with the Republican River, at which point begins the Kansas River. Over this course, the Smoky Hill River drains an area of about 8,180 square miles and contains two federal irrigation and/or flood control projects – the Bureau of Reclamation's Cedar Bluff Reservoir and the Corps of Engineer's Kanopolis Reservoir (KWA, 2005).

Since 1948, when construction on Kanopolis Reservoir was completed, the downstream reach of the Smoky Hill River and the hydrologically connected alluvial aquifer have been extensively developed for surface- and ground-water rights, primarily for irrigation and municipal demands. The City of Salina, located just west of the confluence of the Smoky Hill and Saline rivers, owns the largest and some of the most senior water rights downstream of the reservoir.

In 2002, the State purchased water storage through the Water Marketing Program of the Kansas Water Office (KWO) for anticipated future municipal and industrial water supply needs. Currently, only the Post Rock Rural Water District has contracted for water from this supply. Whereas releases from the reservoir for the Water Marketing Program are protected under State law, other releases – specifically, instream flow from Corps-owned storage – are not. Instream flow is subject to consumptive use by existing water rights, which can reduce the intended downstream benefit.

The regional water supply is sensitive to periods of extensive drought and extreme flooding conditions, both of which have taken place in recent years. As recently as July 2006, extended periods of below normal precipitation and resultant low streamflow in the Smoky Hill River prompted the City of Salina to seek protection of their water rights. The climatic conditions also affected reservoir levels in Kanopolis. Operating levels were far below normal in 2006 only to fill to flood-pool elevations in a matter of months during the spring of 2007.

Project Objectives

The KWO contracted with the Kansas Geological Survey (KGS) in the spring of 2007 to develop a numerical ground-water model as a component of a larger, comprehensive review of the regional water supply in the Smoky Hill River basin. The objective of the model is to better understand the stream-aquifer interactions by simulating streamflow in the Smoky Hill River and ground-water levels in the surrounding alluvial deposits downstream of Kanopolis Reservoir. In addition, the model will be used to simulate climatic, streamflow, and pumping conditions and their effects on the surface- and ground-water supplies.

The project period covered March 2007 to December 2008. The calibrated transient model was completed in July 2008. The final report was completed in December 2008.

Model Oversight

As part of the model development process, the KWO formed a Technical Advisory Committee (TAC) to oversee the project. The TAC met several times in Topeka and the meetings included conference calls and internet-based display options that allowed for Powerpoint computer displays to be viewed by individuals outside of Topeka. Members of the TAC included staff from the KWO, the Topeka headquarters and Stockton field office of the Kansas Department of Agriculture - Division of Water Resources (KDA-DWR), the Salina City Manager, several irrigators and water right holders in the model area, along with individuals from the Kansas Farm Bureau, Kansas Livestock Association, and Burns and McDonnell.

The KGS presented the results of the model midway through the development process at an “Irrigators and Water Users Information Meeting” in Assaria, Kansas, in February 2008. The final calibrated model and scenario results were presented at the Smoky Hill–Saline Basin Advisory Committee meeting in October 2008, also in Assaria.

DESCRIPTION OF STUDY AREA AND GENERAL MODEL SETUP

The study area includes the Smoky Hill River and the hydrologically connected alluvial aquifer from the Kanopolis Reservoir outlet tubes to the confluence of the Smoky Hill River with the Saline River just east of Salina (Figure 1). The total area covered by the model is 699 square miles with 357 square miles in the active model area. The northern extent of Equus Beds Groundwater Management District #2 just crosses over the southern edge of the model area. Except for a small area around the town of New Gottland, the entire active area of the model area falls within the KWO Smoky Hill-Saline Basin.

Previous Geohydrologic Studies

Investigations of the geohydrology for parts of the study area are described in a series of KGS bulletins and reports. Williams and Lohman (1949) reported on the geology and ground-water resources for south-central Kansas, which includes part of the model area, specifically McPherson County. Latta (1949) reviewed the ground-water conditions in the Smoky Hill River valley in Saline County and the region north and east of the model area. These two studies provided numerous predevelopment water-level measurements as well as lithologic records that were used to develop the permeable zone in this model. Finally, Bayne et al. (1971) reported on the geology and water resources in Ellsworth County. At the time of this report, the KGS is in the initial phases of developing new geologic maps for Saline and McPherson counties.

Physiographic Setting

The majority of the model area lies in the eastern portion of the Smoky Hill physiographic province. This hilly region is generally capped with sandstone formed by sediment from shallow seas present during the Cretaceous Period, roughly 100 million years ago. These rugged hills are often known as Dakota sandstone country. The Smoky Hill River is a meandering stream in a relatively flat valley ranging in width of just over one mile below Kanopolis to two to three miles south of Salina. The alluvial and upland terrace deposits in the valley compose the active area of the model. The inactive area located along the eastern edge of the model area is formed by shale of the Wellington formation overlain by Kiowa Shale (Latta, 1949).

The very southern extent of the model area lies in the Wellington-McPherson Lowlands physiographic province and contains the northern extent of the Equus Beds aquifer. This aquifer sub-system of the High Plains aquifer is made up of unconsolidated silts, sands, and gravels and is an excellent source of water. The Pliocene- and Pleistocene-age deposits were named for fossils of Ice Age horses that were found among the unconsolidated deposits (*equus* is the Latin word for horse).

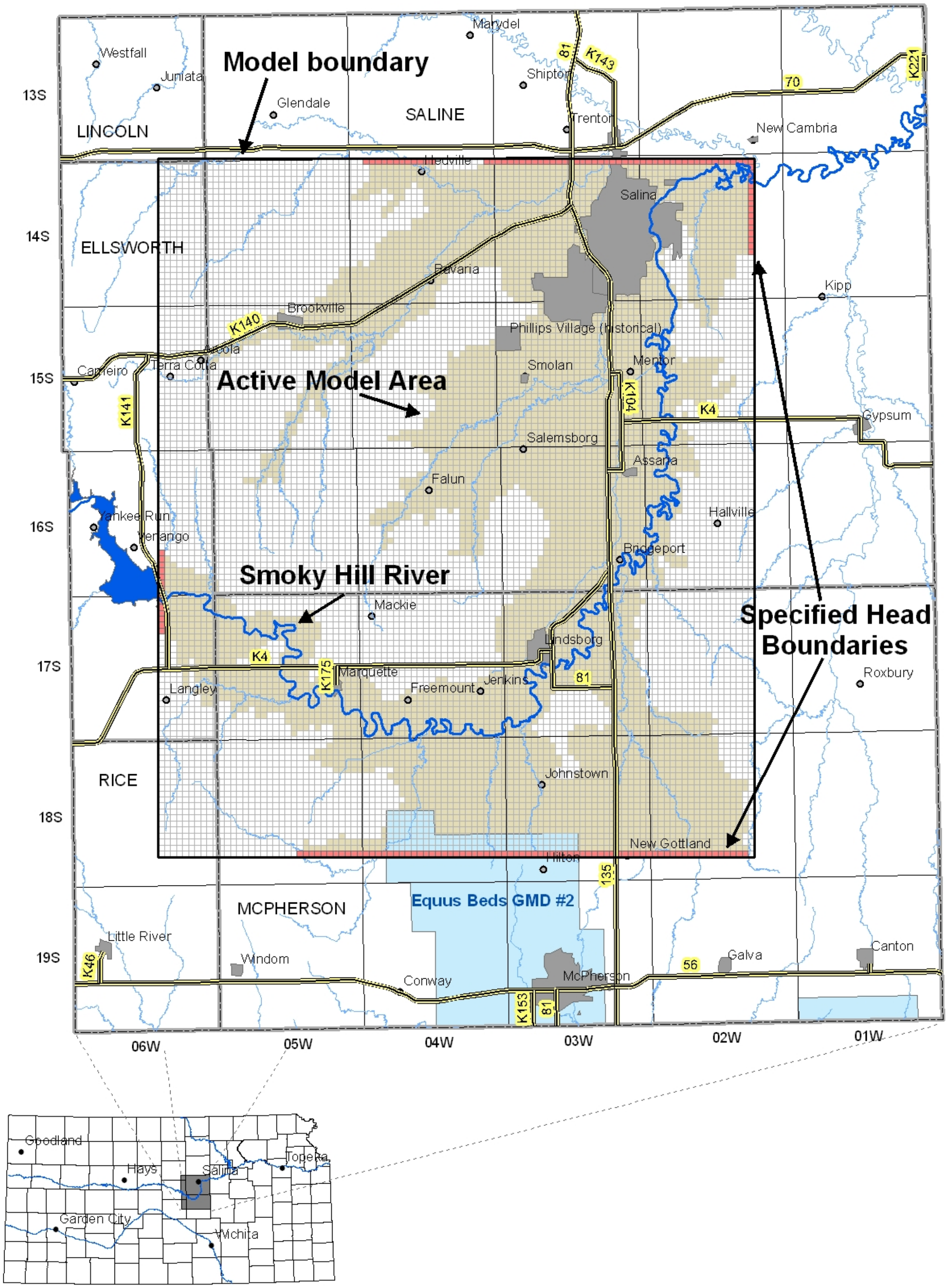


Figure 1. Smoky Hill River and model boundary.

Model Design

The ground-water flow model used 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 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 segments and reaches. A segment is a stream in which streamflow from surface sources (such as tributaries) is added at the beginning of the segment, or a diversion from which streamflow is subtracted at the end of the segment. A reach is the part of a segment that corresponds to an individual cell in the finite-difference grid. A segment consists of one or more reaches. Streamflow in a segment is accounted for by specifying inflow for the first reach and then computing streamflow to the adjacent downstream segment as equal to the upstream inflow plus or minus leakage from or to the aquifer along the segment. 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 the model results. Due to the employment 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 graphs.

The model uses uniform and equally spaced cells, 0.25 x 0.25 miles in size. There are 116 rows and 99 columns resulting in 11,484 individual model grid cells. The model uses one convertible layer that allows both confined and unconfined properties of the aquifer to be simulated, depending on water levels. Time-varying specified-head boundaries are located along the edges of the aquifer units, specifically the model edges of the Smoky Hill alluvial aquifer and the Equus Beds portion of the High Plains Aquifer to the south.

The lower boundary of the model is the top of shale or silty shale bedrock that has extremely low permeability and is treated as a no-flow boundary. The upper boundary of the model is the bottom of a low-permeability layer of fine-grained sediments (clay and silt categories) or land surface where that layer is not present. The presence of this overlying low-permeability layer causes the aquifer to behave as a confined system in some places and significantly reduced the rate of recharge into the underlying alluvial deposits.

The modeling work was divided into two major steps. First, a steady-state simulation was generated for the predevelopment period before 1948, during which large-scale, intensive pumping activities were not present. Second, a transient simulation was conducted for the period between 1948 and 2006 to model the historic evolution of the ground-water system and stream-aquifer interactions. The predevelopment step established the initial conditions for the subsequent transient simulation.

The model uses six-month time steps for its basis of computations. The months of April to September represent the “Growing Season” while October to March represents the “Winter Season”.

The model was calibrated to match area-wide water-levels, long-term hydrographs of selected wells, and flow conditions (especially low flow) in the Smoky Hill River. The USGS gaging stations at Lindsborg and Mentor were used specifically for streamflow calibration targets. Water level data for both the Smoky Hill River alluvial aquifer and the Equus Beds portion of the High Plains aquifer were used as ground-water calibration targets. Given the lack of monitoring wells containing long-term water levels in the area, groups of nearby wells were used to calibrate the model to changing water-level elevations over time.

Active Area and Model Zones

Most ground-water models of this type are broken down into “active” and “inactive” areas. Within inactive cells, there is presumably no flow whereas the actual ground-water calculations are only conducted within the active cells. In this study, due to the extremely low permeability of bedrock, a cell is defined as “inactive” when it contains greater than 50% bedrock outcrop in area. The number of active cells in the model is 5,862, giving a total active model area of 366.25 square miles, a little over half of the model domain.

Use of zones facilitates the calibration process for the model by allowing various hydrologic parameters to be customized for different regions within the study area. Based on the spatial patterns of the geology, soils, land use, and water levels (see section *Data Review and Setup* of the report), four zones were established to better represent characteristics of the aquifer (Figure 2). The zones represent the main alluvial aquifer split into upper and lower reaches, the Equus Beds portion of the High Plains aquifer, and the upland terrace deposits.

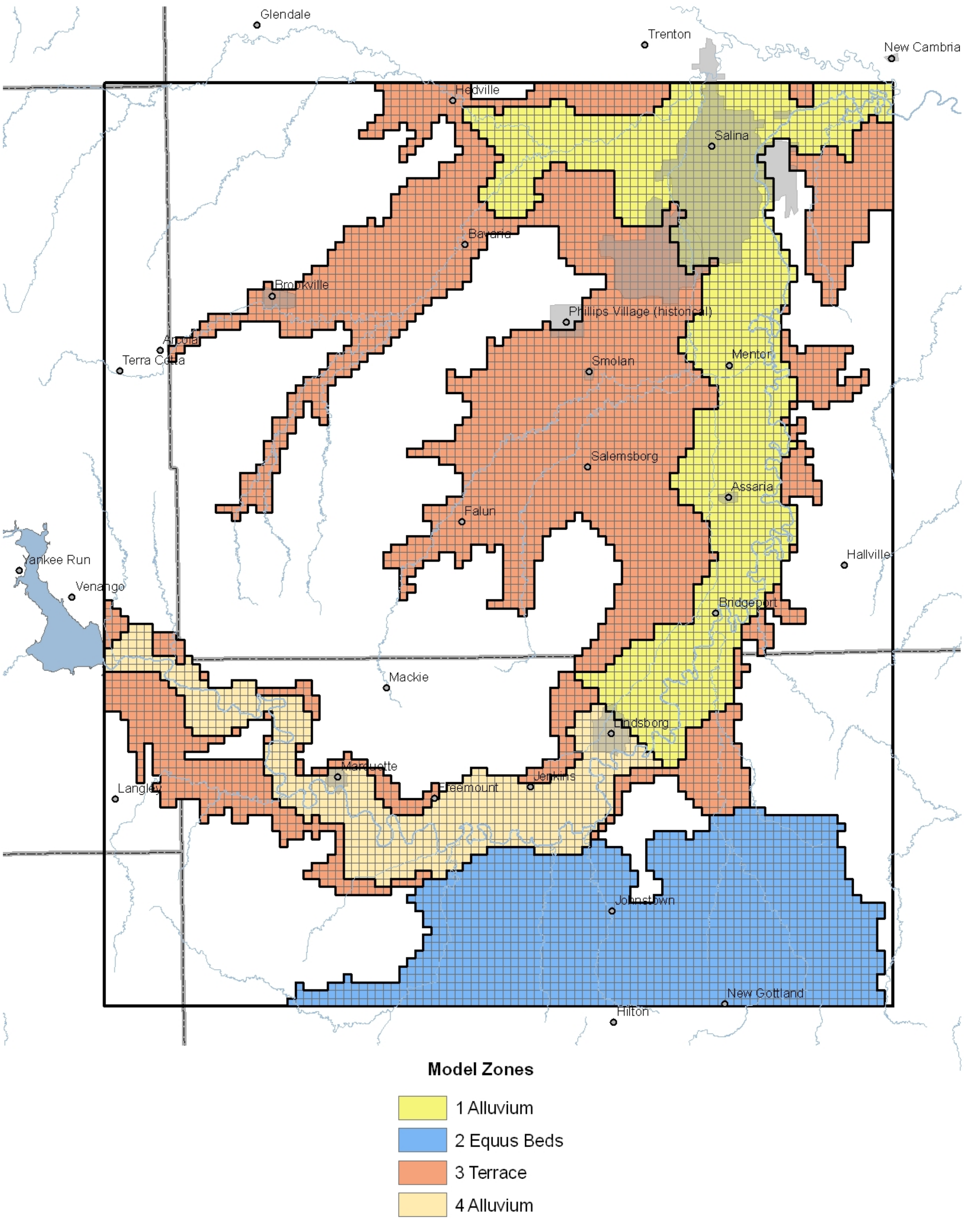


Figure 2. Model recharge and hydraulic conductivity zones.

REVIEW AND SETUP OF DATA PARAMETERS

Soils

Although published soil surveys only exist for Ellsworth County (Barker and Dodge, 1989) and Saline County (Palmer et al., 1992), detailed soils digital data tables are obtained from the Soil Data Mart (http://soildatamart.nrcs.usda.gov) of the USDA Natural Resources Conservation Service. This site contains detailed county-level data, often referred to as SSURGO data, which describe the tabular and spatial soil components across Kansas.

The soils in the model area generally are deep to moderately deep but often thin in the more sloping areas where sandstone outcrops are more common. Soils in the valleys are irrigable and have moderate infiltration (lower runoff) in comparison to the uplands (Figure 3). The soil data tables were queried primarily based on the hydrologic group codes and geomorphologic codes that generally indicate alluvial deposits (e.g., alluvial plains, ephemeral oxbow lakes, flood plains, river valleys, stream terraces, and valleys). This information was used largely in helping to define the active area and zones for the model.

Land Use / Land Cover

Grassland and cropland are the primary land-cover types over the model area. Grassland is found primarily in the upland, sandstone-capped hills bordering the river. A review of the Kansas Gap Analysis Project (Egbert et al 2001) shows that most of the acreage for the Conservation Reserve Program (CRP) is also located in the upland hills. Cultivated acreage exists mainly in the alluvial and terrace deposits of the Smoky Hill River valley, as well as in the southern area of the model where the High Plains aquifer region of the Equus Beds is located (Figure 4). The majority of the classified “cropland” cover types are located within the active area of the model.

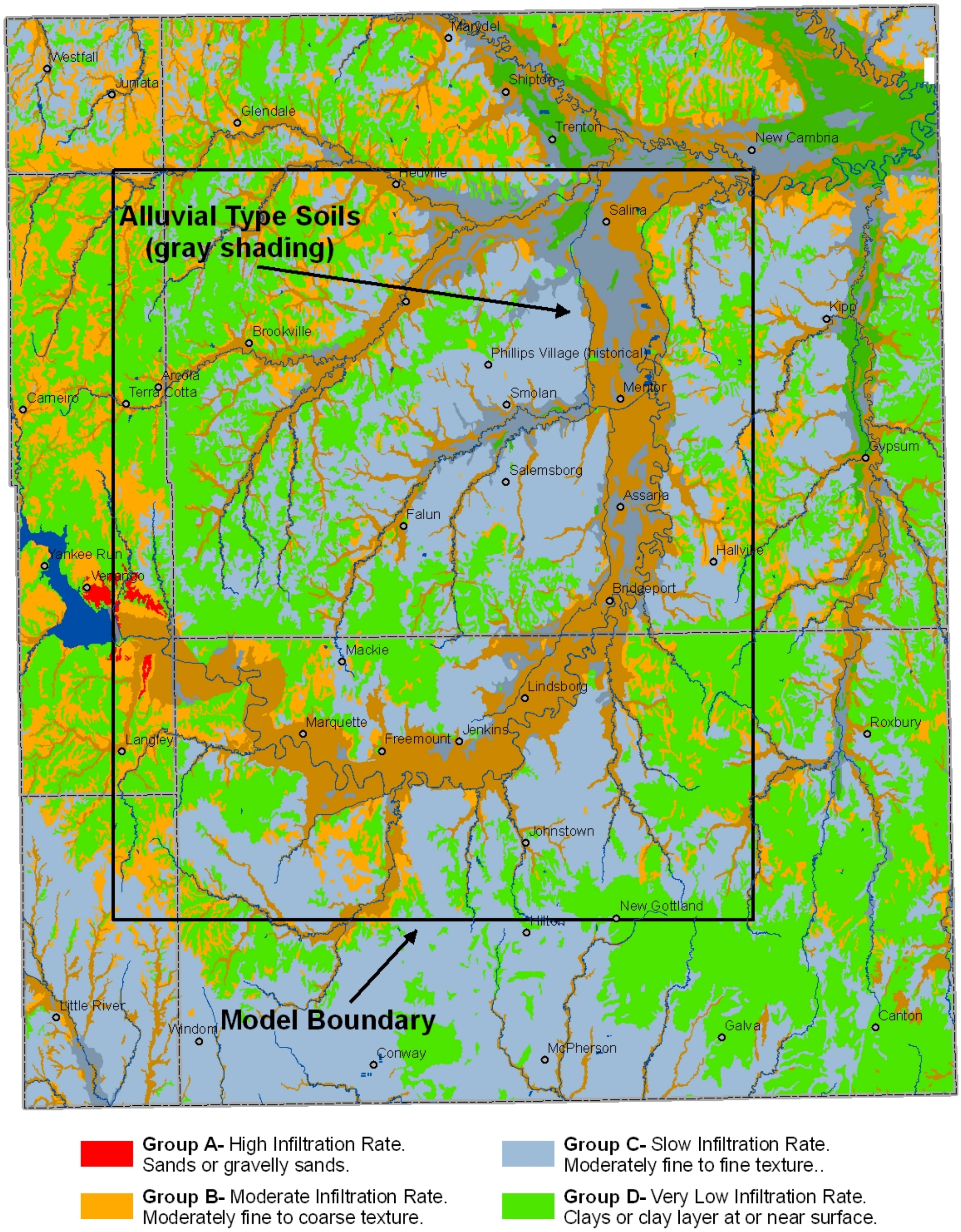


Figure 3. The four hydrologic soil groups and the alluvial type geomorphologic soils in the model region. The gray shading for the alluvial type soils is partially transparent and darkens the colors of the four soil groups where they overlap.

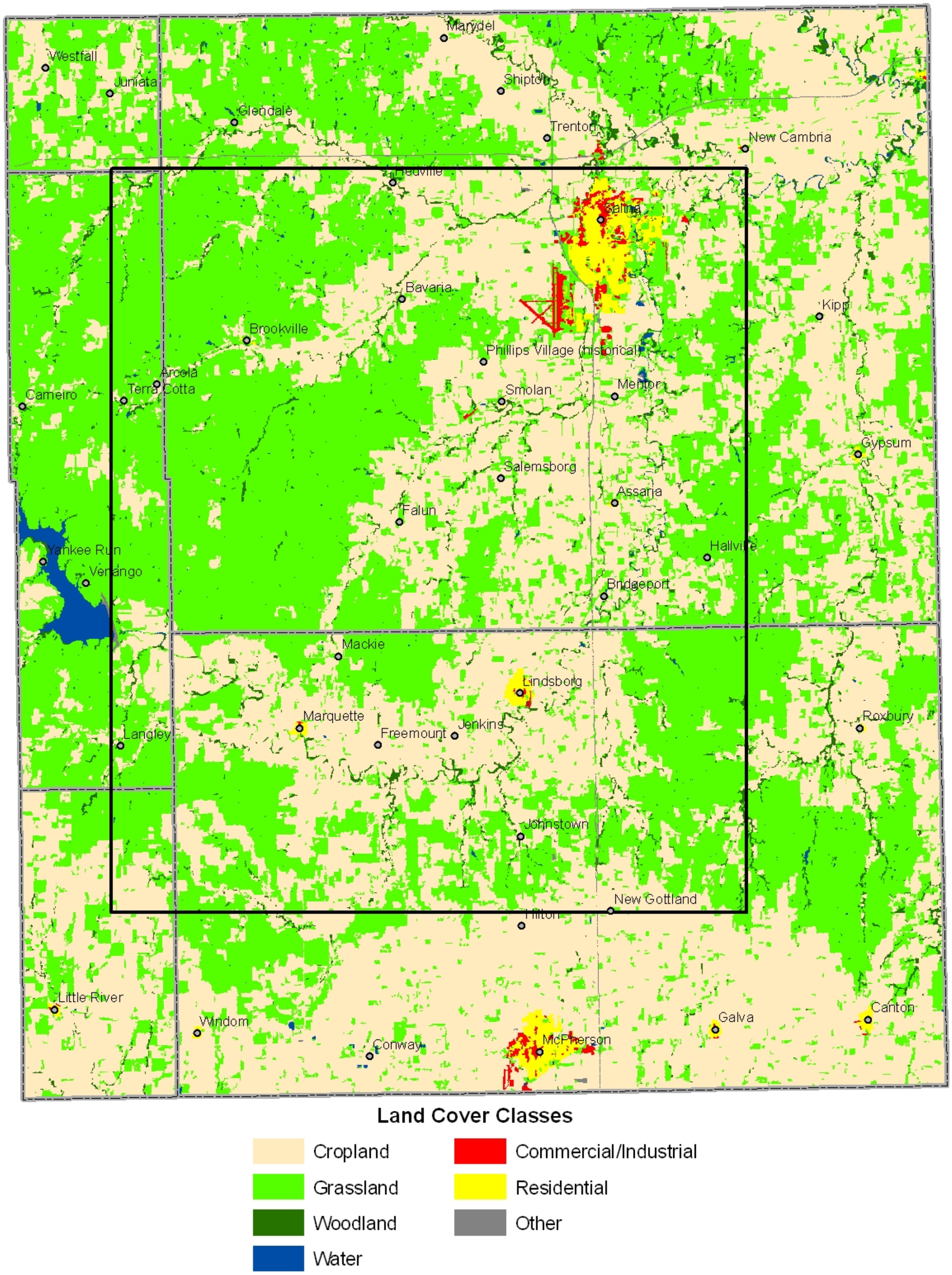


Figure 4. Land cover classifications from Landsat Thematic Mapper, 1991.

Precipitation

Long-term monthly precipitation data were obtained from the National Climatic Data Center (NCDC). This data set focused on NCDC site locations within 100 miles of the model domain. There are years when 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 4 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 2006, the annual precipitation, "seasonal" precipitation (monthly totals between April to September), and "winter" precipitation (monthly totals between October and November) were calculated for each station location. 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 2006 is 29.39 inches, with the majority of that amount falling during the months of April to September. The average precipitation over the "seasonal" or "growing" period of April to September is 21.03 inches (Figure 5). The lowest year of annual precipitation over the time period was 1956 with 15.99 inches and the highest occurred in 1993 at 50.83 inches.

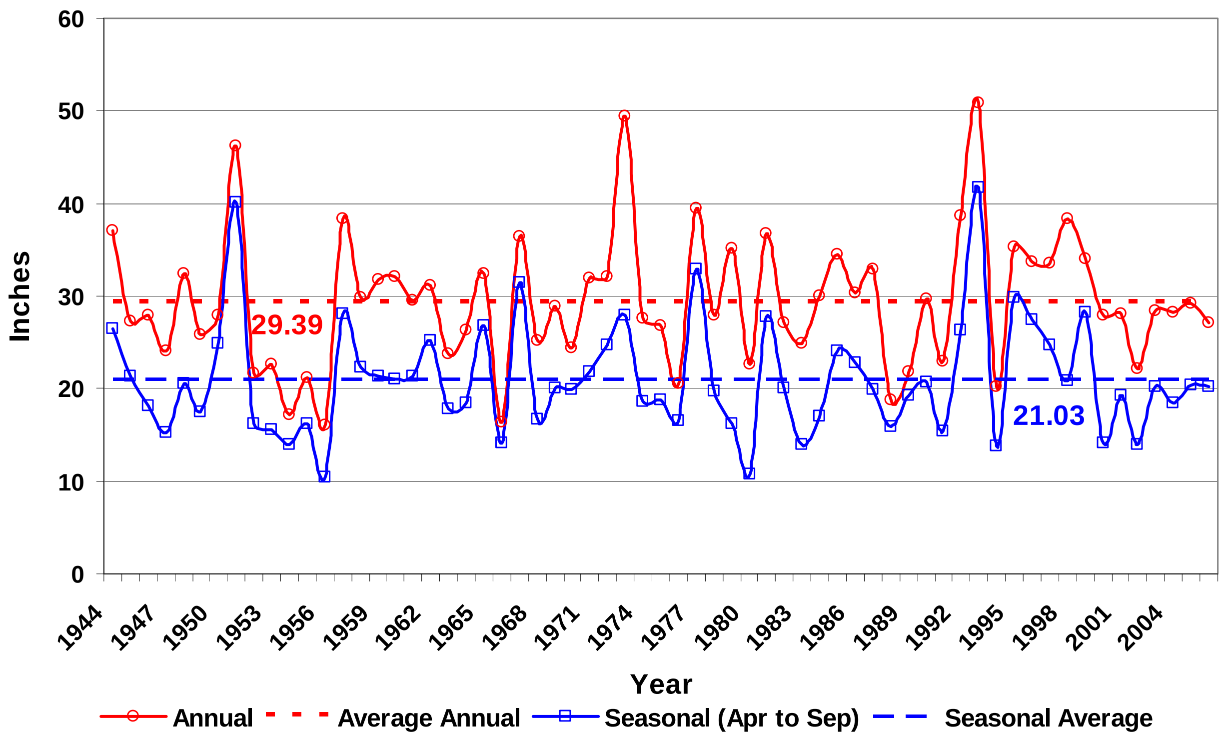


Figure 5. Interpolated annual and seasonal (April-September) precipitation totals 1944 to 2006.

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 6) are similar to those at the state-wide level. For example, lower precipitation levels generally occur along the western and southern edges of the model area and increase eastward to their maximum levels in the southeast, just as they do across the entire state of Kansas.

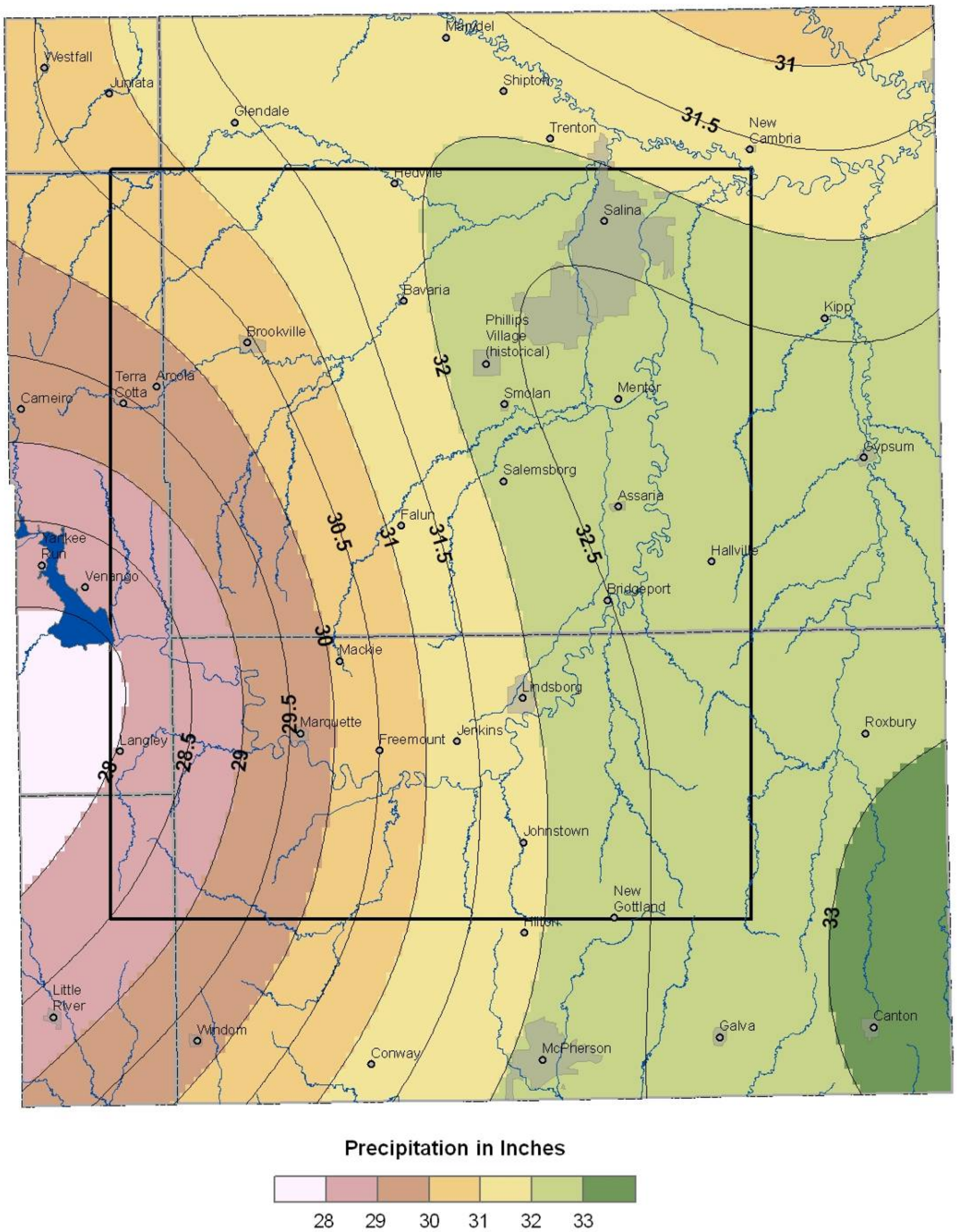


Figure 6. Interpolated normal precipitation (average 1971 to 2000).

Geology and Lithology

Bedrock

The outcropping bedrock in the model area includes Lower Cretaceous Series and Permian Leonardian Series strata (Figure 7). The Lower Cretaceous rocks are at the surface on the uplands in the western and a portion of the easternmost parts of the model area. The youngest exposed Cretaceous unit is the Dakota Formation that consists of sandstone bodies encased in mudstones (Macfarlane et al., 1998). The Kiowa Shale underlies the Dakota Formation and is primarily a shale but also contains some interbedded sandstone, siltstone, and shale. The transition to the underlying Cheyenne Sandstone is gradational with a downward decrease in the proportion of shale and increase in sandstone. Permian strata at the bottom of the Nippewalla Group and the upper part of the Sumner Group occur under the Cretaceous rocks and outcrop along the lower parts of the uplands on the west side of the model area. The bedrock underlying the alluvial deposits of the Smoky Hill River valley is primarily the Ninnescah Shale in the western part and the Wellington Formation in the eastern portion of the model area. Nearly all of the bedrock units underlying the alluvial and High Plains aquifers include shales or silty shales of low permeability. Thus, the expected rate of exchange of water between the bedrock and the overlying unconsolidated sediments is expected to be very low relative to the rate of movement of water in the unconsolidated aquifers.

Unconsolidated Deposits

The unconsolidated sediments in the model area range from remnants of the Ogallala Formation in northeastern McPherson County to recent alluvium along the floodplains of the Smoky Hill River valley and its tributaries (Figure 7). The High Plains aquifer in the southern part of the model area is primarily fluvial deposits of Pleistocene Series that range from clay to silt to sand to gravel. In general, the coarser sediments tend to be found deeper in the deposits. Eolian (wind deposited) loess covers much of the area of the High Plains aquifer in the southern model region. The alluvial sediments of the Smoky Hill River valley range from clay to gravel and generally have a distinct transition from sands and gravels in the lower part of the thicker alluvium to silts and clays in the upper part of the section. Thinner deposits of sand and gravel occur in the deepest parts of the alluvial terrace deposits to the west of the main valley of the Smoky Hill River and along Mulberry Creek. These deposits are also overlain by silts and clays. Further descriptions of the unconsolidated deposits are in Latta (1949) and Williams and Lohman (1949).

Bedrock surface

Data for the depth to bedrock were assembled from lithologic logs in publications and determined for all test-hole and well logs that could be readily located. The test-hole and well logs used included those from Latta (1949) and Williams and Lohman (1959) (129 logs) and in the water well completion records stored at the KGS (752 logs), supplemented by 14 logs obtained from Peterson Irrigation, Inc., in Lindsborg, Kansas, and information for 70 wells or test holes in reports by Wilson and Company for the City of Salina, for a total of 965 points. The elevation for the bedrock surface at the test-hole and well locations was determined by subtracting the depth to bedrock from the land surface elevation based on published survey data or estimated from a ten-meter resolution digital elevation model. Figure 8 shows the locations of the points for the different test-hole and well logs used in generating the bedrock surface map.

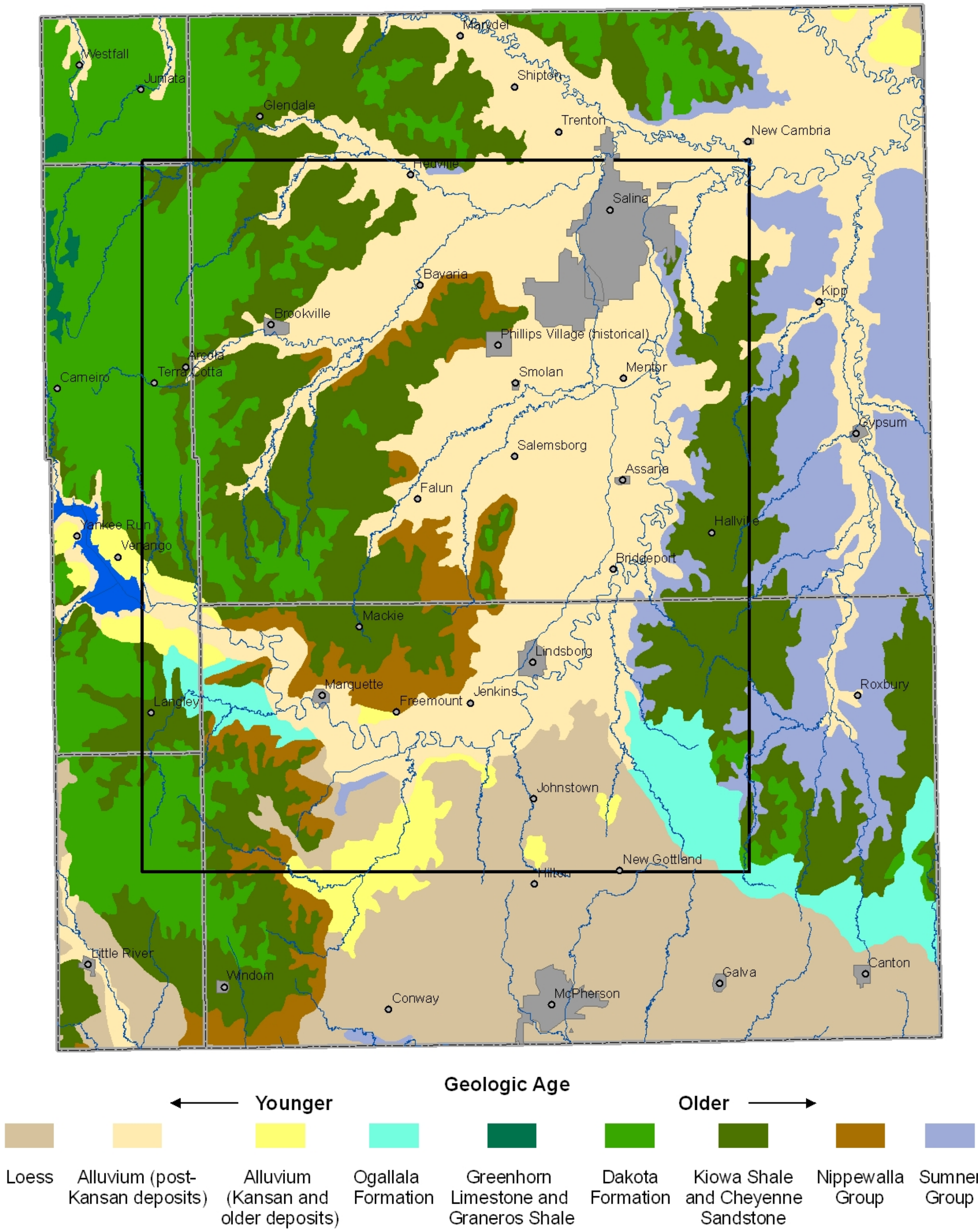


Figure 7. Surficial geology of the study area.

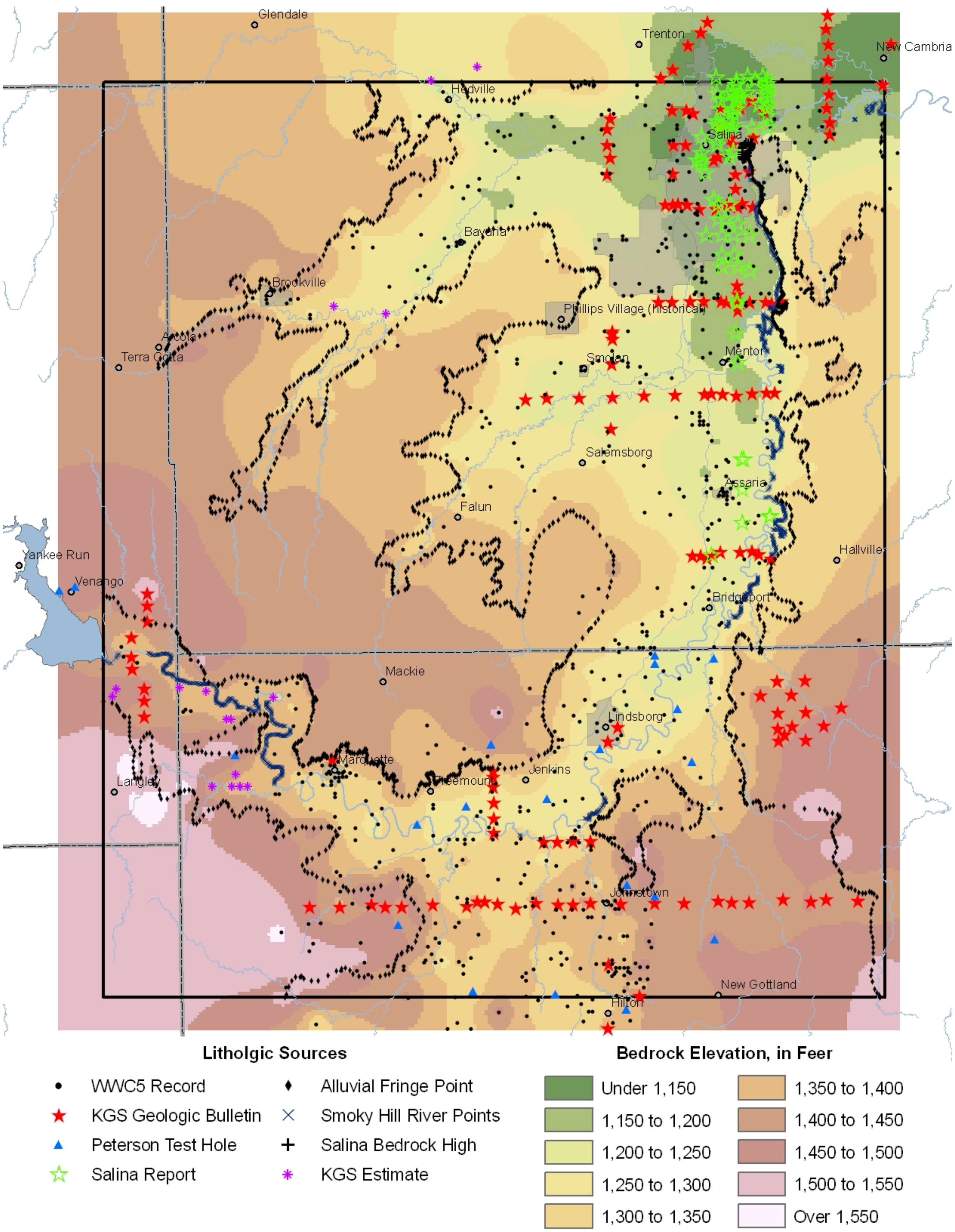


Figure 8. Elevation of the bedrock surface in the study area interpolated from well log data.

After an initial map of the bedrock surface was generated, additional elevation points were added to improve the map based on information for the area. The primary adjustment was to force the interpolation process to recognize the often distinct and abrupt valley walls of the Smoky Hill River valley. This was done by inserting into the interpolation the land surface elevation where bedrock crops out along the edge of the alluvium in the model area. These points are designated as alluvial fringe points in Figure 8 and appear as a string of points outlining the edges of outcropping bedrock. Flood control efforts within the City of Salina included cutting a channel for the Smoky Hill River through a bedrock nose on the east side of the City around 1960. Points around this bedrock high were manually digitized and added to the alluvial fringe points. Several regions within the area of unconsolidated sediments lack good well-log data, for example, within the Smoky Hill River valley downstream of Kanopolis Reservoir. In order to improve the bedrock surface within this area, several bedrock points were estimated based on well logs that did not penetrate or record bedrock (identified as “KGS Estimate” in Figure 8).

The bedrock surface in the model area ranges substantially in topography (Figure 8), from land surface to a little over 200 feet below the surface under sediments of the High Plains aquifer in the southernmost part of the model area. The average depth to bedrock is 51 feet with the majority of values falling between 20 and 80 feet. The elevation of the bedrock follows the same regional pattern as the land surface in that the highest bedrock elevations are found in the southwestern edge of the model and move progressively down-gradient to the lowest levels east of Salina. To better visualize the bedrock surface topography, a three-dimensional (3D) version of the map was generated (Figure 9). The 3D version was animated for one of the Technical Advisory Committee meetings for the study such that the view simulated flying through the bedrock valley of the Smoky Hill River.

Figure 9 shows two lows in the bedrock surface south of the Smoky Hill River valley. One or both of these cuts probably represent the ancestral paleovalley of the river during the early part of the Pleistocene Epoch when it flowed from the general area of the present river valley in the southwest part of the model area to the south between present-day Marquette and Lindsborg to form the beginning of the McPherson channel (Williams and Lohman, 1949). The McPherson channel substantially deepens farther south of the model area. This ancestral valley does not cut as deep into the bedrock surface near the Smoky Hill River as does the ancestral valley of the river as indicated in the figure. Alluvial sediments were later deposited into the paleovalley to produce part of the High Plains aquifer in northern McPherson County. Sometime during the Pleistocene, the stream occupying the part of the current Smoky Hill River valley downstream of Lindsborg cut farther headward until it captured the upstream portion of the Smoky Hill River. After the deposition of coarse-grained sediments, fine-grained sediments were spread across both the alluvial valleys of the Smoky Hill River and of the McPherson channel.

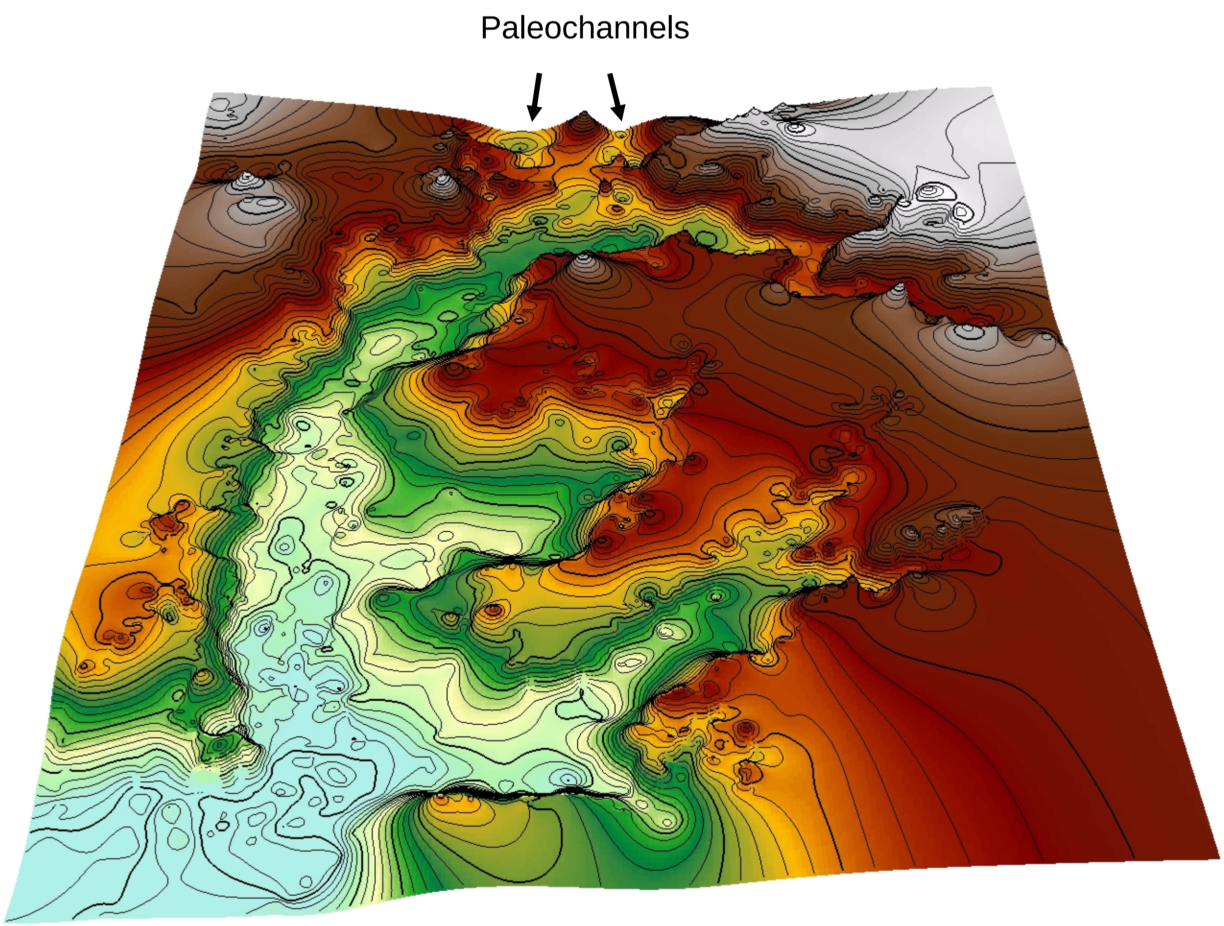


Figure 9. Three-dimensional view of the bedrock surface map, looking to the south. The two lows in the bedrock surface in the southernmost part of the model area are interpreted to be paleochannels, one or both of which were occupied by the ancestral Smoky Hill River when it flowed southward into the McPherson channel underlying the Equus Beds portion of the High Plains aquifer.

A factor in the location of the ancestral valleys, especially the north-south trend of the Smoky Hill River valley in the model area and along the McPherson channel, is the dissolution of salt beds in the Hutchinson Salt member of the underlying Permian Wellington Formation. The subsidence from the salt dissolution created low areas that contributed not only to the location of the valleys but also the thickness of the unconsolidated sediment deposits. Some of the undulations in the bedrock surface of the bottom parts of the Smoky Hill River valley (Figure 9) are caused by differences in the amount of subsidence from salt dissolution.

Aquifer characteristics

Lithology

As indicated above, sediments of the alluvial and High Plains aquifers in the model area consist of sands and gravels that make up the permeable part of the aquifer, and which typically rest on the bedrock surface, overlain by low permeability silts and clays. To characterize the framework of the alluvial and High Plains sediments, the lithology of 959 test-hole and well logs was classified into depth intervals of five categories (clay, silt/sandy clay, fine sand, coarse sand, and gravel) based on generally similar permeability. The upper silt and clay zone was found to be consistent enough across the model area to be considered a confining layer that decreases the rate of recharge and the amount of interaction with streams that do not cut through the layer. The classified lithologic data were used to construct 17 cross sections in which the five lithologic categories were color-coded. Figure 10 displays the areal location of the cross sections.

Figure 11 shows an example of a cross section extending across the Smoky Hill River valley near Lindsborg. The figure illustrates a zone of varying thickness of aquifer materials (fine sand to gravel categories) overlain by fine-grained sediments (clay and silt categories) within the valley. The higher elevations of the sides of the valleys have very little sediment and what sediment is present is typically clay or silt.

The elevation of the bedrock surface and the thickness of the unconsolidated sediments along the south side of the Smoky Hill River Valley between Marquette and Lindsborg were examined to determine the connection between the alluvial aquifer of the Smoky Hill River and the High Plains aquifer to the south. A review of the lithology shows only a relatively small connection between the two aquifers. For example, a north-south cross section passing through the west bedrock low along the southern model boundary (Figure 12) indicates only a small thickness of permeable materials resting on a bedrock ridge between the river valley and the High Plains aquifer. The thickness of the sediments to the south of the valley wall ridge varies substantially depending on where the cross section intersects a tributary valley or the start of the McPherson channel. Part of the thickness variation could also be due to past differential subsidence from Permian salt dissolution. The lithologic cross sections constructed for the southern part of the model area illustrate that any flow of water between the aquifers would be from the High Plains to the alluvial aquifer of the river valley. Given the thin connection between the aquifers, any decline in the water table of the High Plains aquifer would reduce or break the connection. The exact nature of this connection can only be identified by drilling new test holes to better determine details of the start of the ancestral McPherson channel.

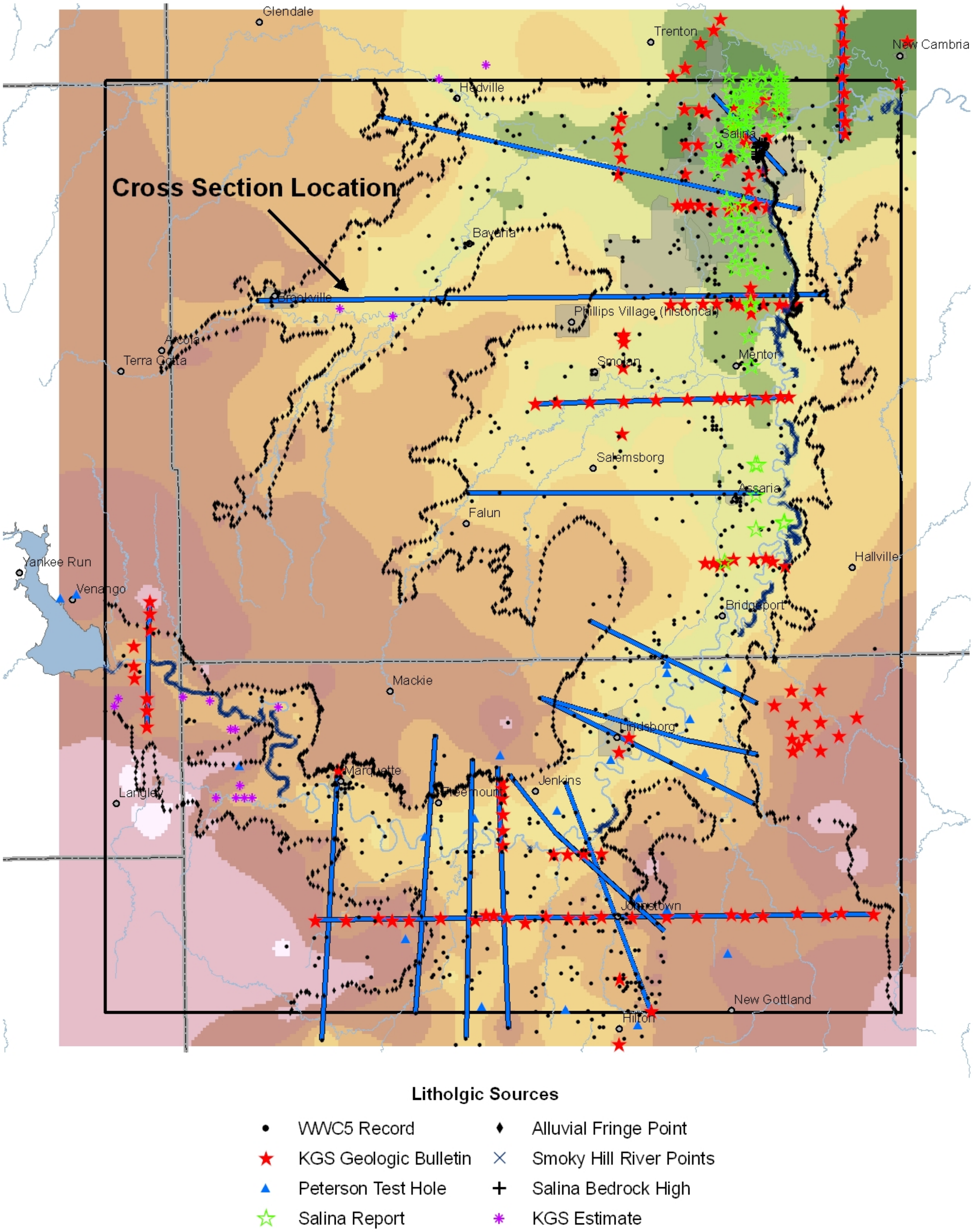


Figure 10. Locations of the 17 lithologic cross sections constructed for determining characteristics of the alluvial and High Plains aquifers.

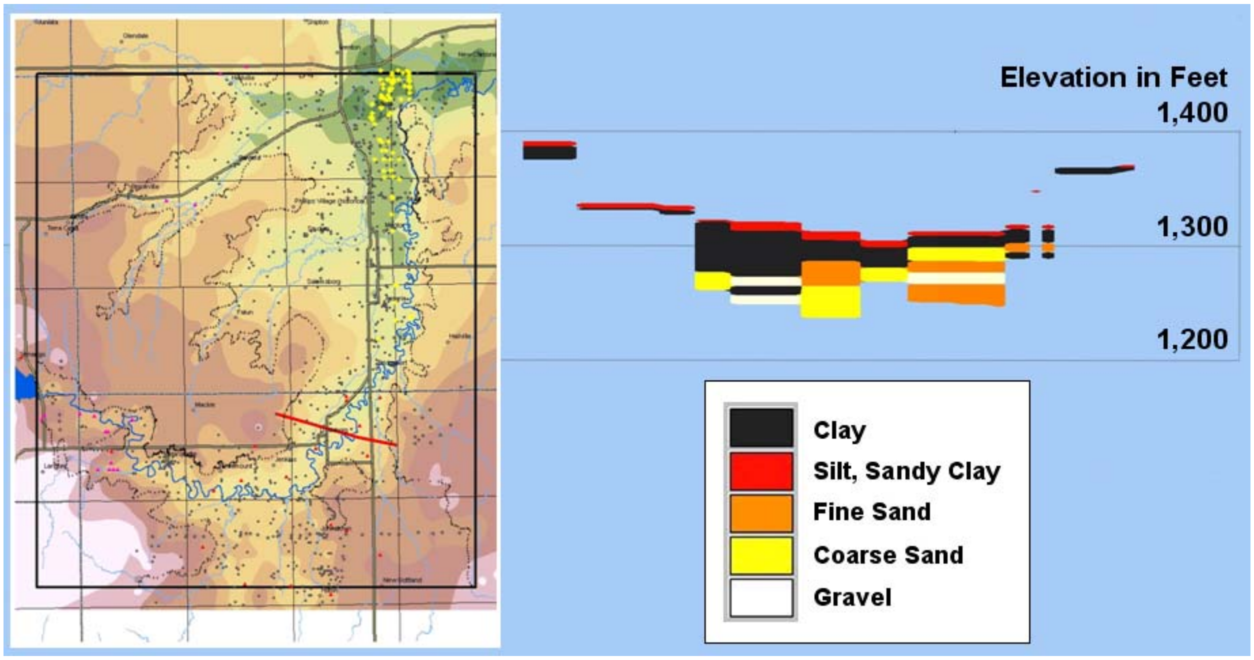


Figure 11. Lithologic cross section across the Smoky Hill River valley. Each column in the cross section represents a different log. The widths of the columns vary depending on the distance between the test-hole or well locations.

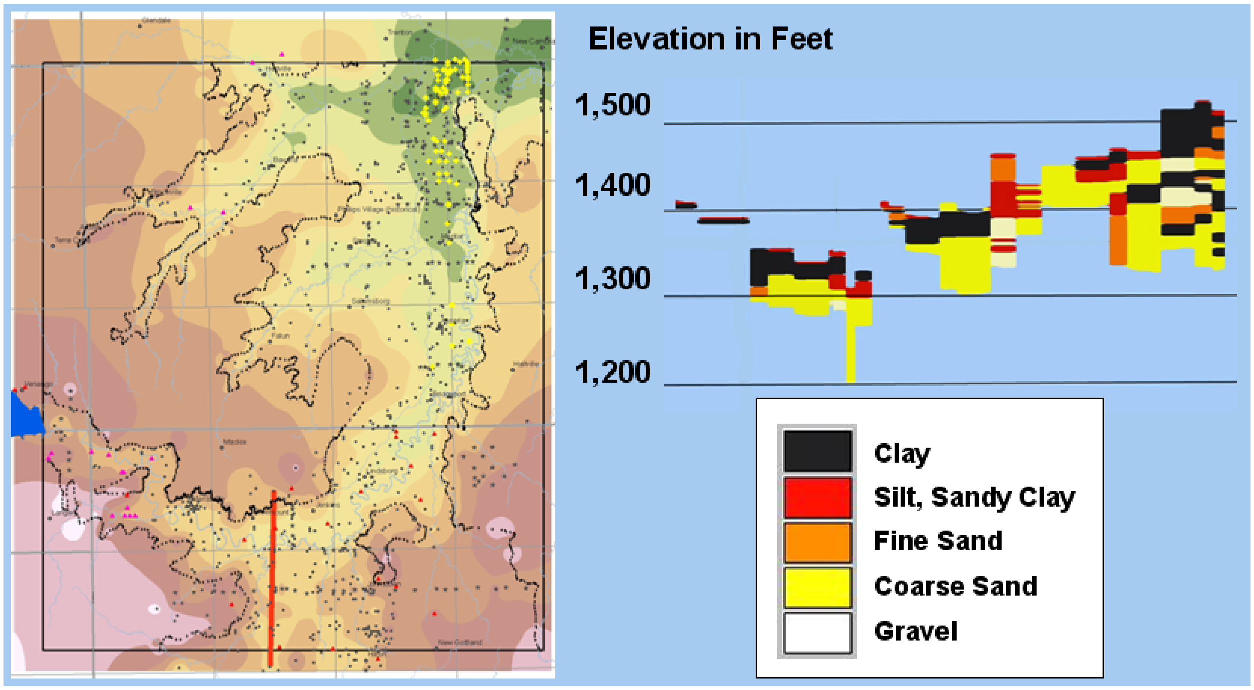


Figure 12. Lithologic cross section across the Smoky Hill River valley and a permeable portion of the High Plains aquifer south of the river valley.

The division between the finer-grained sediments of the confining layer and the underlying permeable aquifer zone was selected for each of the lithologic logs. The elevation of the division and the total thickness of each of the two zones were also determined. The thickness of the low permeability layer ranges from a few feet to just over 60 feet for the Smoky Hill River valley and to over 100 feet overlying the High Plains aquifer near the southern boundary of the model area (Figure 13). The confining layer is typically greater than 10 feet in the main part of the Smoky Hill River valley. The thickness of the permeable sediments ranges from less than five feet to over 50 feet in the river valley and to over 100 feet at the start of the McPherson channel along the middle of the southern model boundary. In general, the low permeability sediment is thicker where the permeable layer is also thick.

The thickness of the permeable layer within the main part of the aquifer of the Smoky Hill River valley tends to increase downstream from below Kanopolis Reservoir to Salina. From Kanopolis to Marquette, the permeable layer within the main aquifer is typically 10-20 feet thick, whereas downstream of Marquette the layer is nearly always over 20 feet thick (Figure 14). Although some of the variations in the thickness along the main alluvial aquifer are due to the distribution of points and whether a log intersects mainly stacked channels filled with coarse sediments in contrast to meander cutoffs filled with fine-grained sediment, some of the locations of thicker permeable sediments are probably related to subsurface subsidence from salt dissolution during the deposition of the coarser, deeper sediments. This latter mechanism may explain the greater thickness of the aquifer materials underlying Salina, where the permeable layer reaches 87 feet.

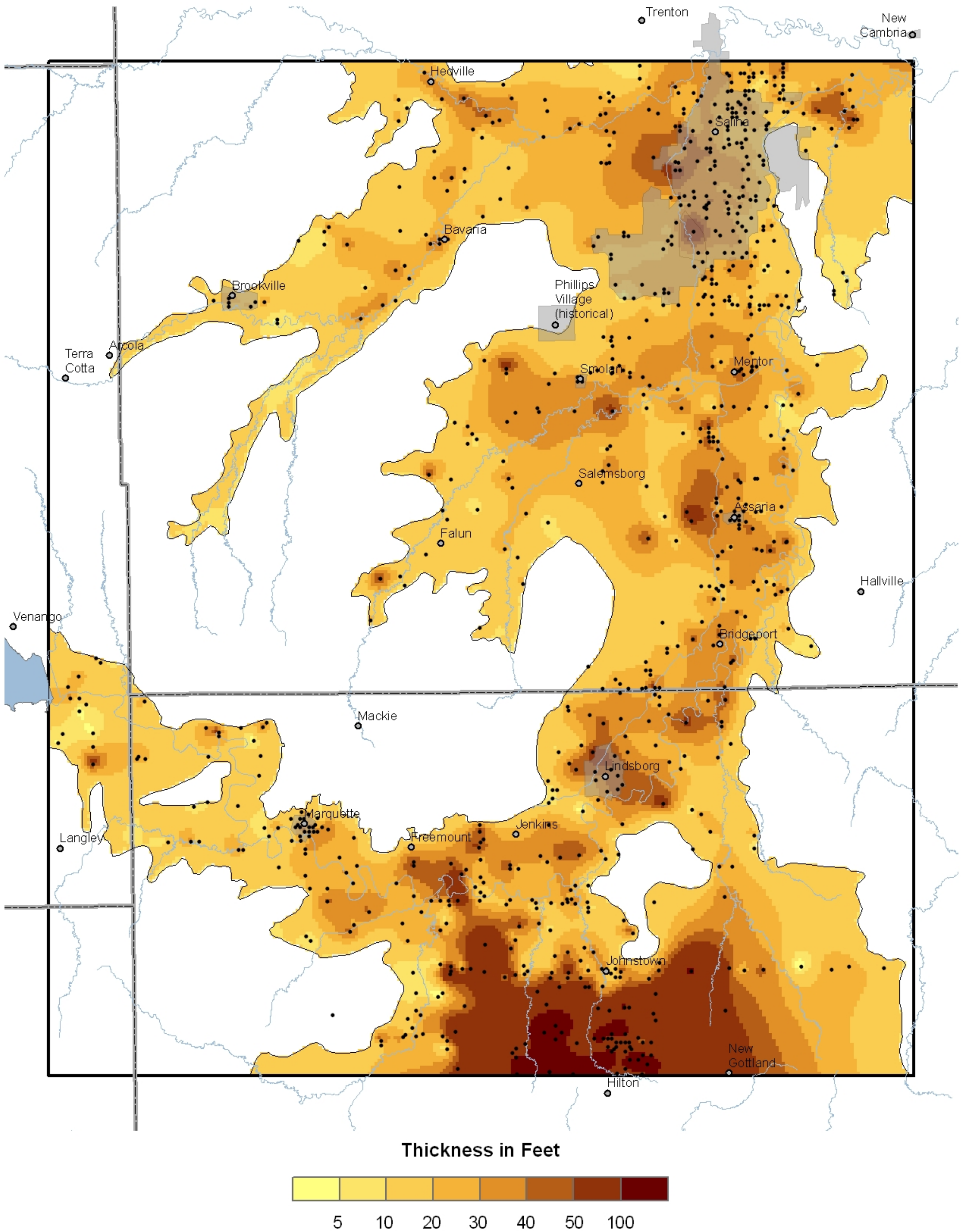


Figure 13. Thickness of the confining sediments of the alluvial and High Plains aquifers in the model area.

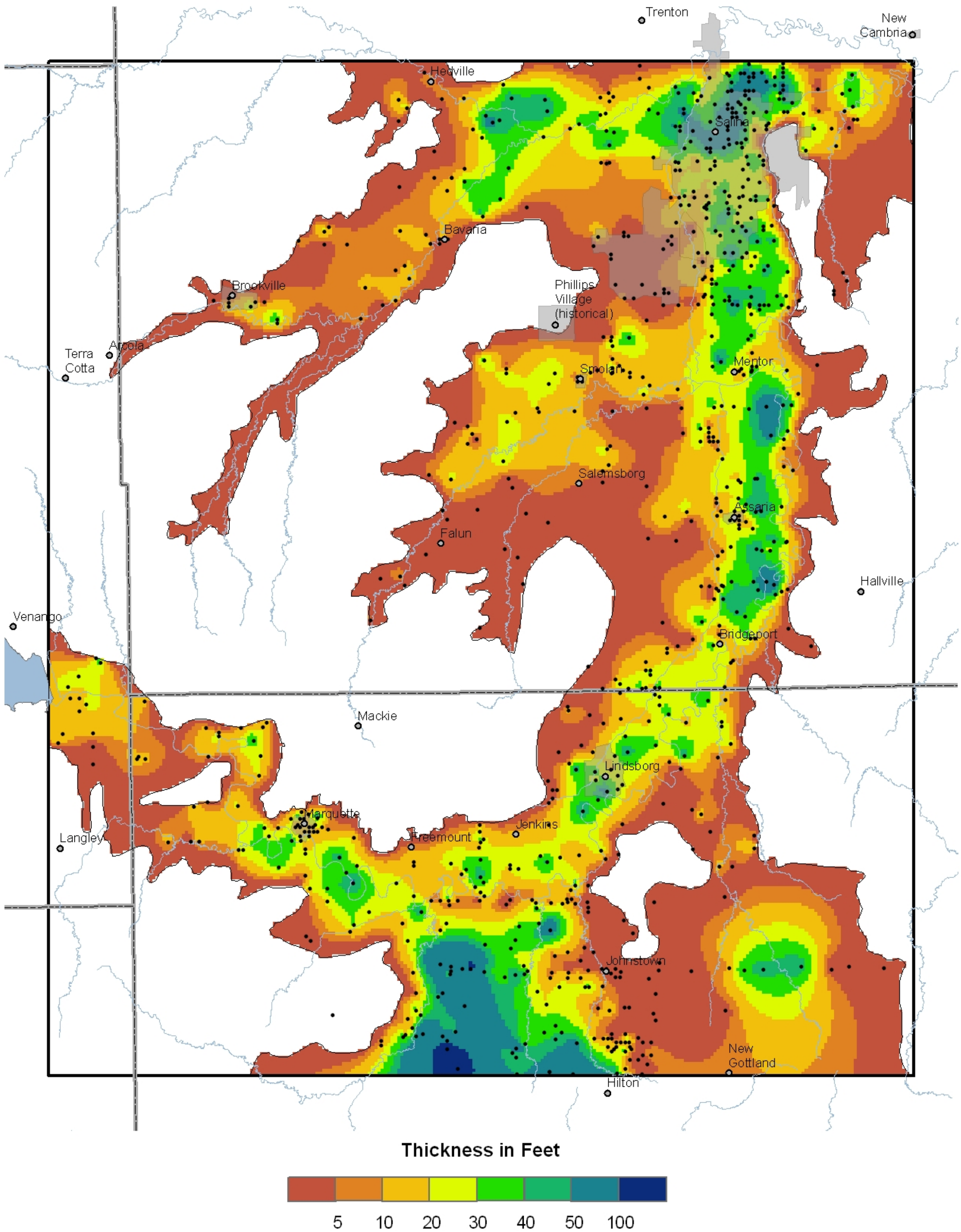


Figure 14. Thickness of the permeable sediments of the alluvial and High Plains aquifers in the model area.

Hydraulic Conductivity and Specific Yield

Several previous studies (Gillespie and Hargadine, 1981; Gillespie and Hargadine, 1986; Sadeghipour et al 1987) provided information on the hydraulic conductivity and specific storage for the permeable aquifer zone in the Smoky Hill River valley. A pumping test conducted at an irrigation well northeast of Salina, which penetrates the full thickness of the alluvium, indicated an average hydraulic conductivity of 330 ft/d. Based on the field investigation conducted at a site located near the town of Solomon (in the Smoky Hill River valley, just east of the model area), Sadeghipour et al. (1987) obtained a rather complex distribution of hydraulic conductivities across the Smoky Hill River valley (Figure 15). The overall patterns of the hydraulic conductivity distribution in the valley were interpreted in terms of local geology. Hydraulic conductivities in the range of 200 to 400 ft/d were associated with coarse sands and gravels found in the lower part of the alluvial aquifer. Hydraulic conductivities that range from 100 to 300 ft/d were associated with fine-to medium-grained sands. Values that are less than 100 ft/d were associated with the more fine-grained sand and silt-size sediments.

The specific yield of the permeable aquifer zone has been estimated as 0.15 ~ 0.20 based on the similarities to aquifers in other Kansas stream valleys. When the aquifer is confined, i.e., the water level is above the base of overlying low-permeability confining layer, the storage coefficient is estimated at 1.0×10^{-5}.

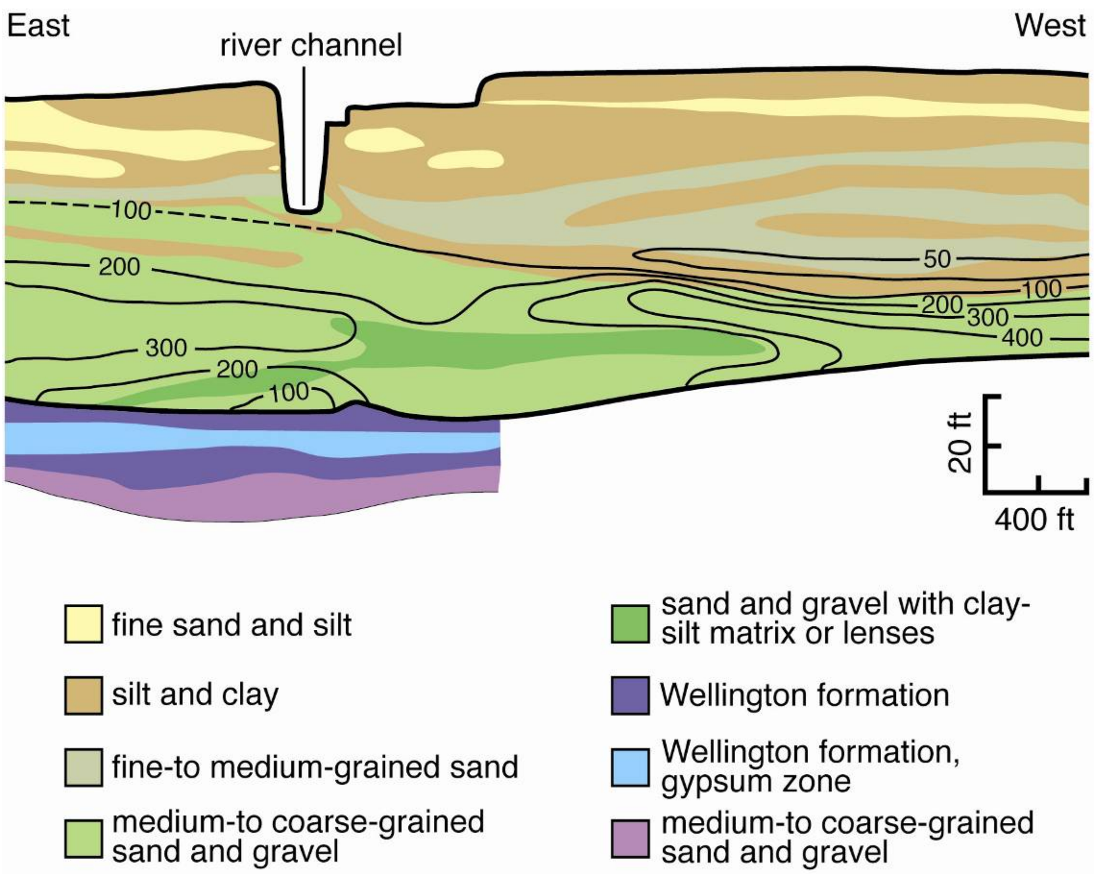


Figure 15. Distribution of hydraulic conductivity, Smoky Hill River valley near Solomon, modified from Sadeghipour et al. (1987).

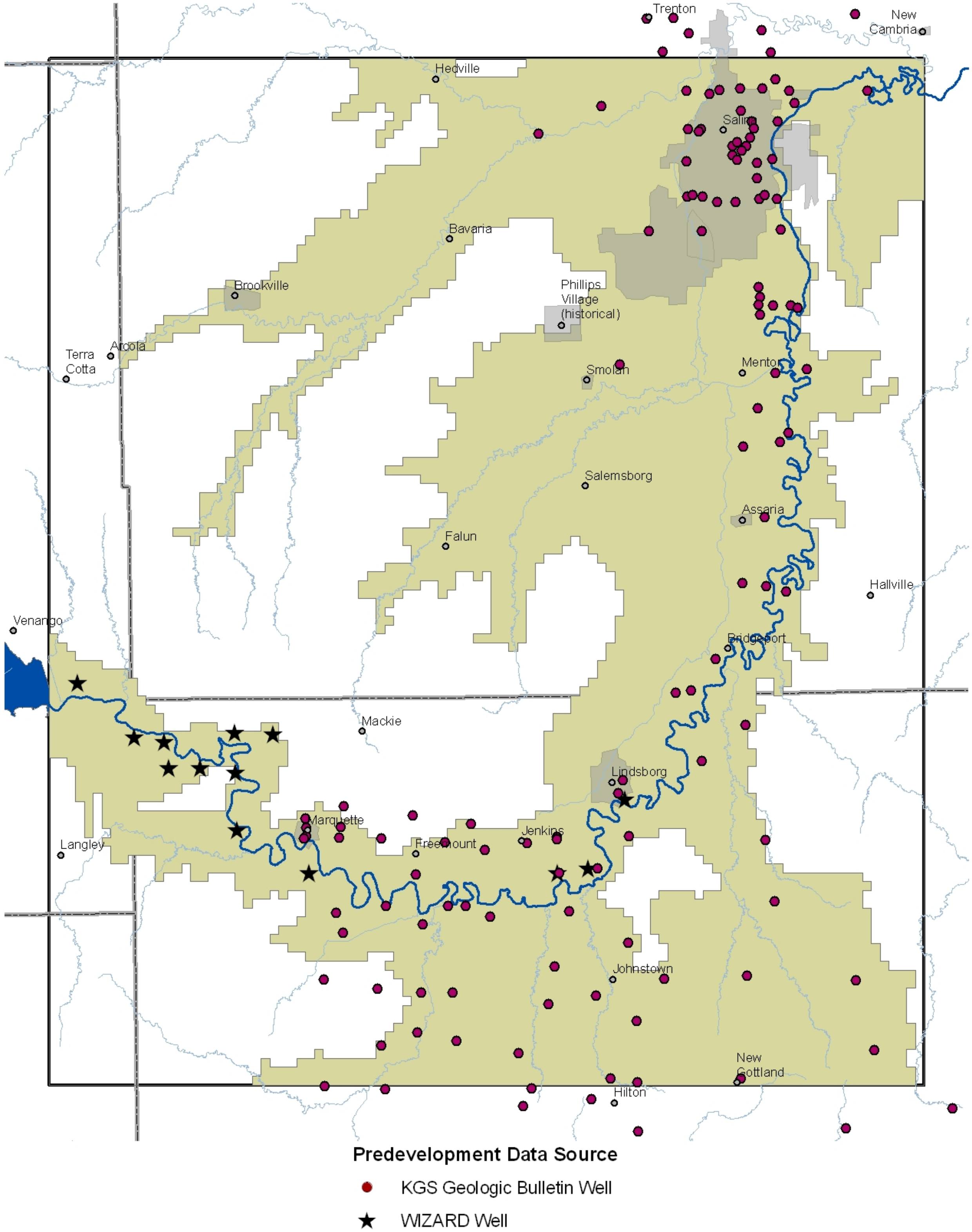


Figure 16. Spatial distribution of ground-water wells with a predevelopment depth-to-water measurement.

Water Levels

Estimates of the predevelopment water levels were constructed primarily based on well data in the two geologic bulletins in the model area (Latta, 1949; Williams and Lohman, 1959). Most of the depth-to-water measurements in these reports range from the mid-1930s to 1946 and were taken from wells located mainly along the Smoky Hill River and within the Equus Beds portion of the High Plains aquifer (Figure 16). To supplement the lack of measured wells in the area just below Kanopolis to Marquette, the KGS Water Information Storage and Retrieval Database (WIZARD) was queried; an additional 13 well sites representing predevelopment conditions were found. The dates of measurement for these wells fall largely in 1950 or 1951, which technically is outside the model's predevelopment time period of 1944 to 1947. However, given the lack of ground-water development in the area, it was assumed that these measurements adequately represent predevelopment conditions.

Water-level measurements beyond the predevelopment periods posed a challenge becasuse there are no long-term, continuous water-level measurements that cover the entire modeling period from predevelopment to 2006. Unlike the KGS geologic bulletins, which provide a relatively good spatial distribution of wells over the area for predevelopment conditions, queries from WIZARD show the number of wells and the number of measurements from those wells over time is much less. Figure 17 displays the number of wells and the frequency of their depth-to-water measurements over the transient period of the model.

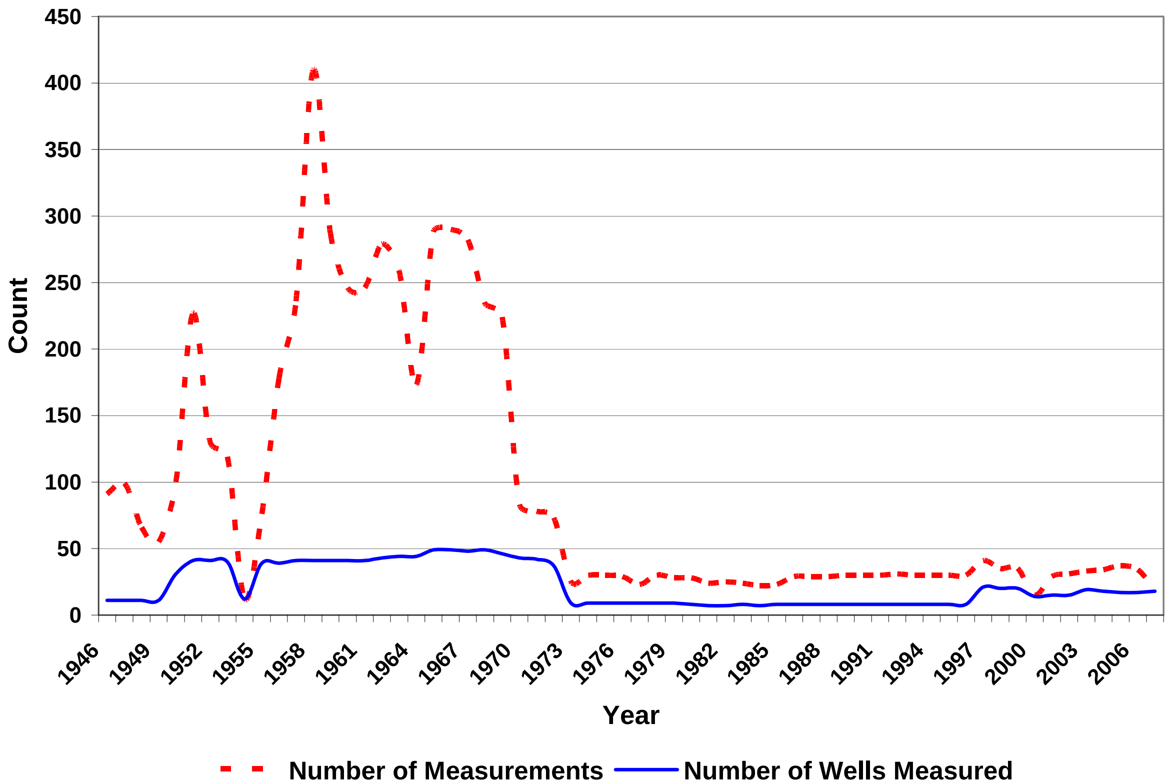


Figure 17. Number of wells and measurements in and around the Smoky Hill model area.

The timing of these measurements within the calendar year is also highly variable. In most cases, historical measurements were taken in January. Starting in 1997, the KDA-DWR started measuring approximately 18 wells in the alluvial aquifer of the Smoky Hill River in March and October. In 1971, the Equus Beds Groundwater Management District No. 2 (GMD2) started a now extensive well network throughout its district. With the exception of the GMD2 wells along the southern edge of the model domain; all of the monitoring wells within the model area are located within the alluvial aquifer of the Smoky Hill River (Figure 18). There are no WIZARD wells located in the terrace deposits of the model.

WWC5-Based Saturated Thickness

Given the lack of water-level data in the upland terrace deposits of the model area from WIZARD and published bulletins, static water levels from Water Well Completion Records (WWC-5) were used as a proxy source to estimate the saturated thickness. 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.

Most of the WWC-5 records for the model area are for wells drilled for domestic water use and provide a good spatial distribution across the upland areas (Figure 19). Although there appears to be a sufficient saturated thickness for good domestic and stock wells in much of the terrace region and areas southeast of the Equus Beds portion of the High Plains aquifer, it is likely that the actual amount of usable water in these areas is limited given the storage properties of the aquifer. This is born out by the lack of water-right development of ground water in these areas (see the *Water Right Development* section of this report). It was assumed that the relatively low rate of water use of the domestic and stock wells has not substantially affected the water levels.

The static water levels from all the WWC-5 records for the terrace deposits (outside the main alluvial aquifer of the Smoky Hill River valley) were used to supplement the predevelopment water-level data in order to generate an estimate of the water-table elevation in predevelopment conditions (Figure 20). Even though the static water levels in the terrace area represent conditions well after the predevelopment time period, they still provide an estimate of the saturated thickness across the aquifer area, which is preferable to little or no data. Points along the valley wall (the edge of the area of active cells in the model), for which the water table was assumed to be five feet below the land surface, were used to help control the interpolation process.

The water-level surface determined for the predevelopment period (Figure 20) follows the same general pattern as the land surface, with the highest elevations located in the High Plains aquifer at the southern model boundary and in the area to the south of the Smoky Hill River valley near Kanopolis Reservoir. As expected, the water-level surface in the alluvial aquifer of the Smoky Hill River valley is highest along the upper end of the river valley near Kanopolis and decreases in elevation downgradient to lows east of Salina.

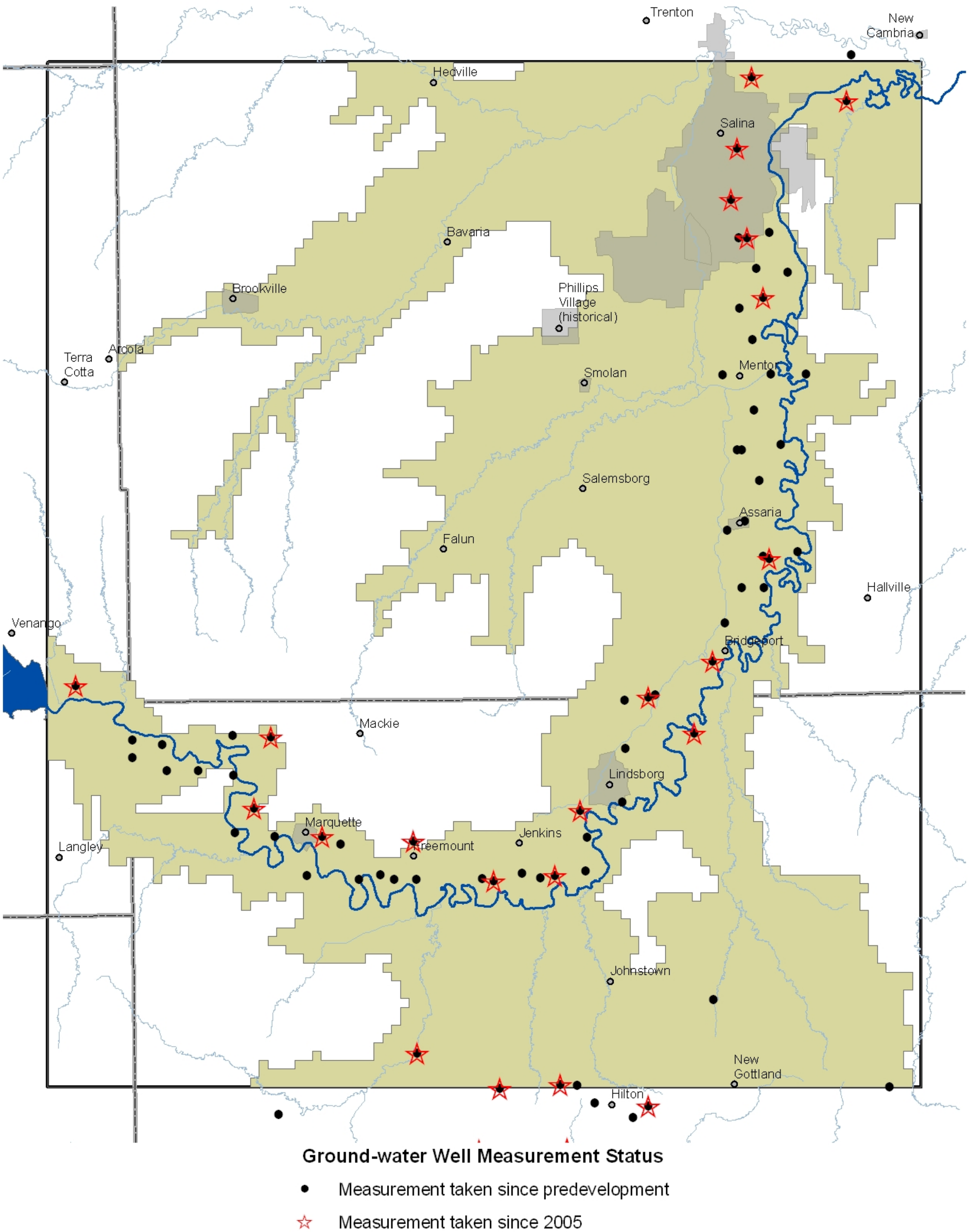


Figure 18. Spatial distribution of ground-water monitoring wells.

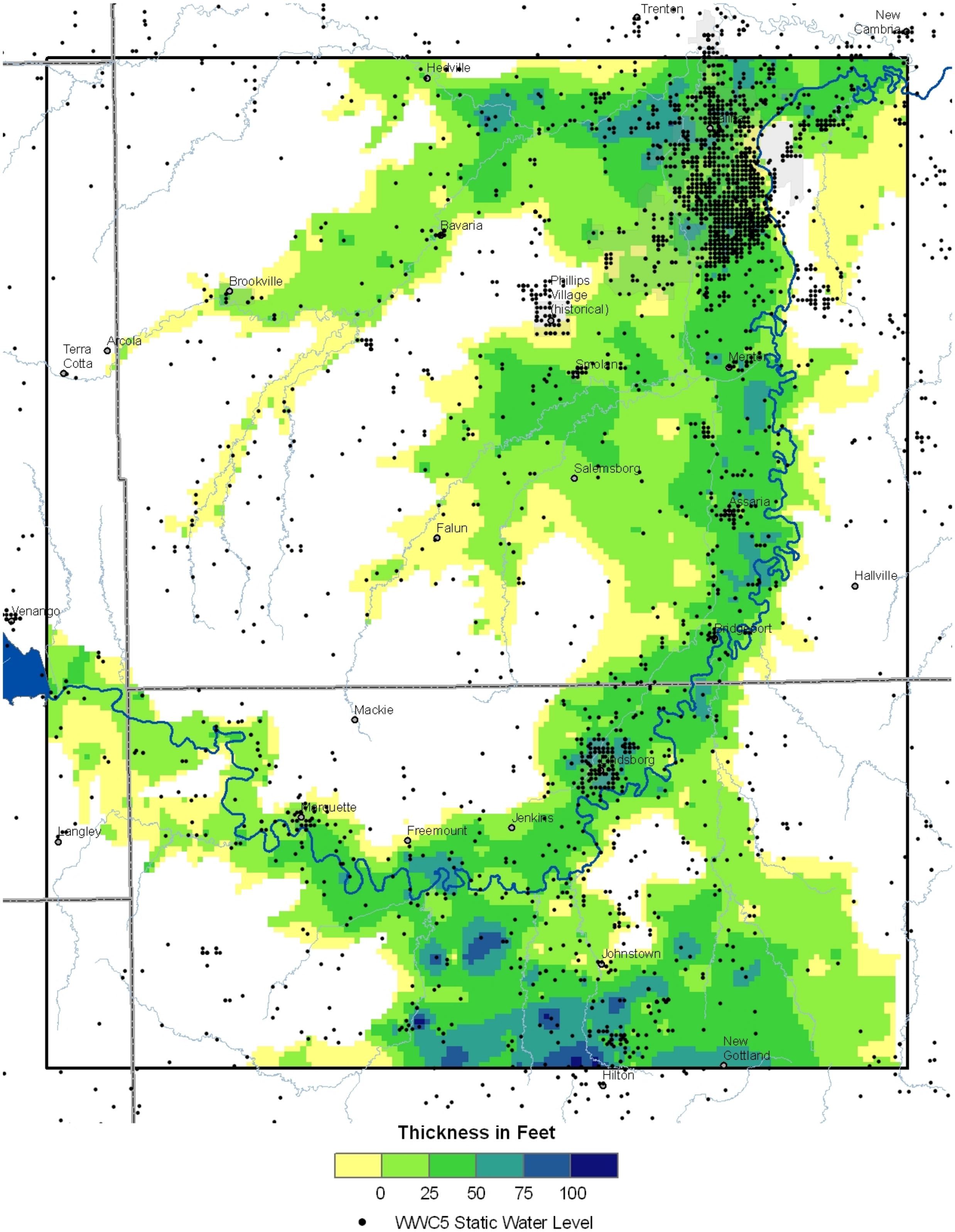


Figure 19. Interpolated WWC-5 static water level saturated thickness.

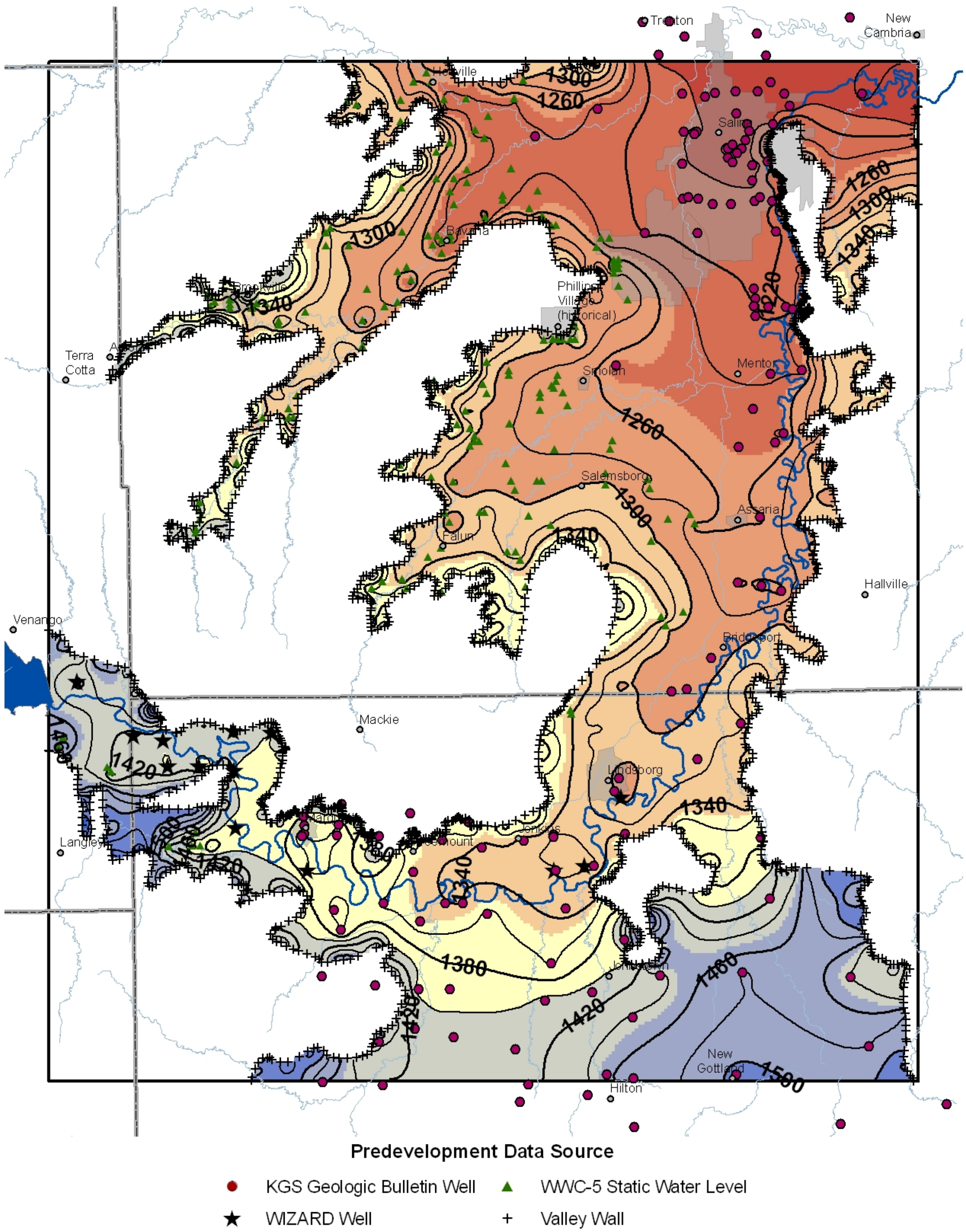


Figure 20. Interpolated predevelopment water table elevation.

Head Boundary Water Levels

The model uses time-varying constant head boundaries on the edges of the model to represent water-level conditions in the aquifer (Figure 1). There are an adequate number of wells over the predevelopment period in the alluvial aquifer. However, over the transient period of the model, predevelopment to 2006, the lack of measured wells and their distribution makes estimating any water level difficult. Two approaches for the three locations of primary head boundaries were used – one for the head boundaries of the alluvial aquifer and the second for the Equus Beds aquifer boundary along the south edge of the model.

Figures 16 and 18 show that, for the alluvial aquifer of the Smoky Hill River valley within the model area, both predevelopment and current (since 2005) depth-to-water measurements exist for wells close to the head boundary cells. All available measurements from these wells were used to estimate the water-level elevations in the head boundary cells closest to the wells. The measurement values were adjusted slightly based on the gradient change in the predevelopment water-table surface (Figure 20). Over the periods without any depth-to-water measurements close to the boundary cells, the change in the water table occurring at the next closest well sites was reviewed. The annual changes occurring for the missing years of record were estimated from this data review and applied to the alluvial head boundary cells.

After water-table elevations were estimated for the years between predevelopment and 2006 for individual head boundary cells closest to monitoring wells, the changes identified between each year for these cells were applied to all the other head boundary cells forming the edge of the aquifer. Thus, all of the head boundary cells on each end of the alluvial valley moved up or down each year based on the annual changes in the boundary cells closest to the monitoring wells.

Water levels for the head boundary cells representing the Equus Beds part of the High Plains aquifer along the southern edge of the model were estimated using a different approach. Part of the justification for the location of the southern extent of the model area is that it splits a series of monitoring wells routinely measured by GMD2, including one well located within a cell along the model boundary and another 300 feet south of a boundary cell just outside the model domain. However, the period of record for these wells only starts in 1971. Outside of predevelopment measurements for a couple of wells, no water-level measurements could be found within the 1948 to 1970 period for the Equus Beds aquifer.

A significant linear trend exists in the available depth-to-water measurements (predevelopment and 1971 to 2006) (Figure 21) for the two GMD2 monitoring wells along the southern model boundary. In order to produce a regression better representing the interval of missing data between the predevelopment and recent data, one or two additional points with the same water-level values were added for subsequent years after the 1945 measurement date to force the regression line to be closer to 1945. The fitted trend in the annual change of the water table statistically explains over 80 percent of the variation from predevelopment to 2006. The linear regression was then used to estimate the missing water levels from predevelopment to 1970 for one well and to 1981 for the other well. The annual water-level values from the measurements and regression line were assigned to the two boundary cells in which one well was located and which was closest to the other well. The annual water-level changes in these two boundary cells were then used to vary the annual levels of the other boundary cells starting from the values of the predevelopment surface.

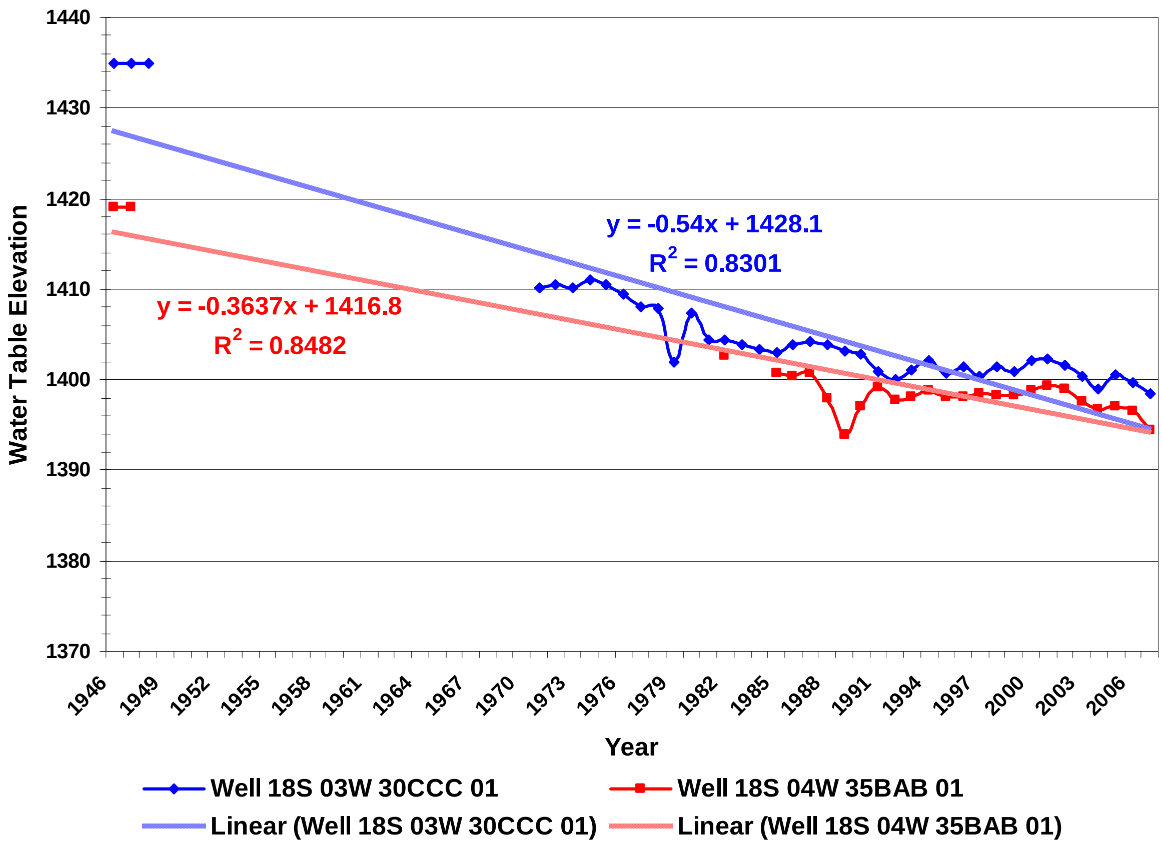


Figure 21. Linear trends in Equus Beds targeting head boundary wells.

Areal Precipitation Recharge

The KDA-DWR uses a modification of the USGS Water Resources Investigation Report 87-4230 (Hansen, 1991) as the principle source to estimate the potential mean annual recharge when dealing with activities related to water right administration. The modification involved the further interpolation of annual recharge isolines from one-inch intervals to quarter-inch intervals. Over the model area, the estimated mean annual recharge based on this modified USGS report is in the range of two to over three inches (Figure 22). However, given the silt and clay layer that overlies of the alluvial aquifer (as described in the *Geology and Lithology* section of this report), which would decrease the infiltration rate of rainfall and increase surface runoff, these estimates were deemed too high. A lower rate of areal precipitation recharge, one inch, was estimated as appropriate for the entire area of the predevelopment, steady-state model.

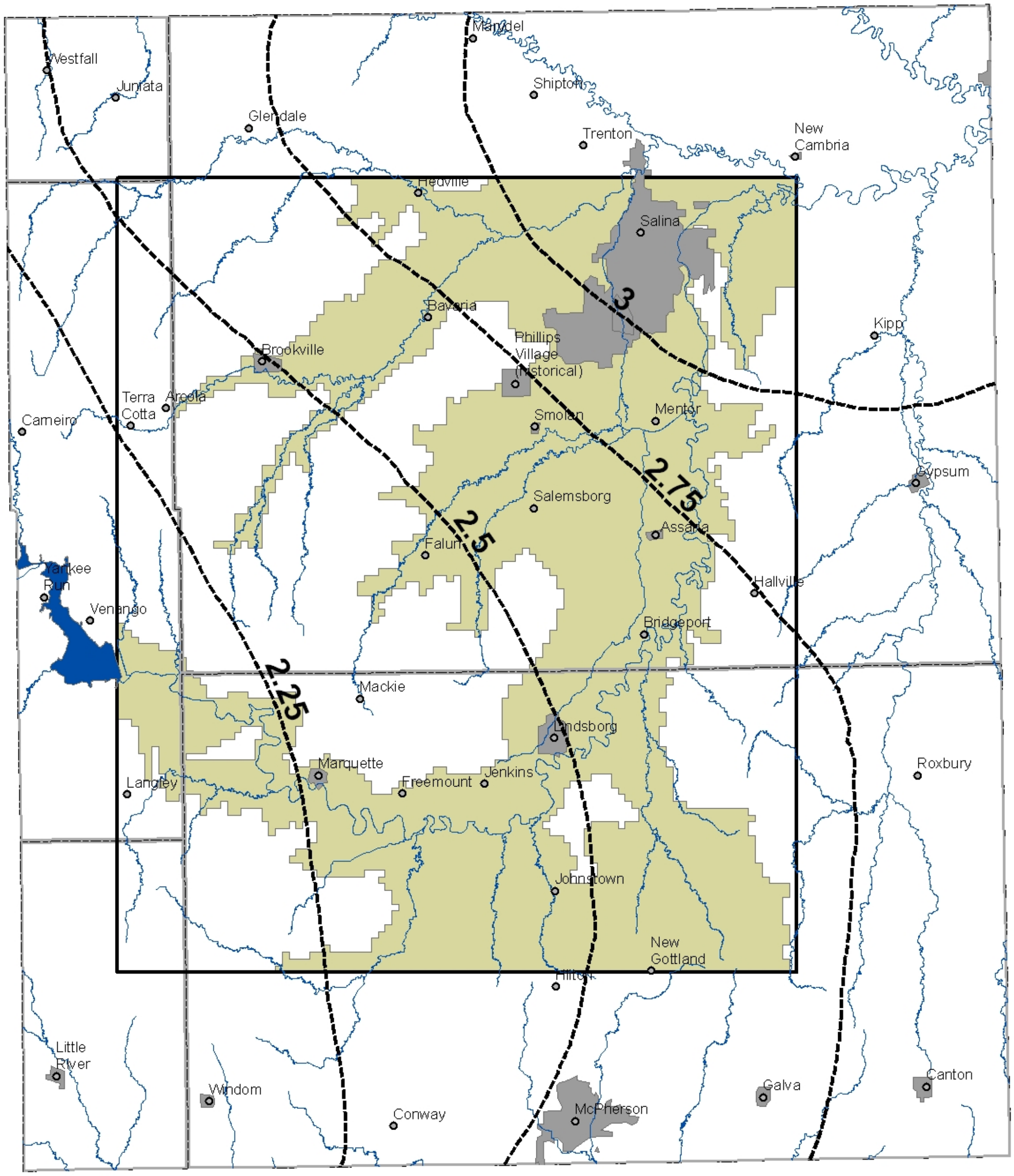


Figure 22. Estimates of mean annual potential recharge from precipitation from Hansen (1991) with modifications by the KDA-DWR.

For the transient model, recharge is based on segmented linear relationships to precipitation. These recharge curves have a break point at which there is no recharge to the aquifer system. After this break point, the estimated recharge increases with increasing precipitation. With further increase in precipitation, the increase in the recharge rate decreases to represent soil saturation and increased runoff. Initially, one set of recharge curves were used for both the non-pumping and pumping periods in the transient model. Later, these were revised to simulate the differences between recharge rates during October through March, when evapotranspiration is low and more soil moisture can be translated to recharge, and April through September, when much more rain returns to the atmosphere as water vapor due to higher temperatures.

No wells with long-term water-level measurements for both winter and summer periods are available in the model area for estimating the recharge differences between non-pumping and pumping periods. However, a monitoring well with a substantial number of water-level measurements that is located just to the south of the model area in the Equus Beds aquifer was determined to be a good proxy for the alluvial aquifer in the model area. The Equus Beds monitoring well (SW SW SE Sec. 32, T. 23 S., R. 3 W.) is located near the town of Burrton and is 41 feet deep, a relatively shallow depth in the range of some of the alluvial aquifer wells. The upper part of the Equus Beds aquifer at the well location has characteristics that are generally similar to those of the alluvial system in the model in that an upper layer of fine-grained sediments overlies more permeable sediments, and the depths to water are relatively similar. The well has a measurement history running from 1939 to present with numerous depth-to-water measurements taken throughout the year (Figure 23).

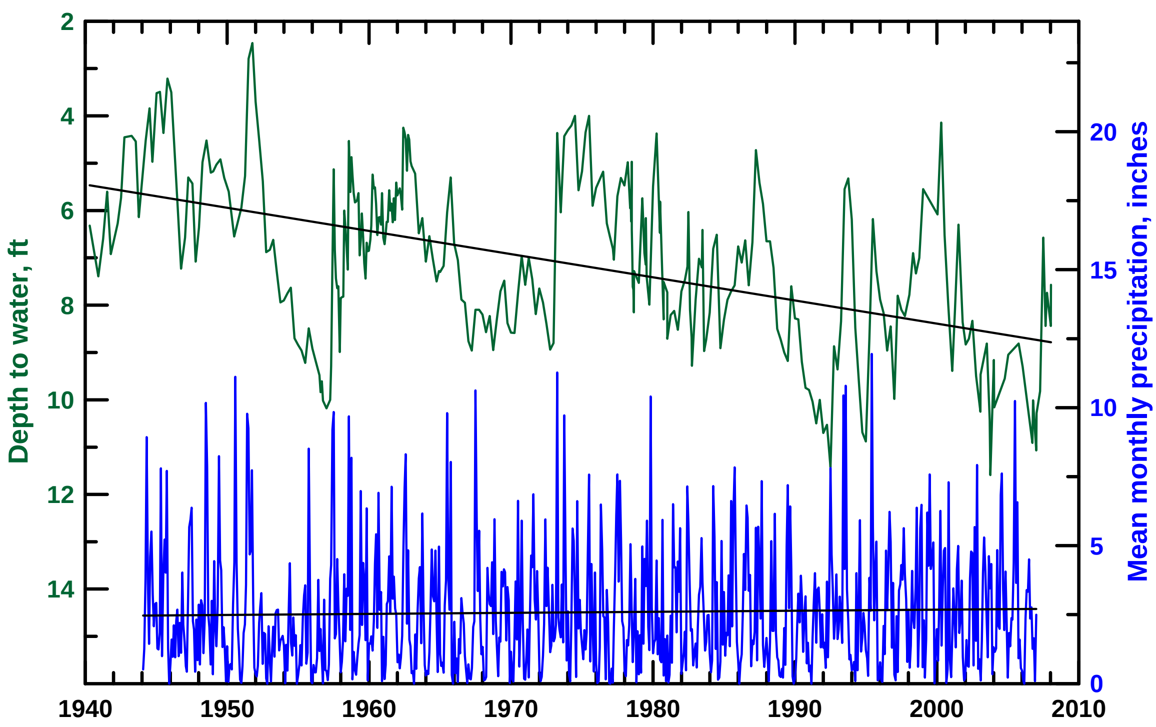


Figure 23. Water-level data for the Equus Beds monitoring well used a proxy for estimating the differences between winter and summer recharge.

The water-levels in the shallow Equus Beds well show a clear declining trend the 1940s to the 2000s. In comparison, the precipitation record shows no trend. The declining water levels are related to the consumptive pumping of water from the Equus Beds aquifer for both irrigation and municipal use.

To determine the relationships between the changes in the water table occurring at this well with the six-month time steps used by the model, the linear regression for the entire set of water-level measurement was used to remove the trend in the data for the Equus Beds well. The water-level values for dates in a window of from three weeks before to three weeks after October 1 (except for one value for September 1 and one for October 25) and April 1 (except for one value for April 28) were then extracted from the data set. The October 1 and April 1 dates represent the end of each of the two recharge periods. Fortuitously, many of the measurements had been made quarterly and were taken close to these two dates. The change in the water level from the beginning to the end of each of the two six-month periods was then plotted against the amount of precipitation occurring during each of the two periods (Figure 24). In short, the de-trended analysis indexes the seasonal change in the water levels to the precipitation that occurred in each season.

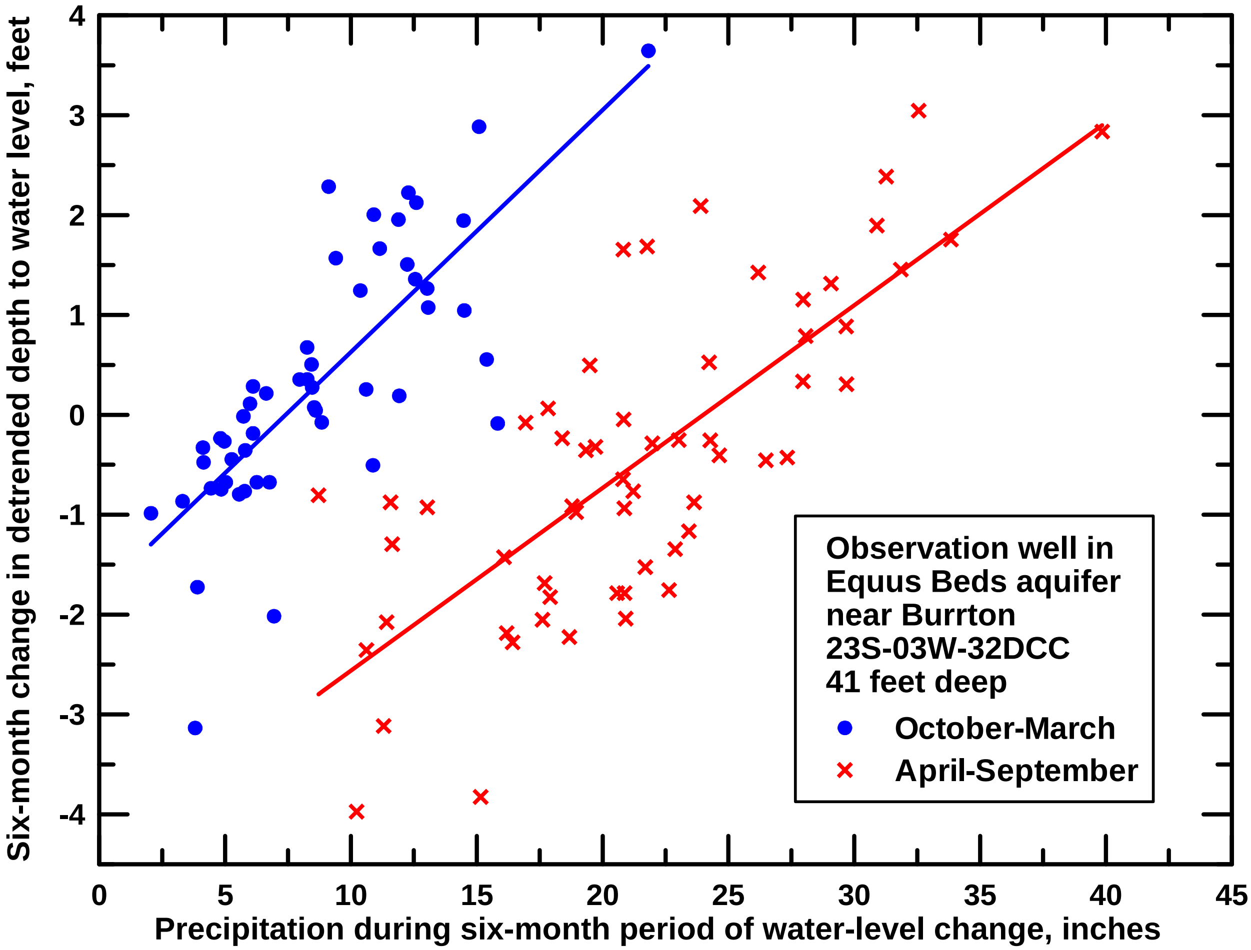


Figure 24. De-trended change in the water table from the beginning to the end of the two six-month periods for a well in the Equus Beds aquifer versus precipitation during the six-month periods. The two lines represent linear regressions for the two periods.

The distribution of the points for the winter and summer periods in Figure 24 are clearly separate. The linear regressions in the figure are both highly statistically significant and show the rate of water-table rise with increasing precipitation. The offset of the two regression lines indicate that it takes, on average, approximately 15 more inches of precipitation in the summer than in the winter period to cause a similar rise in water table.

The recharge-precipitation relationships estimated for the winter time steps (October to March) by model zone (Figure 2) after calibration of the transient model are shown in Figure 25. The average rate of recharge over the transient period is around 1 to 1.5 inches. The best fit obtained during calibration of the transient model for the summer pumping period was produced by shifting the recharge curves in Figure 25 by 15 inches of precipitation, approximately the same shift as determined by Figure 24. Thus, the calibration shift can be supported by field data. The same segmented lines were used for the summer as for the winter period except that the point at which recharge starts to occur is 20 inches instead of 5 inches of precipitation.

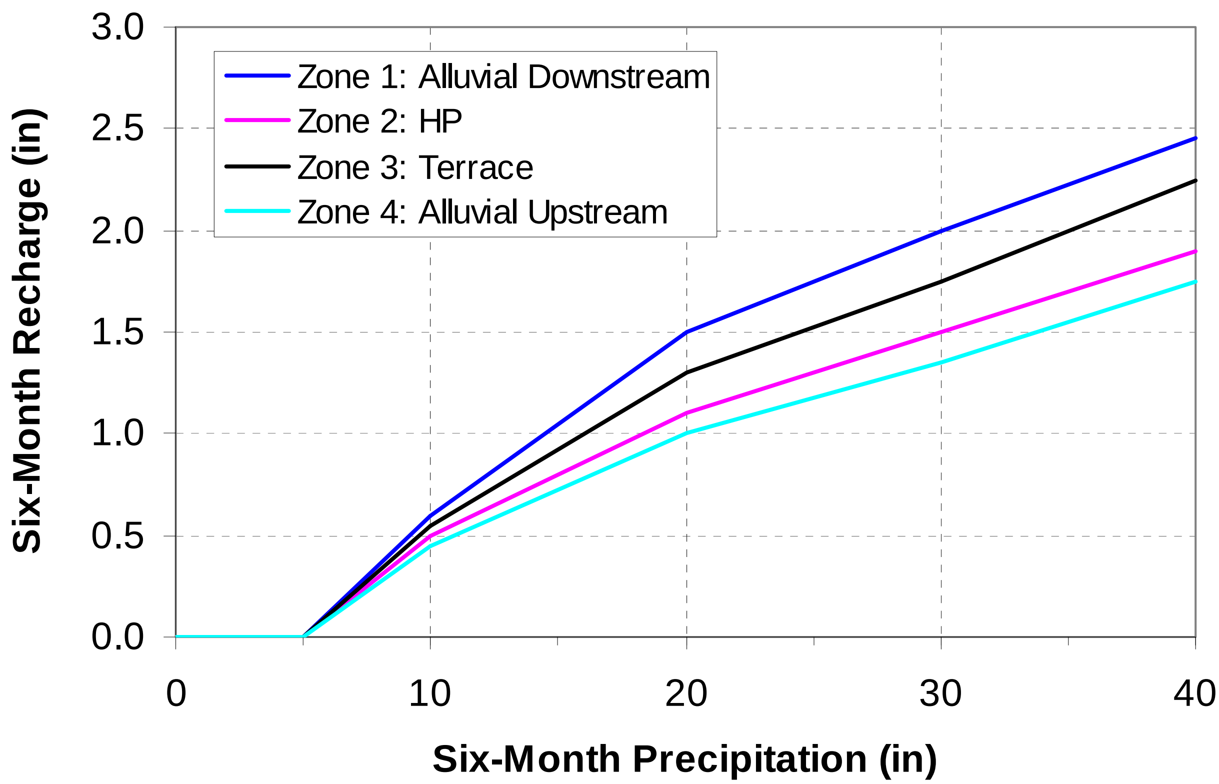


Figure 25- Segmented recharge curves for the six-month winter period (October-March).

One recharge zone was originally used for the main zone of the alluvial aquifer. Later, two different recharge zones (upstream and downstream) were delineated for the alluvial aquifer during calibration of the model. Each of these two zones has different recharge rates, especially at higher precipitation levels, based on the model calibration.

Streamflow Characteristics and Flow

Stream Channel Characteristics

The channel of the Smoky Hill River meanders substantially through the model area. The main river channel formerly passed through the City of Salina. A low head dam is on the river in the old channel within the city. Due to problems from flooding from both the river and the Dry Creek drainage entering the city from the south, the U.S. Corps of Engineers in 1960 cut a channel through the bedrock nose on the east side of Salina, constructed new channels cutting off some of the river meanders just upstream of the river, and cut a channel connecting Dry Creek with the river just upstream of Mentor.

The elevation of the water surface of the Smoky Hill River in the model area was determined from where contours on USGS 7.5 minute topographic maps crossed the river. The average depth of the river water was estimated to range from 1 to 1.5 feet from the USGS Langley gaging station to Salina based on field measurements of the USGS for constructing stage-discharge curves. The streambed elevation was calculated by subtracting 1-1.5 feet from the water surface elevations along the river.

The present streambed is cut 20 to 30 feet into the silts and clays that overlie the main part of the alluvial aquifer. The emplacement of the dam of Kanopolis Reservoir changed the erosional and depositional characteristics of the Smoky Hill River. Water released from any surface impoundment is often referred to as “hungry water” because it contains a smaller amount of suspended sediment than the water entering the impoundment. This results in higher rates of channel erosion on the downgradient side of the impoundment, which causes the streambed to shift downward over time. A USGS report (Juracek, 2001) shows that the Langley stream gaging station, located just below Kanopolis Dam (Figure 26), follows this trend as entrenchment began after completion of the reservoir in 1948.

The USGS report indicates the post-dam change in stage for the mean annual discharge at the Langley gage was about -5.8 ft (a statistically significant change) up to 1999. The post-dam change at the Lindsborg gaging station (for which the record ended in 1965) was +1.0 ft (a non-significant statistical change). The Lindsborg gage was located at about the mid-point of the Smoky Hill River in the model area (Figure 26). After additional review of changes in the water surface elevation and estimated water depth in the river between the gages, adjustments were made to the modeled streambed elevations to account for this entrenchment over time. The area of impact is from the below the dam (start of the river in the model) to an area halfway between the gages near Marquette, as indicated by the solid red triangle symbol in Figure 26 for the end of entrenchment.

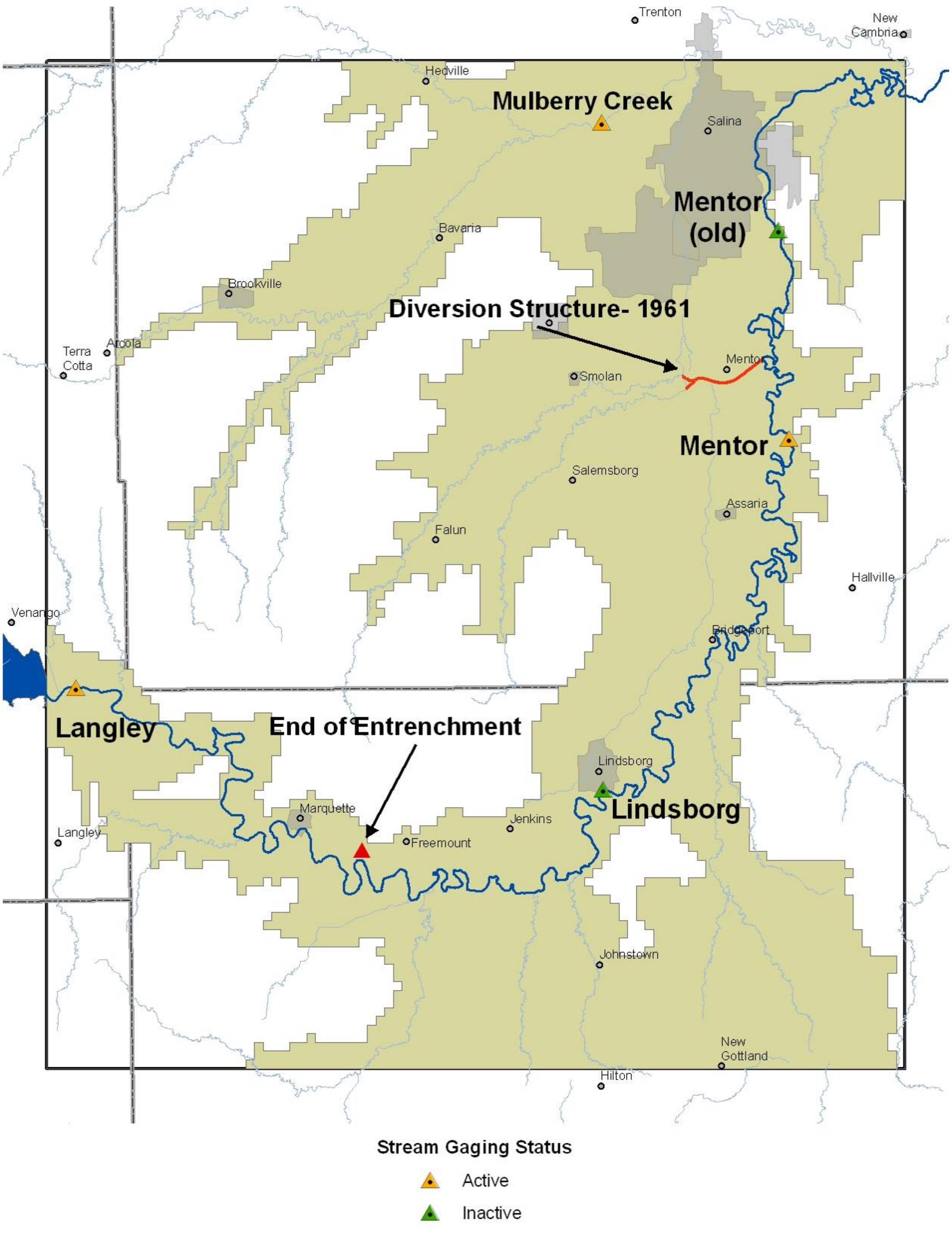


Figure 26. USGS stream gaging stations and the location of the diversion cutoff from Dry Creek to the Smoky Hill River. The stretch of riverbed where entrenchment was considered extends from below Kanopolis Reservoir to the symbol for end of entrenchment. The USGS moved the Mentor stream gage upstream in 2002.

An examination of the change in the river stage for the Langley gage based on a figure in the Juracek (2001) report shows the entrenchment was rapid during the first five years once the dam was completed in early 1948 and then gradually slowed with time. Based on this trend, the recent field data for adjusting the flow rating curve at the gage, and the published dates of the topographic maps (1959), the entrenchment of the Langley gage was divided into different periods relative to the elevations determined from the topographic maps (Table 1). The rate of change between the Langley gage and the ending point of the entrenchment (where streambed adjustment is zero) was linearly decreased based on the river length in each model cell.

Table 1
Estimated Streambed Adjustments (Entrenchment) at the Langley Gage

Time Period	Streambed Adjustment in Feet	Notes
1943-1947	+3.6	Predevelopment period
1948-1952	+2.0	
1953-1965	0.0	Period of published topo maps
1965-2006	-1.7	
2007-Future	-2.7	Continued future entrenchment

Streambed and Aquifer Bedrock Adjustments

The Smoky Hill River meanders greatly within the valley proper, and in the area generally south of Salina, it runs directly adjacent to the valley walls, which are in essence outcrops of the bedrock that forms the surface underlying the aquifer. Depending on how these areas are overlain by the ¼ x ¼ mile grid cells of the model, the parameters of the streambed elevation in relation to the bedrock elevation may not be properly represented for modeling purposes.

Figure 27 shows an example of a model cell, outlined in red, in which the cell is considered a "stream" cell because it incorporates part of the channel of the Smoky Hill River. As such, it contains a host of data parameters describing the various characteristics of the stream channel, including the streambed or the bottom of the river. The cell also contains an estimate of the bedrock (bottom of the aquifer), which, for all of the active cells, was determined automatically by GIS selection of the bedrock surface elevations within the model cell. In this case, the bedrock elevation is near the land surface, which is at an elevation substantially above that of the streambed. Thus, the $1/16^{th}$ square mile area of the model grid cell is too coarse to capture the detail in the elevation variations and lists the bedrock elevation as well above the streambed. Although this determination is correct in terms of the center of the cell, this produces computational errors in the model.

The interpolation of the thickness of the confining layer of sediments sitting atop the alluvial aquifer also has a similar issue. In many cases for cells along the river valley wall, the $1/16^{th}$ square-mile model cells list the streambed at an elevation well below the confining layer. Although this is the actual case in terms of the surface of the floodplain adjacent to the river channel incised into the confining layer, again it causes computational problems in the model. During the calibration process for the transient portion of the model (outlined in section *Transient Model Calibration and Simulation* of this report) it was found the Smoky Hill River was always a gaining stream, meaning that water always flows from the hydrologically connected alluvial aquifer system to the river. This relationship is for the most part correct but it oes not occur all the time, especially during prolonged drought when the river becomes a losing stream.

To overcome the issues associated with interpolating continuous surfaces, the model cells representing the Smoky Hill River were modified so that the bedrock was always at least 10 feet below the river and the confining layer could be at but not above the streambed (Figure 28). These modifications were made only to the model's "streams" cells coded as being part of the Smoky Hill River. The modified values for the bedrock elevation within these cells was then used in the interpolation process to revise the bedrock surface – the values for the cells where the streambed was estimated to be below the bedrock were included as actual input points along with the well logs. These stream bedrock sites are listed as "Smoky Hill River Points" in Figure 8. The minimum thickness of 10 feet of aquifer between the bedrock surface and the streambed is a reasonable estimate for the actual conditions in the river valley.

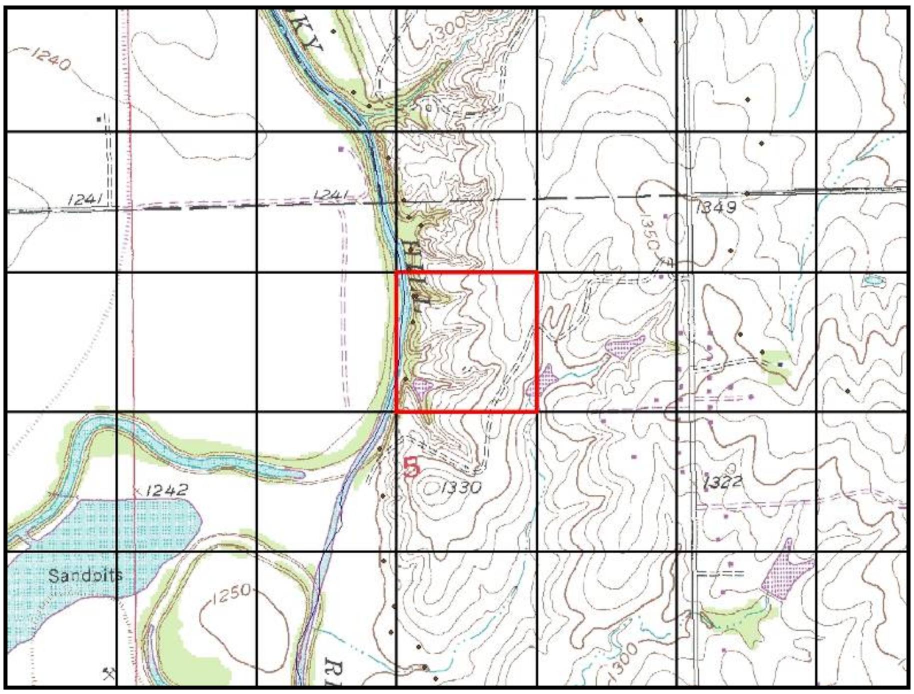


Figure 27. MODFLOW Model Cells. The cell outlined in red shows an example where the bedrock elevation was modified to be at least 10 feet below the streambed.

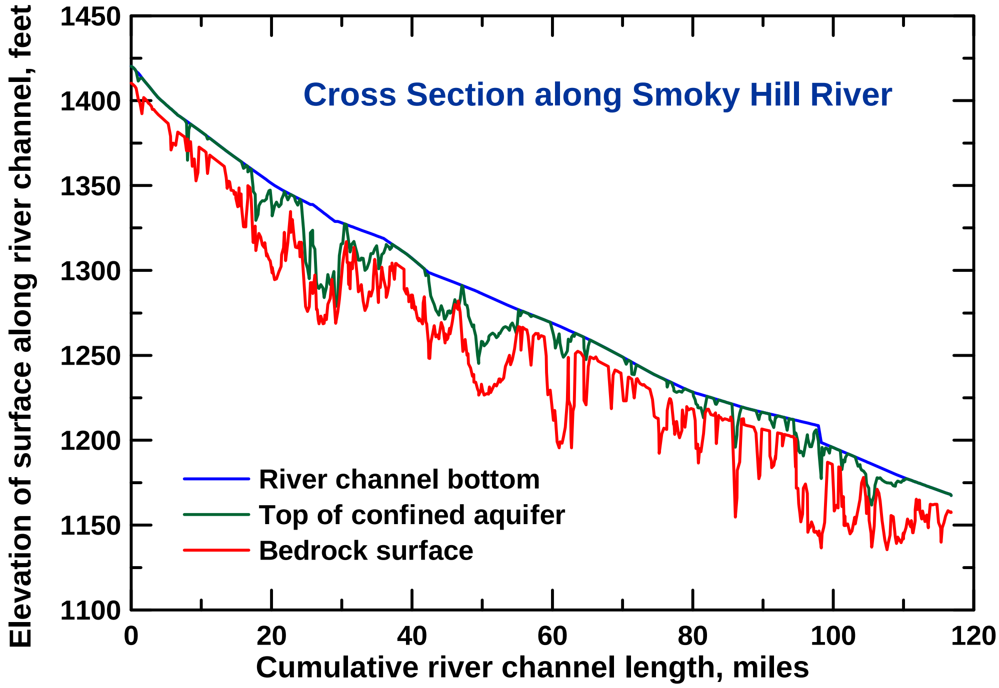


Figure 28. Estimated elevation for the streambed, top of the aquifer confining layer, and bedrock elevation for the model cells containing the channel of the Smoky Hill River.

Figure 28 illustrates the general concave shape of the streambed of the Smoky Hill River from just below Kanopolis Reservoir to where it exits the model area northeast of Salina. The streambed elevations were taken from USGS topographic maps and are for the period before the channel cutoff was constructed through bedrock on the east side of Salina. The small, abrupt drop close to the cumulative channel length of 100 miles in Figure 28 is the location of the low-head dam on the river channel in Salina. Locations where the top of the confining bed is substantially below the streambed elevation are expected to have much smaller rates of stream-aquifer interactions in comparison to those locations where the confining bed elevation is the same as that of the streambed. The figure shows that greater thicknesses of the confining layer are generally associated with larger thicknesses of the permeable aquifer between the bedrock surface and the confining layer. The greater thicknesses typically represent locations where the river channel crosses deeper parts of the bedrock surface, including those areas possibly affected by subsurface subsidence from Permian salt dissolution.

<u>Gaged Streamflow</u>

Four USGS stream gaging stations are located within the model area, three on the Smoky Hill River and one on Mulberry Creek (Figure 26). The Langley gage has been in operation since 1941 (the start of the dam construction for Kanopolis reservoir) to the present, and is located about 0.8 mile below the dam. Flow data from this gage represent the primary surface inflow of the Smoky Hill River for the model. The Lindsborg gage (continuous record from 1931 to 1965) and the Mentor gage (continuous record from October 1947 to present) are used for stream calibration during the transient phase of the model.

The Mentor gage site has undergone several changes over the modeling period. In 1961, flood control structures were constructed on Dry Creek, Middle Dry Creek, and West Dry Creek to divert all surface flow into the Smoky Hill River near Mentor. In addition, the actual gage location was moved 11.8 miles upstream in March 2002 to its present location between Mentor and Assaria (a location from downstream to upstream of the cutoff connecting Dry Creek with the Smoky Hill River [Figure 26)].

Even though all three gaging stations are located on a regulated stream (a stream course in which the flow is controlled by a reservoir or other surface impoundment) the mean annual flow patterns (Figure 29) roughly mirror annual precipitation. For example, the wet years of 1951, 1973, and 1993 are reflected in very high flows and the droughts of the mid-1950s, 1988-1991, and 2002-2006 are represented by the very low flows.

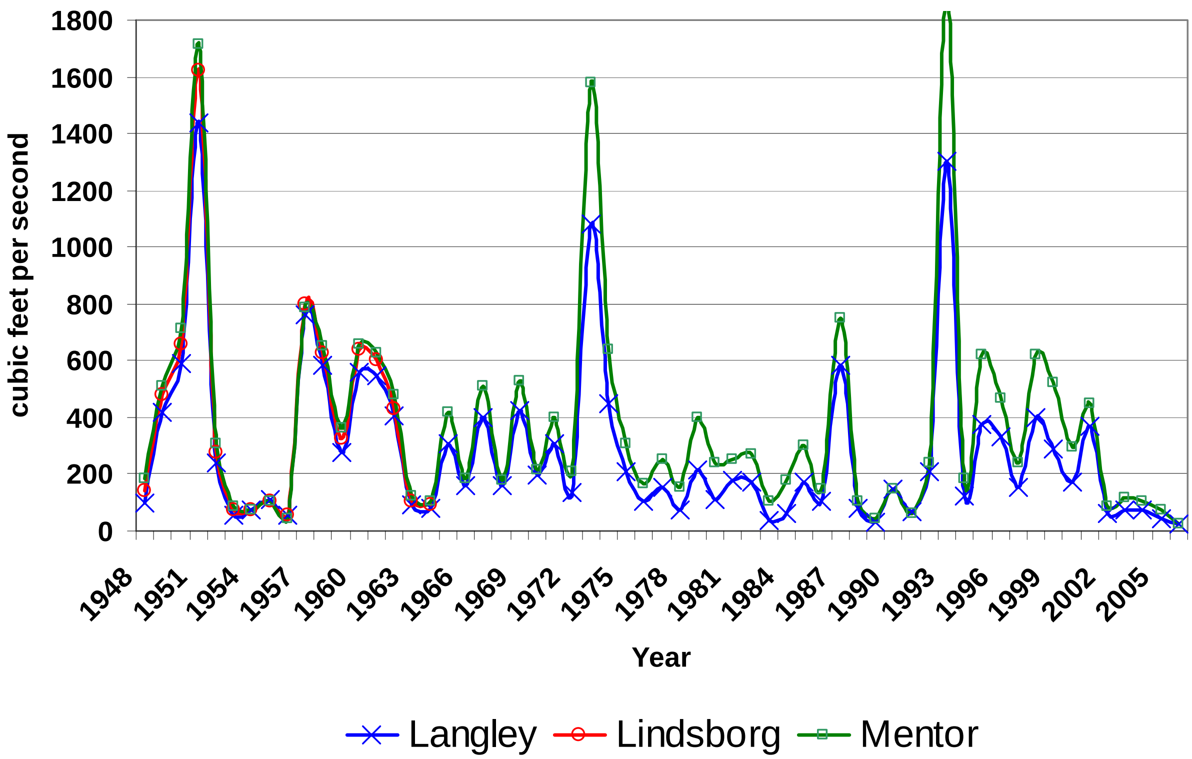


Figure 29. Mean annual flow in the Smoky Hill river.

Stream Segments and Reaches

The stream package for MODFLOW 2000 requires all surface water courses to be broken down into individual segments and reaches. A "segment" is a portion of a stream or river that is book-ended by notable characteristics, such as the confluence with another stream course or place of water diversion. Segments are further divided into "reaches" that represent a portion of a stream segment within an individual model cell. To adequately represent the Smoky Hill River and the various tributaries in the model, 64 segments were created with 1,018 reaches (since the construction of the Dry Creek flood control works). An example of this data structure is shown in Figure 30.

The Smoky Hill River contains 28 unique segments that are book-ended by points where inflow from 11 tributary streams, such as Wolf Creek (segment number 14 in Figure 30), enter the river or where the accumulated amount of surface diversions taken directly from the river along a particular segment are removed from the flow volume (segment number 16 in Figure 30). The locations of the individual diversion points from the Smoky Hill River, which were extracted from the Water Information Management and Analysis System (WIMAS) webs site, were assembled into small groups along sections of the river to reduce the stream complexity to a manageable level for the model. The surface-water diversions in the model are represented by 16 points, each indicating an individual diversion or group of diversions occurring within a relatively short stretch of the river. The WIMAS web site is the public portal to obtaining Kansas water right information via the internet. Data from the site is updated each day.

The segment/reach assignments change over the course of the transient period in order to account for the channel diversion structures along Dry Creek (Figure 26). This 1961 flood control structure captures all the surface runoff from Dry Creek and diverts it into the Smoky Hill River near Mentor. This is a change in the flow pattern requiring a new segment and reach number system.

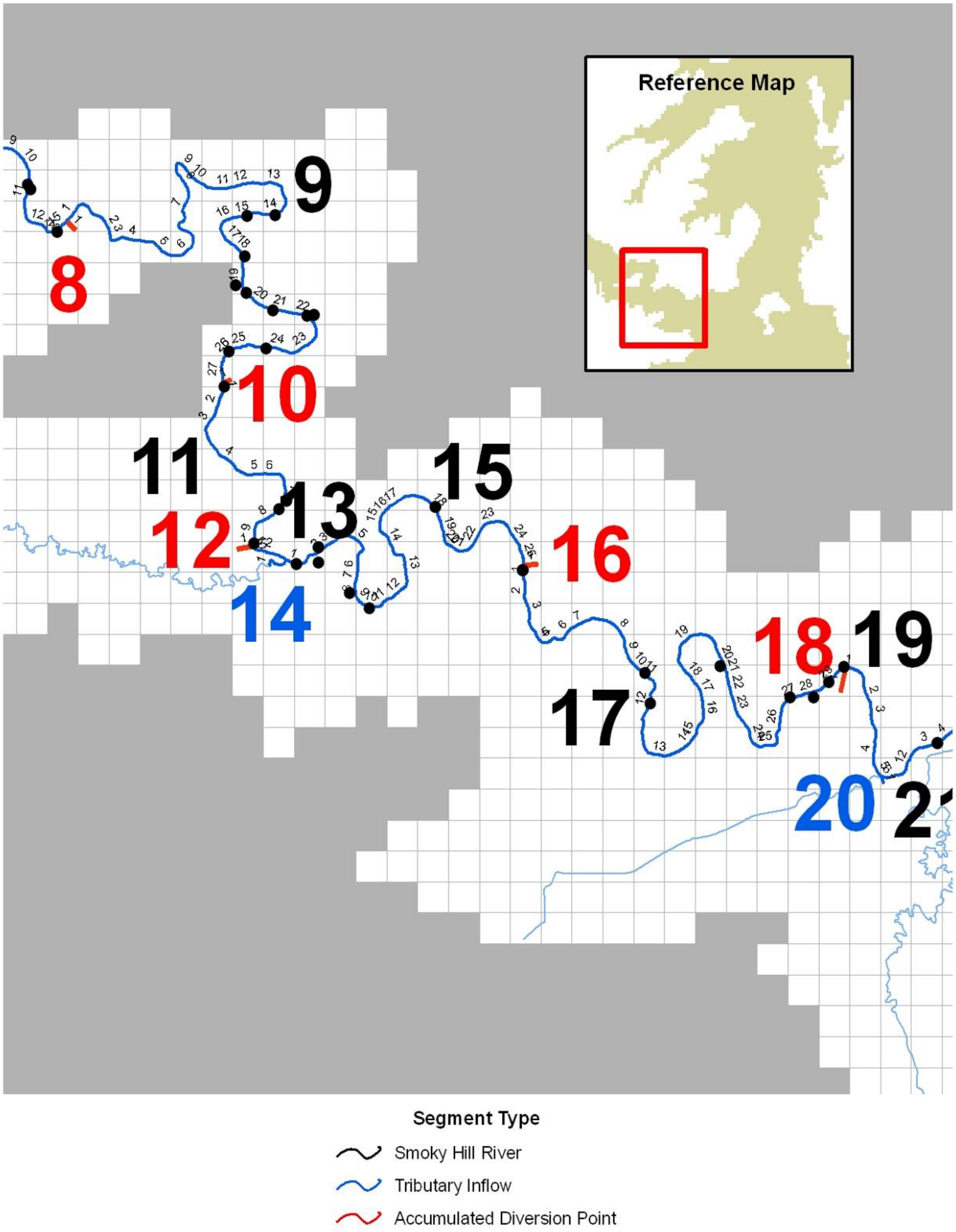


Figure 30. Selected area of the model showing segment and reach designations along the Smoky Hill River. For example, segment 14 is Wolf Creek, and segment 16 represents the accumulated diversion flow withdrawn from the river by the seven diversion locations (the black dots) along segment 15 of the river.

Tributary flow

Mean annual tributary flows for the predevelopment model were based primarily on data for estimated flows for Kansas streams in a USGS report (Perry et al., 2004). Flows for tributaries not listed in the USGS report were approximated by using a rough estimate of contributing source area and the general flow for this area relative to the USGS tributary data. The flow of each tributary was then adjusted by a factor computed from the mean flow of the Smoky Hill River at Langley during 1943-1947 divided by the mean river flow in the USGS report. Finally, the tributary flows were multiplied by 0.75, a factor used to reduce the tributary flows so that the sum of the tributary flows in the Langley to Lindsborg stretch of the river matches the difference in the river flows between Langley and Lindsborg during 1943-1947 minus a small amount for the expected ground-water discharge from the aquifer to the river in this area.

One of the larger uncertainties in the transient model period of 1948 to 2006 is establishing the flow values for each six-month time step for the 11 ungaged tributary streams simulated in the model. Just as a proxy well record was used for estimating the difference between winter and summer recharge, proxy records of streamflow for gaged streams in the region were employed for estimating the tributary flows from precipitation.

To setup this relationship, gaged flows from Gypsum Creek (just east of the model area), Salt Creek (north and west of the model), and Mulberry Creek (in the model area but only gaged from 2002 to present) were evaluated in relation to precipitation patterns (Figure 31). These gaging sites were selected because the sizes of their drainage areas are in the general range of some of the tributaries in the model area and their locations in the region mean that they have relatively similar precipitation patterns to the model area

Twelve-month totals of precipitation that were antecedent to each six-month transient period (October-March and April-September) for each year for which Gypsum, Salt, and Mulberry Creek flow data exist were computed using precipitation data best representing each of the three watershed areas. The 12-month precipitation records were used to classify antecedent moisture conditions as dry, normal, or wet relative to the average precipitation within each proxy watershed. The total precipitation for each of the six-month winter and summer periods was then calculated. The mean six-month streamflows for each of the winter and summer periods were calculated from observed data for each of the proxy watersheds and then plotted against the six-month precipitation values. Each point was identified as a dry, normal, or wet condition based on the 12-month antecedent precipitation. A power curve for each of the sets of points for the antecedent moisture conditions for each winter and summer period was visually fitted to the data because of the substantial scatter of points and to make the shapes of the curves for each watershed similar to one another. For example, Figure 32 illustrates the power curves for the three moisture conditions antecedent to April-September flow and precipitation for Salt Creek. A total of 14 curves were generated – one for each of the antecedent moisture conditions for both of the two winter and summer periods for the Gypsum and Salt Creek gages, and two for the Mulberry gage because of lack of long-term data (one curve each for the winter and summer seasons).

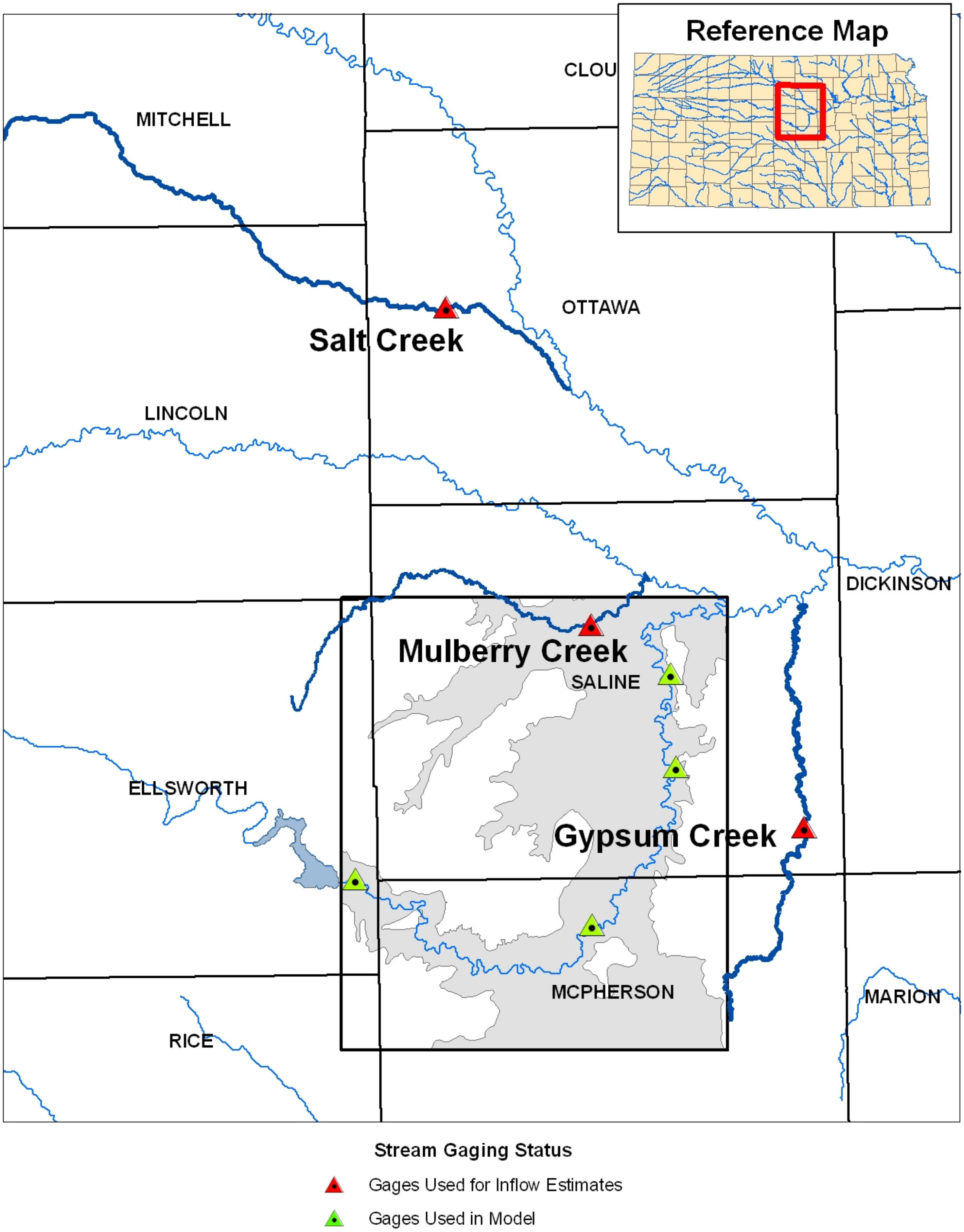


Figure 31. Gaged stream locations used for model tributary inflow estimates.

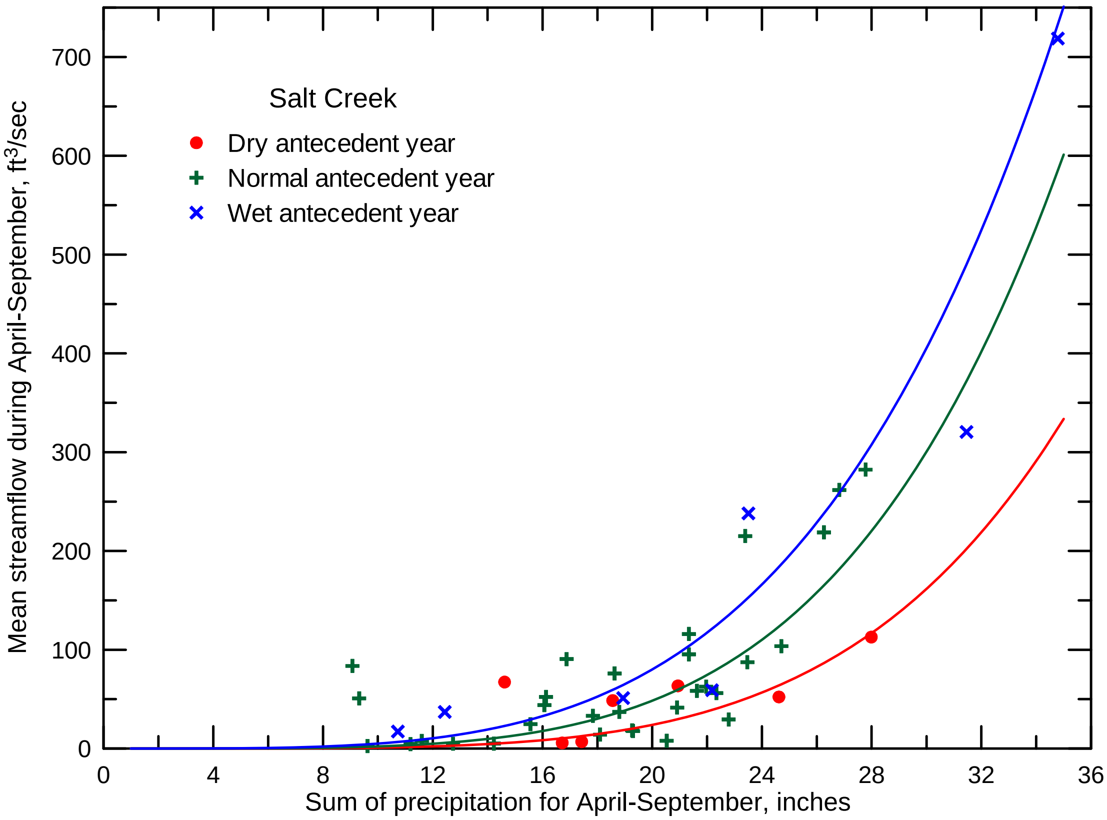


Figure 32. Example of visually fitted power curves.

The 14 curves were then divided by the area of the watershed above each gage site to produce 14 curves for flow versus area relationships. One power curve was then visually estimated to best represent each of the three antecedent moisture conditions for the two six-month periods for all of the proxy watersheds. The seven power curves and the three visual averages for these curves for the six-month winter and summer periods are shown in Figures 33 and 34, respectively.

The next step was calculation of the 12-month totals of precipitation antecedent to each of the six-month winter and pumping periods for each of the recharge zones in the model. These 12-month sums were used to classify the antecedent moisture conditions as dry, normal, or wet compared with the average long-term precipitation for each zone. This allowed the application of the appropriate curve in Figures 33 and 34 to the calculation of the streamflow for each six-month transient period based on the area of each watershed and the six-month total precipitation values for each zone.

During the final calibration phase of the model, in which small adjustments were made to better fit the river flow data, the application of the flow/area versus precipitation curves to computing tributary flow was modified slightly for selected six-month transient periods and recharge zones:

> 1951 April-September high flow – used dry antecedent function instead of normal function for zone 1, and used zone 3 precipitation for the three creeks (Kentucky and Pawnee creeks and Dry Creek south) downstream of zone 4 instead of zone 1 precipitation;

1993 April-September high flow – used normal antecedent function instead of wet function for all zones and used zone 3 precipitation for Kentucky and Pawnee creeks and Dry Creek south instead of zone 1 precipitation;

1980 October-March high flow – used dry antecedent function instead of normal function for zone 4;

2006 April-September low flow – used dry antecedent function instead of normal function for zones 1 and 3, and used zone 4 precipitation for Kentucky and Pawnee creeks and Dry Creek south instead of zone 1 precipitation.

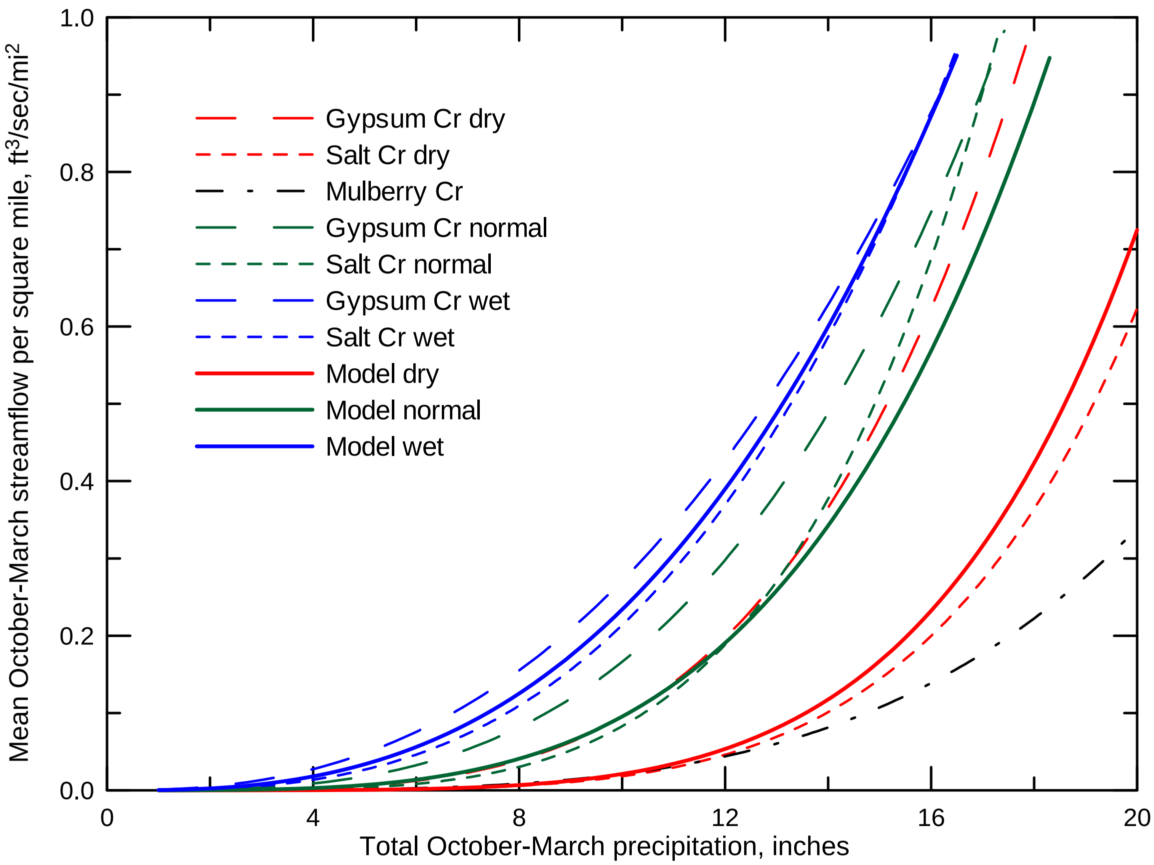


Figure 33. Power curves for streamflow versus precipitation for the October-March period classified according to antecedent moisture conditions. The three solid curves are the visual averages used to estimate tributary flow during the winter season in the transient model.

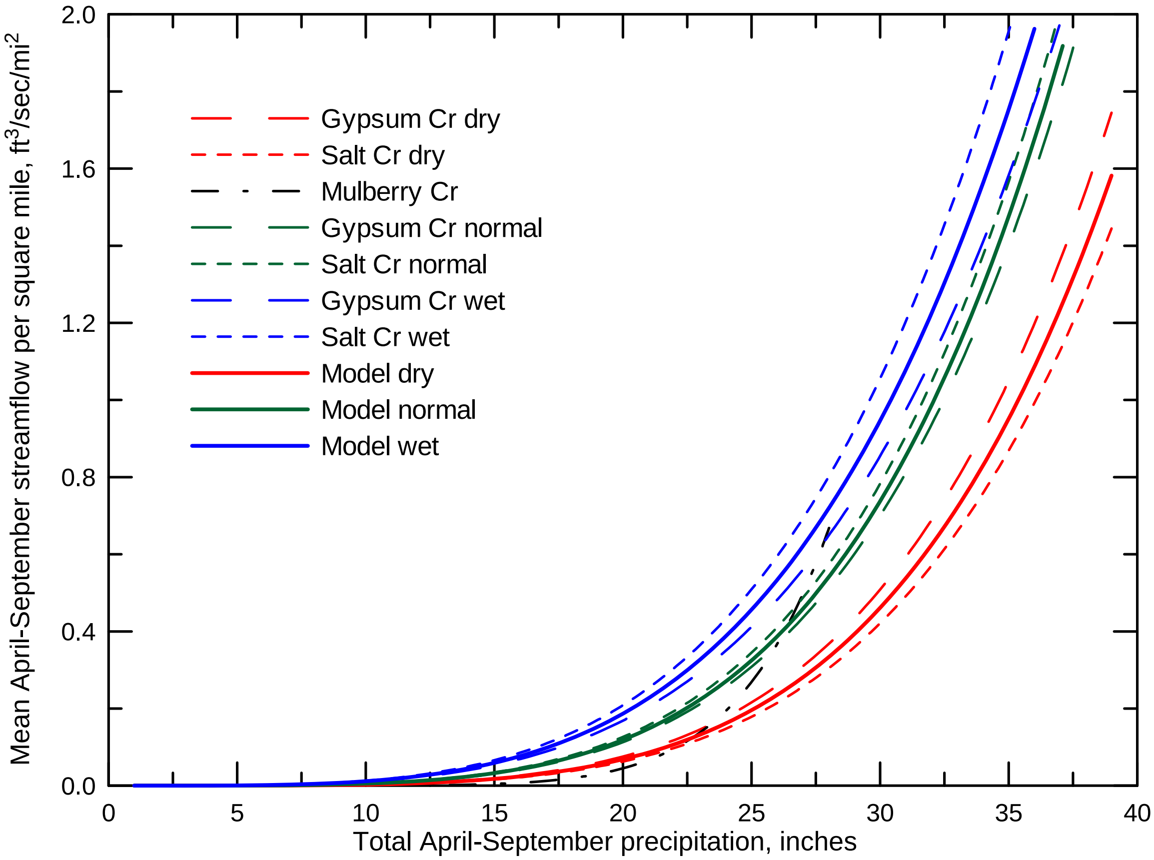


Figure 34. Power curves for streamflow versus precipitation for the April-September period classified according to antecedent moisture conditions. The three solid curves are the visual averages used to estimate tributary flow during the pumping season in the transient model.

Stream-Aquifer Interactions

During low to moderate streamflow conditions in the Smoky Hill River, some ground-water discharge from the alluvial aquifer is expected to occur, especially following a wet antecedent period, and some ground-water recharge from the river is expected during high stream stage. However, withdrawals of ground water from the alluvial aquifer for supply purposes could increase the periods when the river loses water to the aquifer. The difference in flow between the Langley Gage (start of the model) and Mentor (in the downstream end of the model) shows that most of the time the Smoky Hill River is a gaining stream, meaning that as the stream flows across the model area, it gains additional water from surface- and ground-water sources (Figure 35). There are periods, however, when the river becomes a losing stream between the two gaging stations, especially during periods of dry conditions during the summer pumping season. Under these conditions, water is lost from the river, either from direct diversions or seepage into the hydrologicially connected portions of the alluvial aquifer system.

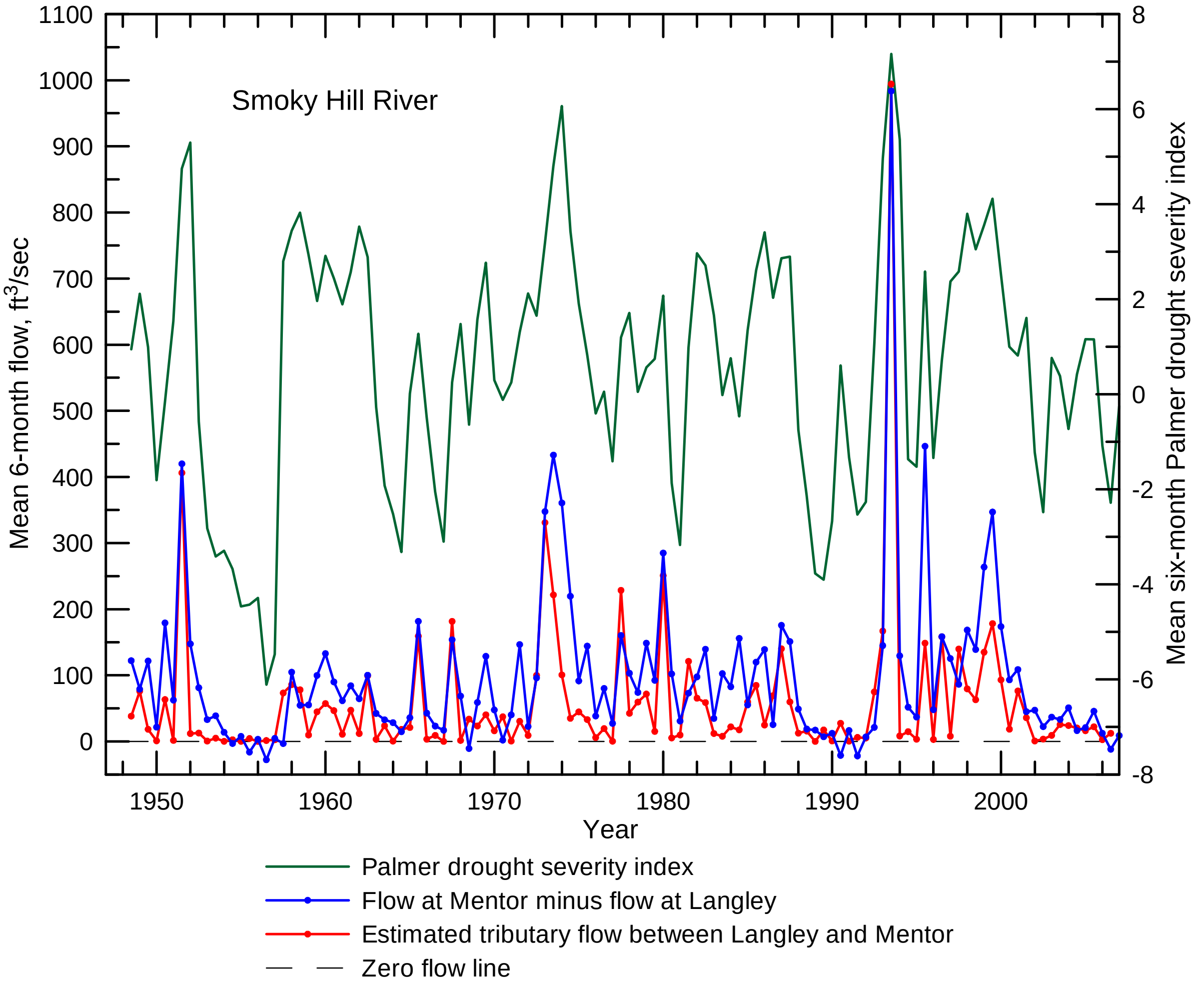


Figure 35. Observed mean six-month flow at Mentor minus flow at Langley compared to estimated mean six-month flow for tributaries entering the Smoky Hill River between Langley and Mentor and the mean six-month Palmer drought severity index for the central climatic division in Kansas.

Three periods of a few years of continuously low tributary flows and of either little gain or a small loss in river flow in the Smoky Hill River are evident in Figure 35 – the mid-1950s, 1988-1992, and 2002-2006. An indicator of climatic conditions, the Palmer drought severity index (PDSI), was also generally low during these periods, especially in the mid-1950s. A flow loss occurred in the river between Langley and Mentor during the April-September periods of 1954-1957, 1968, 1990, 1991, and 2006. The PDSI was the lowest during the mid-1950s, and correlated well with the stream losses during this time. However, some of the other periods of negative flows do not correlate as well with the PDSI, partly because the PDSI represents the conditions over the entire central division of Kansas rather than the specific area of the model and partly because water-supply withdrawals have become a more important influence on streamflow. In general, the flow losses have occurred during increasingly less severe PDSI drought conditions since the mid-1950s.

The greatest gains in river flow between Langley and Mentor have occurred when the PDSI has indicated very wet conditions (Figure 35), especially for flows during April-September of 1951, 1973, 1993, 1995, and 1999 (flow gains of about 350 ft^3/sec or greater). The total tributary flows entering this stretch of the river were also high during these periods. For some of these and other very high flow-gain periods, the total tributary flow was nearly as great as the river gain. These periods often occurred when there was a spike in the PDSI following a few years of normal to dry conditions. In other instances, there was a significant difference between the tributary flow and the river gain, meaning that ground-water discharge to the river was substantial. These periods often occurred when the PDSI for the previous few years indicated wet conditions, during which ground-water recharge could have been substantial.

The river flow differences during the dry conditions illustrated in Figure 35 were used as targets to refine the numerical model during the end of the project. The goal involved improving the match with the flow gains and losses during the dry periods using the flow difference, which is a more sensitive indicator of stream-aquifer conditions than the flows at the individual gaging stations.

Water Right Development

Water rights in Kansas can be very dynamic and change over time in a variety of fashions and for a number of reasons, requiring extensive data processing operations to be time-stamped. The authorized quantity and water right locations used in the model represent conditions as of February 26, 2007, and May 14, 2007. The data represent 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.

Virtually all the surface-water development within the model area is from the Smoky Hill River and nearly all the ground-water from the alluvial deposits in the river valley, with a much smaller amount from the northernmost part of the Equus Beds aquifer to the south of the river valley (Figure 36). There are some wells screened in the Dakota aquifer and Wellington Formation but these are outside the active area and thus not considered in the model.

Within the model area, withdrawals for irrigation and municipal uses from both ground and surface water sources represent the largest development types. Ground-water based irrigation is the largest use of water followed by ground-water based municipal uses (Table 2). Surface water irrigation and municipal uses of water are the next highest authorized quantities in the area. Domestic, industrial, recreational, and stockwater uses are all relatively insignificant in terms of total authorized volumes.

Table 2
Total Authorized Quantity by Use Made of Water and Source of Supply
Smoky Hill Model Area
Represents conditions as of February 26, 2007

	Domestic	Industrial	Irrigation	Municipal	Recreation	Stockwater	Total
Surface	12.79	29.70	7,694.60	5,028.07	245.75	0	13,010.90
Ground	70.98	594.91	14,446.08	8,470.27	234.27	439.80	24,256.32
Total	83.77	624.61	22,140.68	13,498.33	480.02	439.80	37,267.20

The WIMAS database only stores the current authorized quantity for water rights. Historic trends in the authorized quantity are based on the priority date of water rights and are assumed to be representative of past conditions. Over the model period of 1945 to 2006, development of the ground-water source in the model area, particularly for irrigation, has been steadily increasing in comparison to surface-water sources, which have remained fairly static since the 1970s (Figure 37). The City of Salina represents the largest water right holder in the model area and the main development of the City's surface water (1954) and ground-water (1957) are apparent in the increases in the lines representing municipal and industrial uses in Figure 37.

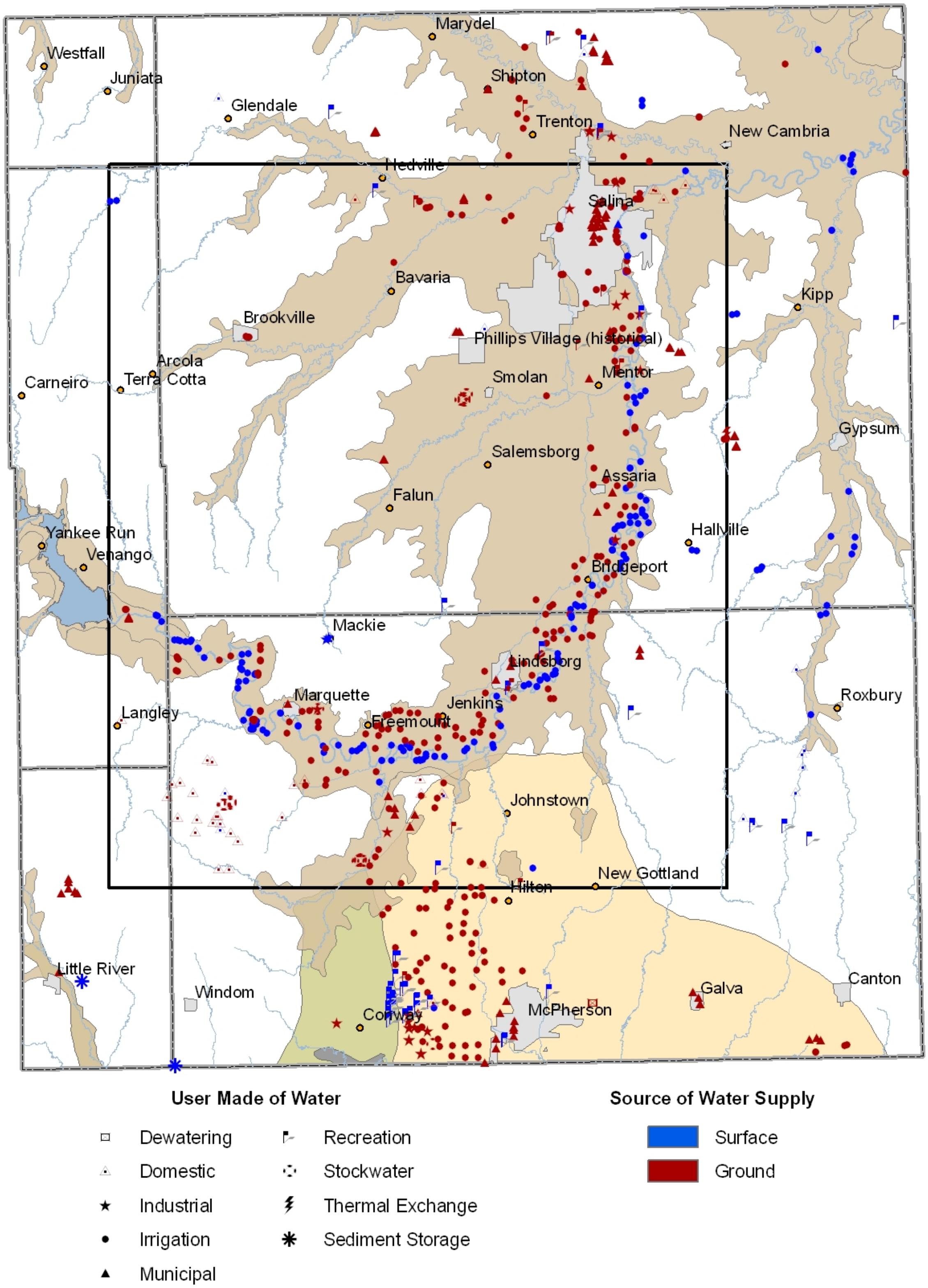


Figure 36. Water right development across the model area.

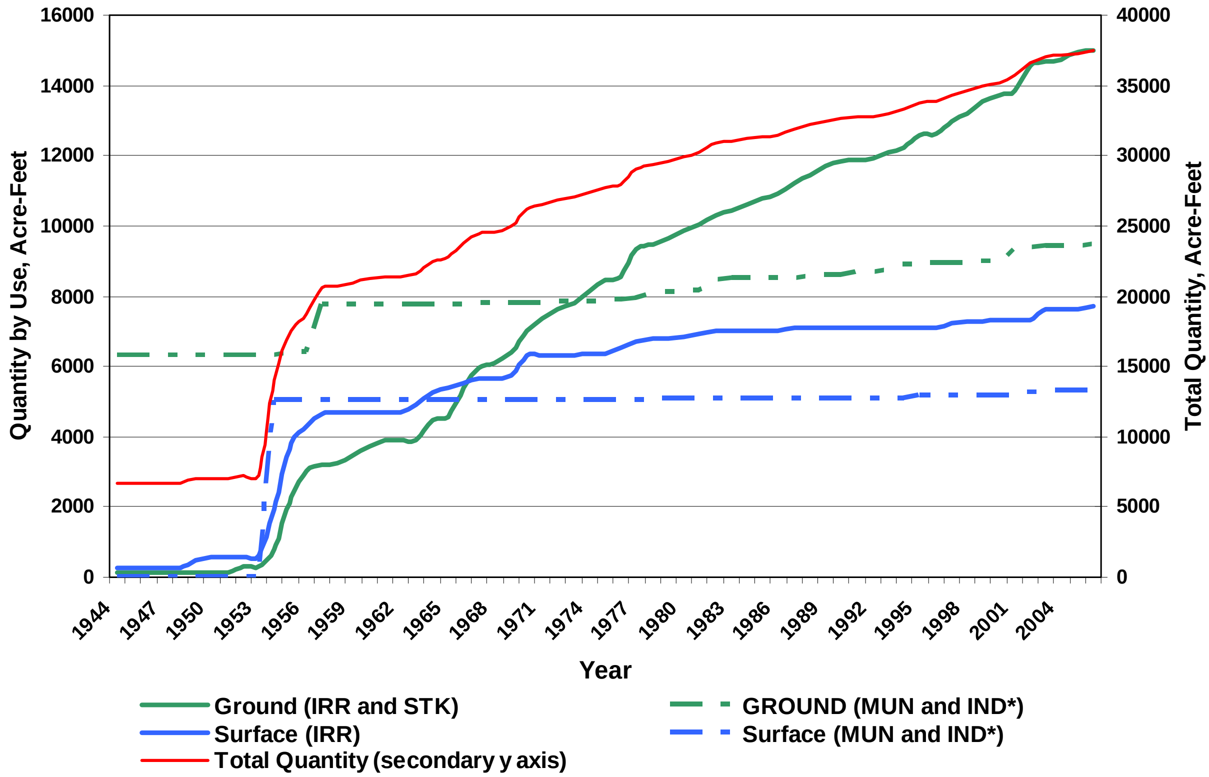


Figure 37. Total authorized quantity for the Smoky Hill River model area, May 14, 2007.

<u>Historic Water Use</u>

Reported water use records from 1990 to 2005 were downloaded from WIMAS on May 16, 2007 (at the time of the model development, 2006 water use was not publicly available). The 1990 water use is the first year the Water Use Program of the Kansas Water Office was initiated. Now operated through the KDA-DWR, this program provides quality control and assurance to water use reports submitted annually to the KDA-DWR.

Over the 1990-2005 period, ground-water was the primary source of water reported to be diverted for both agricultural (primarily irrigation) and municipal/industrial uses (Figure 38). Surface water, however, also represents a significant source of supply for irrigation and municipal/industrial applications. All surface-water uses and ground-water use for agriculture peaked by the end of the 1988 to early 1992 drought, fell substantially during the wet period from the last half of 1992 through 1993, and then generally increased to 2005. The total water use for all purposes and from all sources also shows this pattern. Ground-water pumped for municipal and industrial uses increased from 1990 to 1997 and then generally decreased to 2005 to amounts about the same as for surface water used for these purposes.

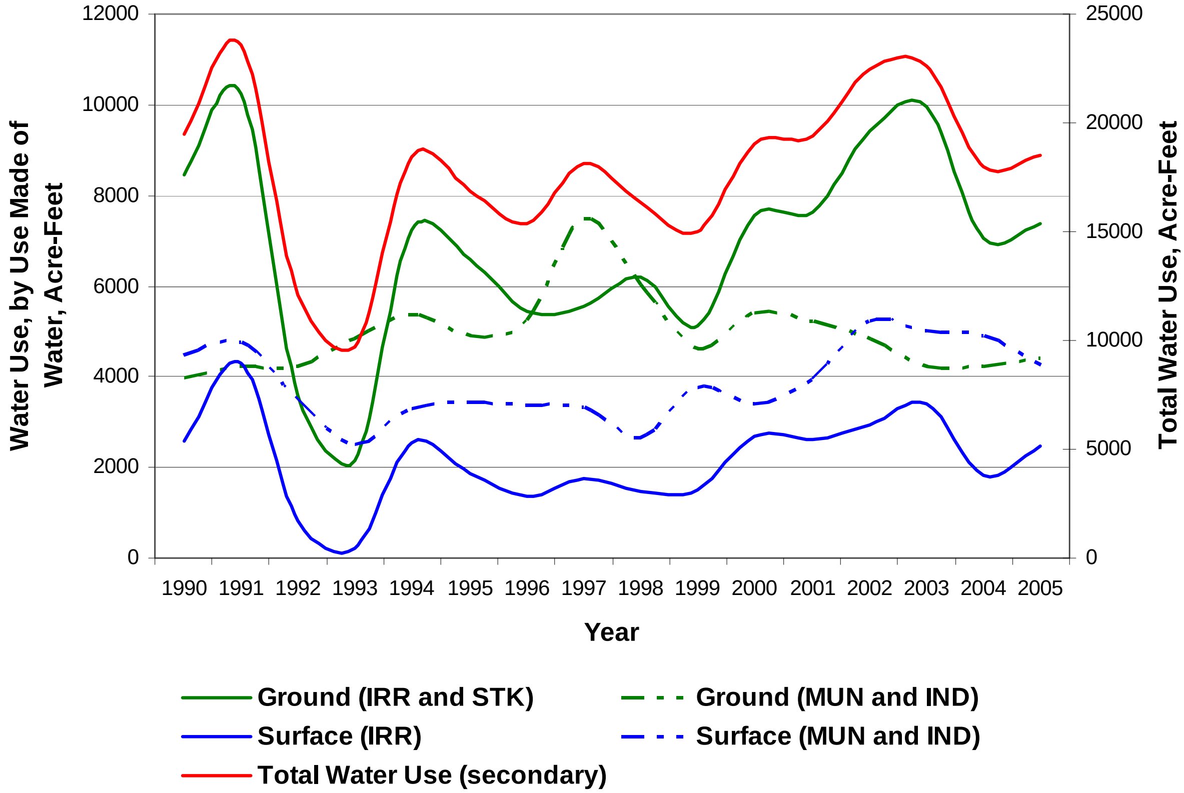


Figure 38. Total reported water use, 1990 to 2005, for the model area.

Annual rates of precipitation and the total amount of water diversions reported are inversely related, for which the statistical correlation coefficient is -0.8588. This relationship is statistically significant at the .01 level (statistically speaking, there is a 1 in 100 chance this relationship exists by mere chance). This inverse relationship, shown in Figure 39, was used to estimate how much ground-water pumping and stream diversions occurred before 1990.

In order to estimate historical pumping and stream diversions prior to 1990, linear regression equations were determined for the ratio of water use/authorized quantity versus precipitation for both use types (agricultural and municipal/industrial) and water sources (ground and surface). The actual reported volumes could have been used for the regressions; however, the steep slope of authorized quantities during the early development period often results in negative water use being calculated for the early years of the transient period. The computed ratio of reported water use divided by the authorized quantity (what could be pumped) is always a fraction. This fraction is then multiplied against the authorized quantity to get an estimate of water use each year.

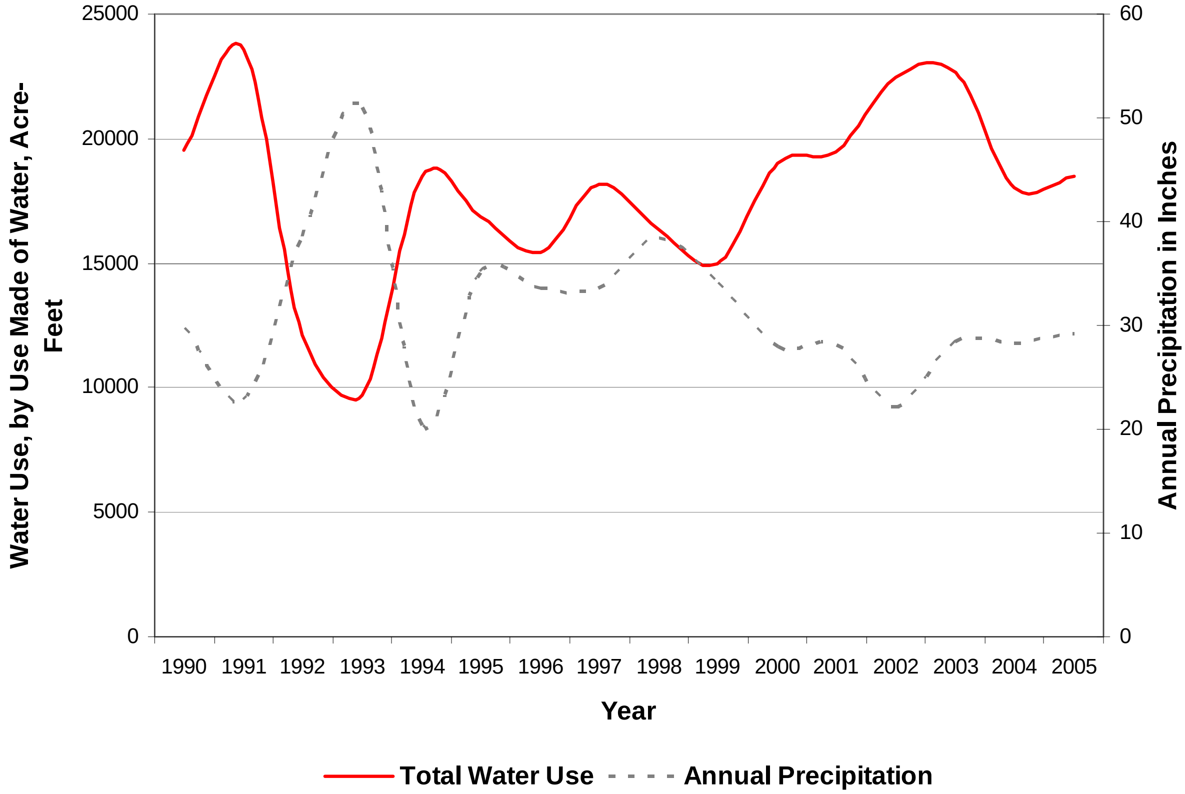


Figure 39. Total Reported Use and Annual Precipitation, 1990 to 2005

The linear regression equations were established based on the 1990 to 2005 time periods and are listed in Table 3. Irrigation and stockwater uses were combined to represent agricultural uses, although irrigation is by far the dominate use. Likewise, municipal and industrial uses were combined to represent population based uses although municipal is by far the largest use. Linear regression equations for surface water sources and applications that were from streams other than the Smoky Hill River were also developed. However, given that the amount of water estimated reported actually diverted was so small relative to the rest of the model, this information was not used.

Table 3
Linear Regression Equations for Water Usage
Smoky Hill Model Area

Use/Source	Wuse/Qty Equation	R-Squared
Ground-water Agriculture	1.0292 + precipitation * -0.0171	0.7066
Ground-water Population	0.43031 + precipitation * 0.00270	0.8631
Surface-water Agriculture	0.78894 + precipitation * -0.01577	0.6762
Surface-water Population	1.03778+ precipitation * -0.01222	0.4223

Regression results for ground- and surface-water sources are shown in Figures 40 and 41, respectfully. Within the model area, water diversions for ground-water sources were taken out of the cells in which the wells are located. For surface-water sources, the total diversions along a limited stretch of the Smoky Hill River were summed and taken out at the downstream end of that river segment. There are 16 points for surface-water diversion along the river (see the section on stream characteristics and flow for an illustration of example river segments for which surface-water diversions are summed). Figures 40 and 41 show the substantial annual variations in water use based on precipitation while following the general trend in the authorized quantity. The regressed values of water use for 2006 plotted in both figures were used in the model. The reported quantities for 2006 became available from the KDA-DWR later during the modeling project. The figures indicate that the 2006 use values derived from the regression equations match the reported 2006 values relatively well.

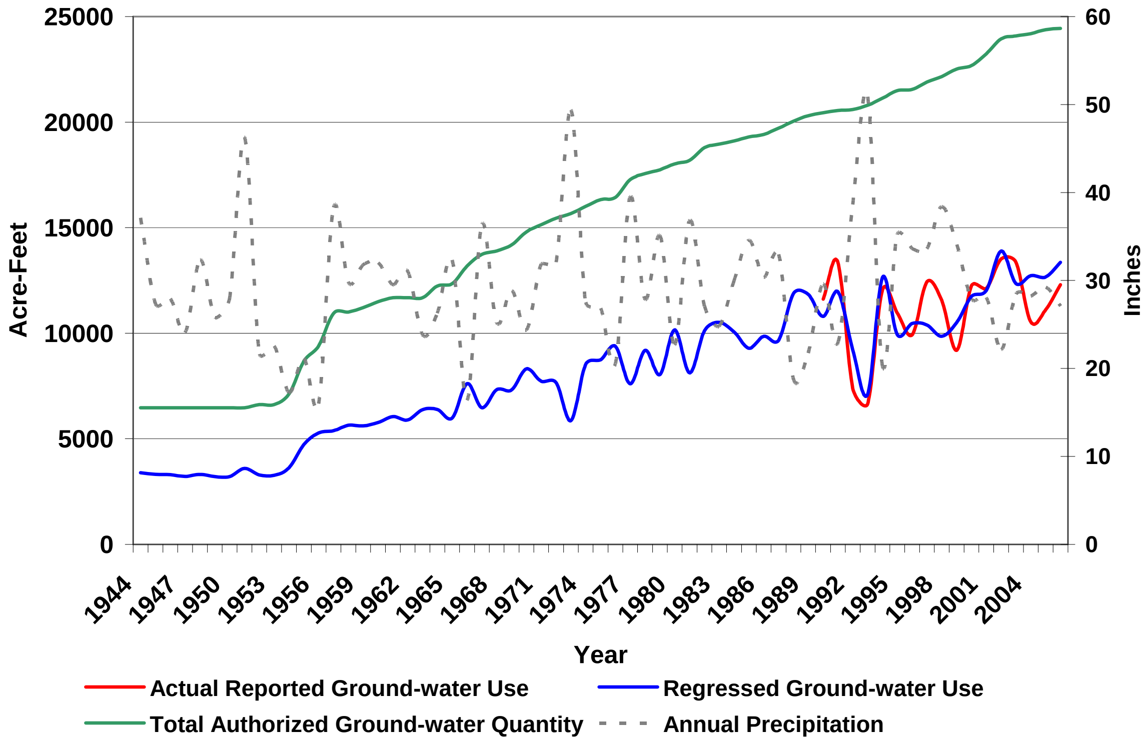


Figure 40. Regressed versus actual reported ground-water use.

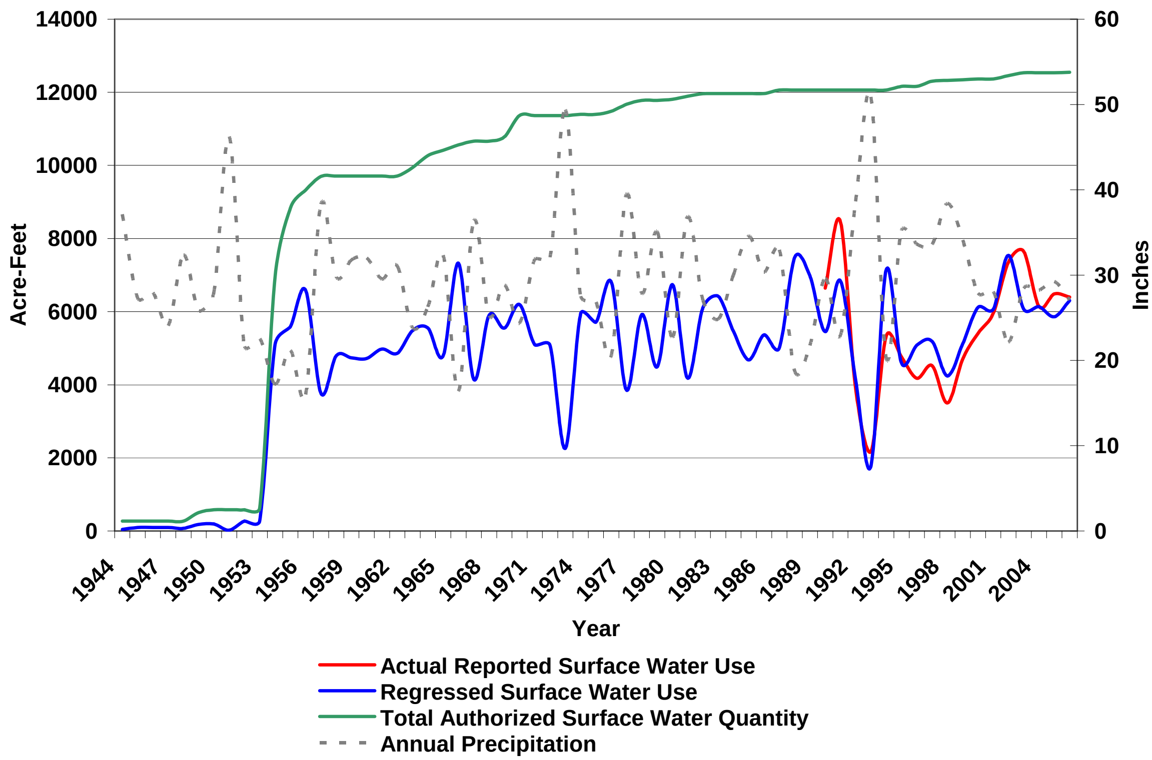


Figure 41. Regressed versus actual reported surface-water use.

Reported water use represent annual values. To fit within the model's six-month time steps, all irrigation-based water use occurs in the growing season step from April to September. All non-irrigation water use is divided so that 62% of the annual total is used in the growing season step and 38% during the winter months of October to March. This ratio follows a monthly water use percentages used by the KWO when dealing with water use on a state-wide basis.

<u>Irrigation Return Flows</u>

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 flow. The rate of this return flow is determined by a variety of factors, one of which is the type of irrigation system deployed. For the most part, flood irrigation systems are the most common in the modeling area, followed closely by center pivot systems. 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 flow over time.

To simulate irrigation return flow in the model, return flow 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. Each designation of system type listed in the KDA-DWR water use reports was assigned a particular fraction of return flow as follows in order of decreasing percentages: flood irrigation 20%, center pivot and flood 13%, center pivot 7%, sprinkler other than center pivot 7%, center pivot LEPA 5%, subsurface drop (SDI) in combination with other type 3%, and trickle drip 2%. These percentages are a few percentages smaller than used in the Middle Arkansas subbasin model because it is estimated that the relatively low permeability of the silts and clays in the soils and in the upper confined layer of the aquifer in the alluvial valley in comparison with the generally sandier soils in the Middle Arkansas subbasin reduces irrigation return rates.

Data on the irrigation system types reported with water use were extracted from WIMAS for 1991-2005 for the model area. The average return flow percentage was computed for each year of 1991-2005 based on the count of each type of irrigation system and the percentages of return flow assigned for each type. 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 transition between the dates along with manual adjustment for small variations based on fluctuations in return flow fraction determined for the Middle Arkansas model, for which some data on irrigation systems were available for before 1991. Figure 42 shows the change in the fraction of irrigation water returned with time for the model compared to that used in the model for the Middle Arkansas River subbasin. The trend in the return flow fraction for the Smoky Hill River valley is gentler than that for the Middle Arkansas subbasin due to the larger number of flood irrigation systems still in use today.

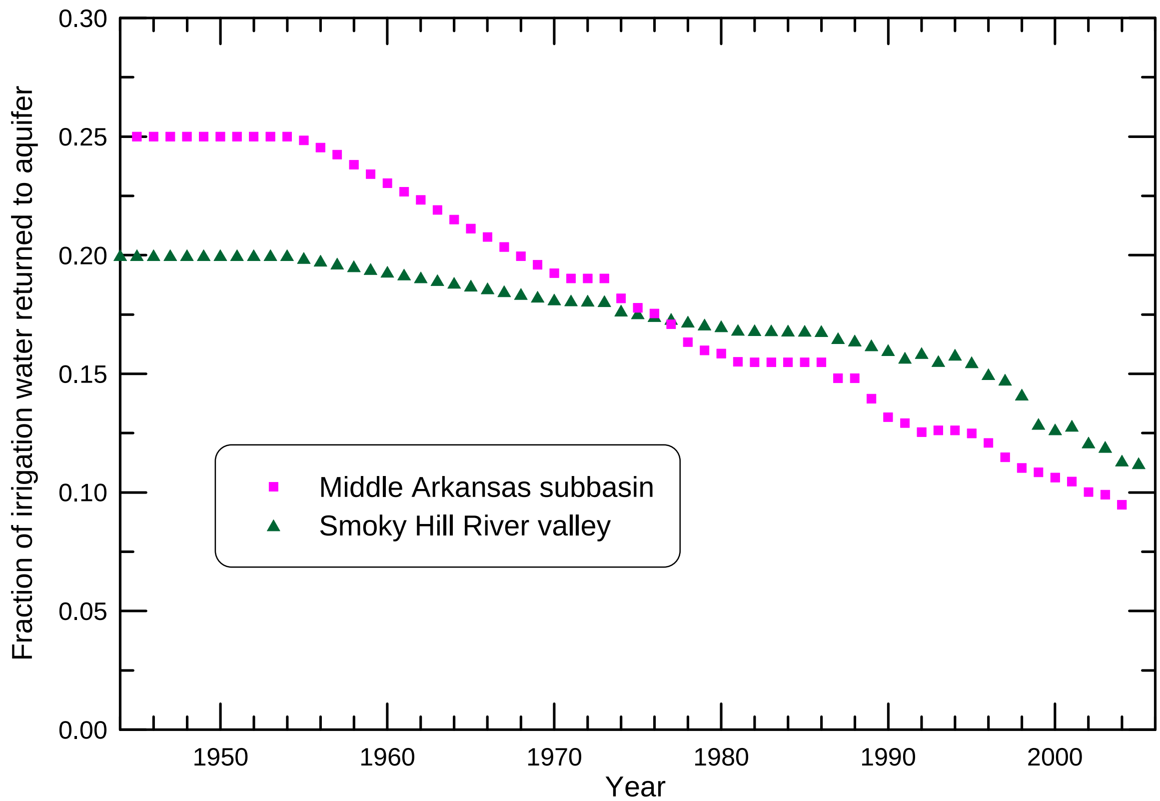


Figure 42. Fraction of applied irrigation water returned to the aquifer for the Smoky Hill River Valley and Middle Arkansas River subbasin models.

The fraction for each year in Figure 42 was multiplied by the irrigation water use to obtain the return flow. For ground-water pumping, the amount of irrigation water returned to the aquifer was removed from the gross diversions occurring each year in each model cell. This essentially creates a net pumping volume. For irrigation surface diversions, which are totaled along stream segments of limited length before being removed from the 16 diversion points along the river, the return flow volumes are applied to the model cell in which the point of the stream diversion is located. In essence, these points of surface irrigation withdrawals also become recharge points where the calculated return flow is passed back to the aquifer.

Evapotranspiration

Annual evapotranspiration (ET) is simulated within the main alluvial zones 1 and 4 (Figure 2) to represent the amount of water removed from the aquifer by phreatophyte-induced water loss along the river. Annual ET depends on water levels in the aquifer and the loss from aquifer only occurs if the water level is at five feet or less below the land surface. The maximum ET rate that can occur each year is 15.55 inches, which occurs when the water-level is at the land surface. The ET is linearly interpolated between the land surface maximum and five-foot extinction depth based on the water-level surface in the cells in zones 1 and 4 for each year of the transient model.

PREDEVELOPMENT MODEL CALIBRATION AND SIMULATION

In addition to establishing the initial conditions for the subsequent transient simulation, the predevelopment simulation also allows determining some model parameters because of the relative abundance of predevelopment data in the area. The predevelopment simulation was taken as steady-state as there was no large-scale, intensive pumping and water levels remained relatively constant. The major data sources for predevelopment simulation were compiled for the period between 1943 and 1947, as the majority of KGS bulletin water-level data were collected during this period. The hydrologic conditions, including precipitation, temperature, and streamflow, were similar to their historic mean values between 1943 and 2006. The Palmer Drought Severity Index (PDSI) values for 1943 through 1947 ranged from -0.84 to +2.18, which is a moderate range for the drought index, and there are no extremely wet or dry conditions during that time span.

Model Characteristics

The model incorporates zones for hydraulic conductivity, recharge, evapotranspiration (ET), and streambed conductivity. As indicated in Figure 2, four zones are used to represent the hydraulic conductivity and recharge in the model area. The zonal values for the hydraulic conductivity and recharge are calibrated using the observed water levels and streamflows.

ET was only considered in the main alluvial zones. The maximum ET rate at land surface and the extinction depth were estimated using the observed water levels and streamflows during the predevelopment simulation, and remained unchanged in the subsequent transient simulation. 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.

Streambed conductivity was divided into two zones: the Smoky Hill River and the tributary streams. The streambed conductivity values were estimated using the observed water levels and streamflows during the predevelopment simulation, and remained unchanged in the subsequent transient simulation.

Predevelopment Model Calibration

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 the ground-water levels and stream flows at the gaging stations (Figure 43). As the ground-water levels and stream flows are very different in terms of their units, data accuracies, and practical relevance, the stream flow data were log-transformed and multiplied by a factor of 50 before they were used in the calibration. Recharge, hydraulic conductivity, and streambed conductivity were considered as the parameters to calibrate due to their relatively large uncertainties and high impacts on the model results. Specifically, a total of 10 parameters, including the hydraulic conductivity for zones 1 through 4, recharge for Zones 1 through 4, streambed conductivity for the Smoky Hill River, and streambed conductivity for the remaining tributary streams, are calibrated to improve the match between the simulated and observed groundwater levels in the selected wells and stream flows as indicated on Figure 43. To facilitate the calibration process, the parameter estimation program PEST (Doherty, 2004) was employed. Table 4 displays the calibrated values and sensitivities for hydraulic conductivity, recharge, and streambed conductivity for the predevelopment simulation.

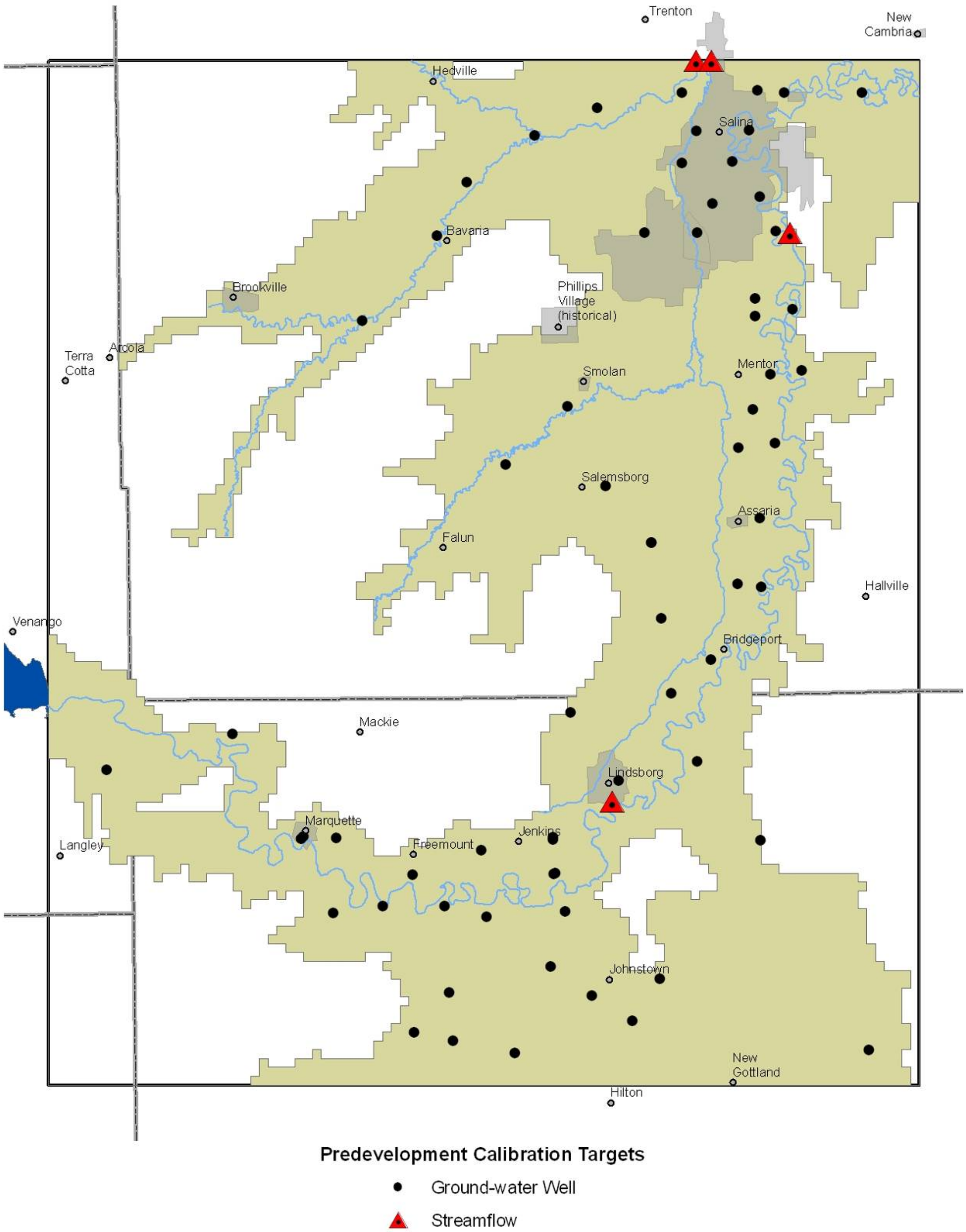


Figure 43. Calibration targets in the predevelopment simulation.

Table 4 **Calibrated parameter values and sensitivities in the predevelopment simulation** Streambed conductivity for the Smoky Hill River is 0.1 ft/day with sensitivity 0.26 Streambed conductivity for the tributary streams is 0.5 ft/day with sensitivity 0.24					
		Zone 1 Main Alluvium	**Zone 2 Equus Beds**	**Zone 3 Terrace**	**Zone 4 Upland alluvium**
Hydraulic Conductivity (ft/day)	**Estimate**	230.0	172.0	123.0	220.0
	Sensitivity	0.38	0.45	0.67	0.24
Recharge (inch/year)	**Estimate**	1.34	0.64	1.05	0.64
	Sensitivity	0.27	0.44	0.99	0.06

Sensitivity Analysis

Sensitivity analysis is an approach for assessing the impact of parameter uncertainty on model results, which 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 estimated as reliably as possible. As sensitivity results will change when any part 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,

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

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 stream flow at observation time *i*. *N* is the total number of observation data points used in sensitivity calculation. Similar to the model calibration process, data d_i include the groundwater levels and stream flows at the gaging stations. Scaling the sensitivity by the corresponding base value $\hat{p}$ gives results that are more indicative of the actual influence of p and allows us to compare more appropriately the values computed for different parameters.

Table 4 lists the sensitivities of hydraulic conductivity, recharge, and streambed conductivity computed by a parameter estimation package, PEST [Doherty, 2004]. During the predevelopment simulation, the most sensitive parameter is the recharge specified for the terrace deposits in Zone 3.

Predevelopment Model Results

Figure 44 shows simulated groundwater levels using the calibrated parameter values, as compared to the GIS interpolated predevelopment data. Despite the local mismatch in certain areas (e.g., the eastern part of High Plains Zone 2, the upstream portion of Smoky Hill River valley), simulated ground-water levels show excellent agreement with the observed data, particularly in the main alluvial aquifer zone along the Smoky Hill River valley. In terms of practicality, the main alluvial aquifer is where the water has been developed and we have the most information to properly compose the model. The Residual Sum of Squares (RSS) between the simulated and observed water levels at the target locations is 0.93×10^4 ft^2. Note that between Kanapolis Reservoir and Marquette, the permeable zone is thin, the hydrogeological conditions (such as hydraulic conductivity, bedrock elevations) show significant variations, and data coverage is extremely limited. As a result, the calibrated model does not match the ground-water level data collected from the few wells in this area.

Table 5 shows the simulated versus observed or field-estimated streamflows at various gaging stations in the predevelopment simulation. Overall, the calibrated model provides a good match to the stream-aquifer interactions and the streamflow data. The data indicate that the Smoky Hill River is a gaining stream during the predevelopment period. Table 6 shows the ground-water budgets in the predevelopment simulation. Precipitation recharge is the main source of inflow and accounts for 60% of the total inflow budget. On the other hand, discharge to the Smoky Hill River and tributary streams accounts for 86.6% of the total outflow.

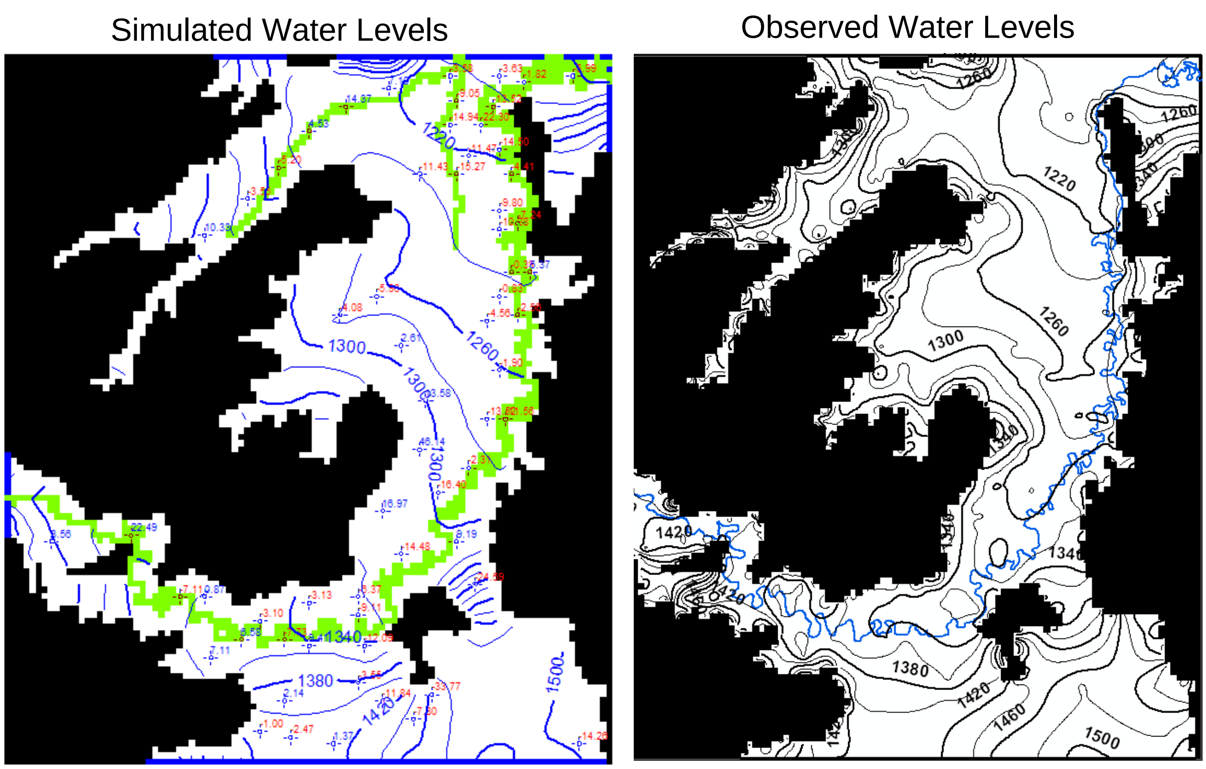


Figure 44. Comparison of the simulated water levels based on the calibrated parameter values in Table N1 and the GIS interpolated data during the predevelopment period. The Residual Sum of Squares (RSS) between the simulated and observed water levels at the target locations is 0.93E+04 ft^2.

Table 5 Simulated versus observed or field-estimated streamflows at the gaging stations.					
	Net Gain of the Smoky Hill River and Tributary Streams (cfs)	**Stream Flow @ Mentor (cfs)**	**Stream Flow @ Lindsborg (cfs)**	**Stream Flow @ Dry Creek (cfs)**	**Stream Flow @ Mulberry Creek (cfs)**
Observed	31.72	308.8	265.4	22.1*	48.5*
Calibrated Model	28.05	293.9	274.2	19.8	55.0

* USGS Estimate

Table 6 Predevelopment groundwater budget.				
	Constant-head boundaries	**Streams**	**Recharge**	**ET**
Inflows (acre-feet/yr)	8,374	4,106	18,912	0
Outflows (acre-feet/yr)	4,106	24,413	0	4,106

TRANSIENT MODEL CALIBRATION AND SIMULATION

The transient simulation was conducted to model the historic evolution of ground-water systems and stream-aquifer interactions from predevelopment to 2006, during which ground-water pumping and streamflow diversion activities became intensive and produced noticeable changes in ground-water levels as well as streamflows over the period. The transient simulation starts with the predevelopment steady-state period that establishes initial conditions. Between 1948 and 2006, a six-month stress period was used with the months of April to September representing the “Growing Season” and October to March representing the “Winter Season.” Irrigation-related pumping activities are assumed to occur in the growing season. Non-irrigation water uses are divided into 62% in the growing season versus 38% in the winter season based on water-use data from the Kansas Water Office. There are a total of 119 stress periods in the transient simulation.

Some of the model settings in the transient simulation are identical to those in the predevelopment period. Specifically, the ET settings, the hydraulic conductivity for different aquifer zones, and streambed conductivity for the Smoky Hill River and tributary streams in the predevelopment period were held constant in the transient simulation. It is noteworthy that water-level data are relatively more abundant in the predevelopment period. Therefore, the values for the hydraulic conductivity and streambed conductivity obtained from the predevelopment calibration were considered to be reasonable and adequate. Recharge is the only parameter that was calibrated in the transient simulation.

The model settings that needed to be modified for the transient simulation include the time-varying specified-head boundaries, aquifer storage, recharge, ground-water pumping and irrigation return flow, and stream characteristics.

Model Characteristics

Time-varying specified-head boundaries

Time-varying specified-head boundaries were used for the active model boundaries during the transient simulation. As described earlier, the lack of long-term, continuous water-level measurements in the model area made their creation a challenge. Two approaches for the three locations of primary head boundaries were used – one for the head boundaries of the alluvial aquifer and the second for the Equus Beds aquifer boundary along the south edge of the model.

The water levels interpolated for the specified-head boundaries were assumed to be constant during each six-month stress period, whereas between different stress periods, the boundary heads were changed stepwise. This stepwise approach is more reasonable as the main aquifer zone in the model area is confined and shows quick head responses to aquifer stress changes such as irrigation pumping.

Aquifer storage

As ground-water levels change with time in the transient simulation, the aquifer releases or absorbs water, the rate of which depends on both the magnitudes of water-level change and the aquifer storage coefficients. Based on the previous study by Gillespie and Hargadine (1986), a uniform value of 0.15 was applied to the specific yield of the entire model area. For portions of the aquifer that are under confined conditions, a storage coefficient of 1.0×10^{-5} was used. The aquifer was assumed to always have a minimum saturated thickness of five feet.

During model simulation, the unconfined or confined condition of each aquifer cell is determined by comparing the simulated water level to the top elevation of the permeable zone. If the simulated water level is above the top of permeable zone, the aquifer cell is confined and the storage coefficient of 1.0×10^{-5} is used to calculate the amount of water gained or lost in the cell. If the simulated water level is below the top of permeable zone, the aquifer cell is unconfined and the specific yield of 0.15 is used. Clearly, the water-level change is much more significant in a confined cell than that in an unconfined cell given the same amount of ground-water pumping or recharge.

Recharge

In the transient simulation, recharge was calculated based on segmented linear relationships to precipitation. The distribution of recharge zones remained identical to that in the predevelopment period (Figure 2). The recharge rate is assumed constant within each zone in each stress period. In this study, the following three major steps are required to compute the recharge rate for each zone and stress period:

1) Interpolate the precipitation data so that an average precipitation rate is obtained for each recharge zone for the six-month stress period.
2) Calibrate the segmented linear precipitation-recharge curves for each zone.
3) Apply the calibrated precipitation-recharge curve to calculate the recharge rate based on the precipitation rate interpolated in step 1.

Stream characteristics

As described earlier, 64 segments are used to represent the Smoky Hill River and the various tributaries in the model. In the model setup additional artificial one-reach segments were also used to represent various tributary inflows and surface diversions along the major streams that are explicitly simulated. The segment/reach assignments were changed for all of the stress periods following the construction of the diversion structure that connected Dry Creek to the Smoky Hill River in 1961. Streambed conductivity was calibrated for the predevelopment period and remained constant in the transient simulation. Streambed elevation was adjusted over the time based on the entrenchment data. Six-month streamflow input data for the Smoky Hill River were based on the Langley gage that is located below the outlet of Kanopolis reservoir. Flows of the ungaged tributaries entering the Smoky Hill River were estimated using regression equations (power curves) that were generated based on a relationship between tributary inflow and precipitation and surface drainage area under different antecedent moisture conditions. The streamflow data from the Lindsborg and Mentor gages on the Smoky Hill River were used in calibrating the simulated stream-aquifer interactions.

Ground-water pumping and irrigation return flow

Ground-water pumping data were primarily derived from the water right database via the WIMAS web site. In the model area, ground water is used mainly for irrigation and municipal needs. Reported ground-water pumping records are available for the period from 1990 to 2006. These reports are subject to quality control and assurance by the state's water use program and thus considered accurate. The historic pumping data prior to 1990 were estimated based on linearly regressing the ratio of water use/authorized quantity versus precipitation. The pumping data, either directly from water-use reports or estimated based on the regression equations, are on an annual basis. To divide these data into six-month stress periods in the model, ground-water pumping for irrigation was assumed to occur in the growing season only, while the non-irrigated water uses were distributed as 62% in the growing season versus 38% in the winter season.

Irrigation return flow is computed by assigning a particular fraction of return flow (to the aquifer) that ranges from 25% for flood systems to 7 to 9% for various sprinkler systems. This return flow is accounted for by removing it from the gross irrigation pumping in each year. That is, the ground-water pumping actually used in the model for an irrigation well serving a flood system is the gross pumping minus the estimated 25% return flow (the net pumping will be 75% of gross pumping).

Transient 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 hydrological conditions. The calibrated values of model parameters must be consistent with geologic conditions in the area. In the transient simulation, recharge was considered to be the parameter to calibrate. The data used in the recharge calibration include the historic ground-water levels for selected target years, several long-term well hydrographs that spread across the main aquifer zone, and the observed streamflows at all gaging stations in the model.

As mentioned earlier, the recharge in the transient simulation was estimated using segmented linear precipitation-recharge curves. For each of the four zones, a precipitation-recharge curve for the winter season is defined by a break point (5 inches) below which there is no recharge to the aquifer system, followed by four linear segments for each range of precipitation between 5, 10, 20, 30, and 40 inches (Figure 25). The break point of five inches was determined during preliminary modeling investigations. Four independent parameters are needed to characterize the precipitation-recharge curve in a recharge zone for a six-month season. Furthermore, because it takes significantly more precipitation in the growing season than in the winter season to produce the same amount of aquifer recharge, a precipitation offset is applied uniformly to all different recharge zones to produce the precipitation-recharge curves for the growing season. That is, the precipitation that goes into the curve-based recharge calculation in the growing season will be the actual precipitation minus the precipitation offset. This offset was independently determined to be 15 inches during preliminary modeling investigations, which is consistent with the data collected at a well south of the model area (Figure 24). As a result, there are a total of four (number of parameters per zone) times four (number of recharge zones) to equal 16 independent parameters to calibrate in the transient simulation (Table 8).

The first category of target data for transient model calibration is historic ground-water levels collected during selected years. Water levels sampled in the winter of 1957, 1968, 1979, 1989, 1994, 2004, and 2006 were used, with more emphasis given to recent low-precipitation years. In addition, water-level data from the predevelopment period were also incorporated to ensure that the transient model after calibration remained consistent with the predevelopment data. The second category of target data is long-term well hydrographs. As there are no wells in the model area that contain long-term depth-to-water records over the entire transient period, groups of wells that are located within proximity to each other and whose measurement histories together provide an extended timeline were selected as calibration targets (Figure 45). The third category of target data is the streamflow from the gaging stations. Figure 45 shows that the USGS gaging stations on the Smoky Hill River at Lindsborg and Mentor were used as the streamflow calibration targets. Note that the actual gage location at Mentor was moved in 2002 to its present location (labeled as "Mentor old" and "Mentor new", respectively). The total number of observation data points from all three categories is 481 for the transient model calibration.

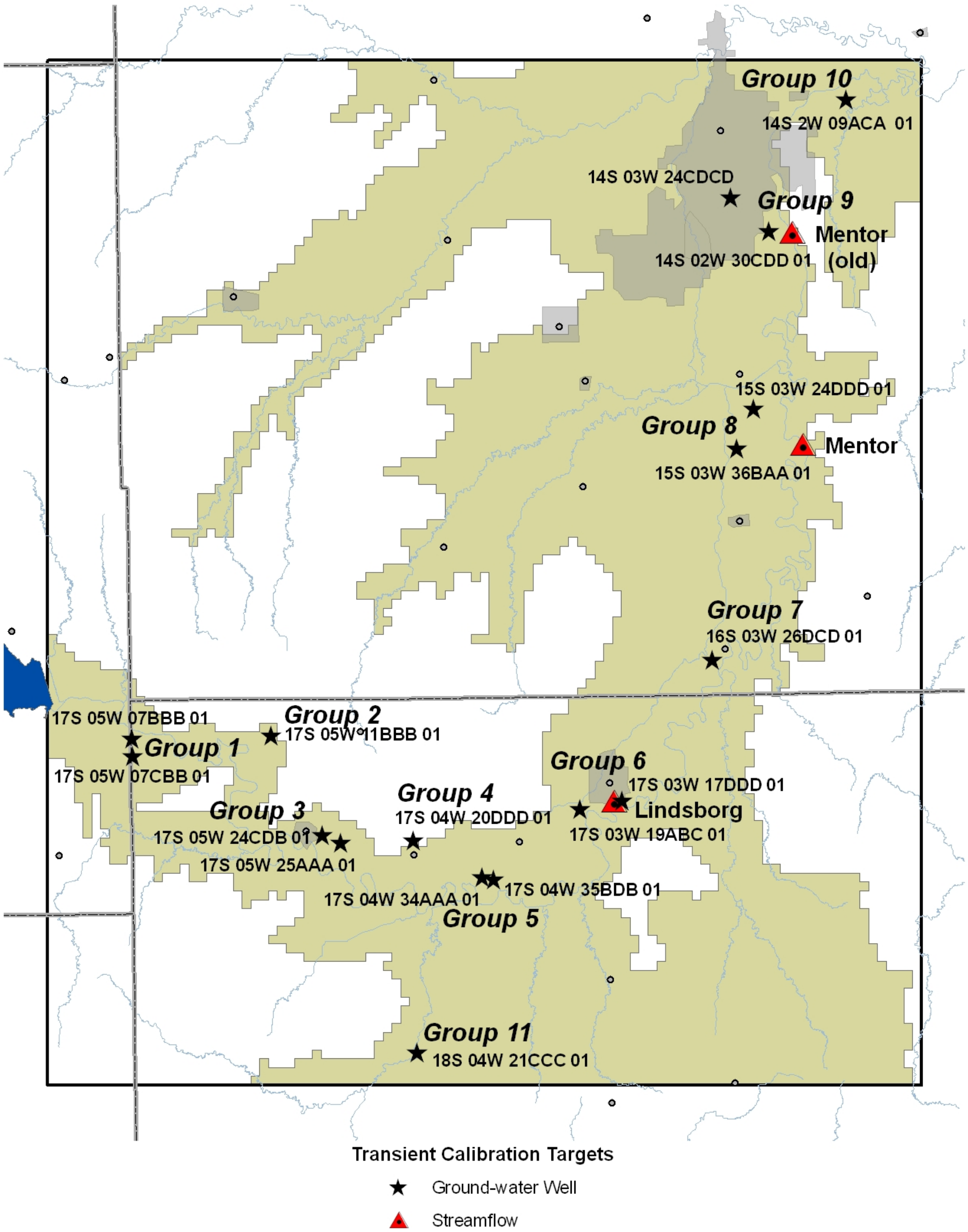


Figure 45- Calibration targets in the transient simulation. Groups 1~4 were later removed from the calibration process as they were located outside the main alluvial zone.

Figure 25 shows the calibrated recharge curves after the transient model calibration. Given the same precipitation rate, recharge is highest in the main alluvial zone downgradient of Lindsborg and gradually becomes smaller in the terrace deposits, the Equus Beds portion of the High Plains aquifer to the south, and the thin alluvial zone upgradient of Lindsborg. The calibrated recharge trend is consistent with the local geologic and hydrologic conditions as described in the previous sections.

Table 7 displays the mean residuals and mean absolute residuals for all three categories of target data. The mean residual is given as the mean of measured minus simulated values, while the mean absolute residual is the mean of the absolute of measured minus simulated values. The mean residual for the water levels in selected years is typically less than three feet except for 2004, when a water-level was measured upgradient of Lindsborg and near the edge of the alluvial aquifer with a residual of over 41 ft. The mean residual for the group well hydrographs is less than 3 ft except for well group #10 where the time-varying specified-head boundaries appear to have significant impacts on the well due to their proximity. The mean residual for streamflow targets is negative at all gaging stations. This is because the model is geared toward simulating low-to-average streamflow conditions and consistently produces large overpreditions for high streamflow events. These overpredictions, although occurring in a small number of high streamflow years, have significantly shifted the mean residual statistics to the negative side. Note that because the streamflow data were log transformed before they were applied to model calibration, low flows had the same weight as high flows in the calibration process and those few high flow events did not have inappropriately large impacts on the final calibrated model.

The mean absolute residual is generally less than 6 ft for both the water levels in selected years (except 2004) and the group well hydrographs. The relative mean absolute error, which is the mean absolute residual divided by the maximum difference in observed water-level elevation across the active model area (285 ft) times 100, is 2.6% or less for all seven of the historic target years and averages 1.6% for these years.

Figure 46 shows the simulated versus observed water levels for the years selected for model calibration. The straight line is the reference for perfect agreement between the model and data. Most of the data points collapse onto the reference line, indicating that the calibrated model produces an overall good agreement with the observed data. Three data points near the center of the plot show a relatively larger residual error. These three points are the water levels measured from the same well that is located upgradient of Lindsborg and near the edge of alluvial aquifer. As indicated earlier, despite the obvious efficacy of the calibrated model in the main alluvial zone, the model is not accurate for representing the edge of alluvium and the upgradient portion of the valley where the aquifer is thin, the hydrogeological conditions show significant variations, and data coverage is extremely limited.

Figure 47 shows the simulated versus observed water levels for the group well hydrographs used in the calibration. Similarly to Figure 46, most of the data points converge to the reference line. The largest residual errors occur toward the upper-right corner of the plot (group 11), where the well was situated in the Equus Beds portion of the High Plains aquifer in the southernmost part of the model.

Table 7 Mean residuals and mean absolute residuals for transient calibration targets.			
Target	**No. of Data**	**Mean Residual**	**Mean Absolute Residual**
Water levels predevelopment (ft)	63	-2.40	7.44
Water levels 1957 (ft)	28	-1.64	4.13
Water levels 1968 (ft)	41	0.81	4.41
Water levels 1979 (ft)	12	0.92	2.68
Water levels 1989 (ft)	8	-1.38	2.97
Water levels 1994 (ft)	9	1.67	4.45
Water levels 2004 (ft)	17	4.02	7.43
Water levels 2006 (ft)	16	2.74	6.06
Hydrograph group 5 (ft)	21	1.05	2.28
Hydrograph group 6 (ft)	30	0.09	3.06
Hydrograph group 7 (ft)	27	-2.48	3.35
Hydrograph group 8 (ft)	20	-0.80	2.49
Hydrograph group 9 (ft)	56	1.25	3.28
Hydrograph group 10 (ft)	9	4.13	4.13
Hydrograph group 11 (ft)	47	-1.71	5.49
Streamflow @ Lindsborg (cfs)	18	-176.6	207.4
Streamflow @ Mentor Old (cfs)	54	-121.8	153.9
Streamflow @ Mentor New (cfs)	5	-12.5	19.7

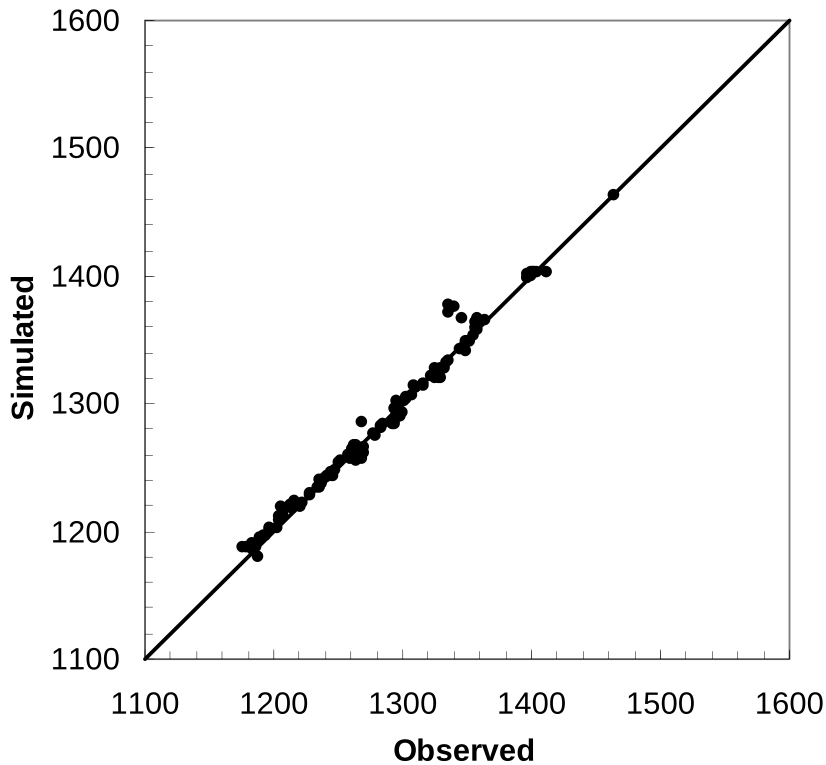


Figure 46- Simulated versus observed water levels for 1957, 1968, 1979, 1989, 1994, 2004, and 2006.

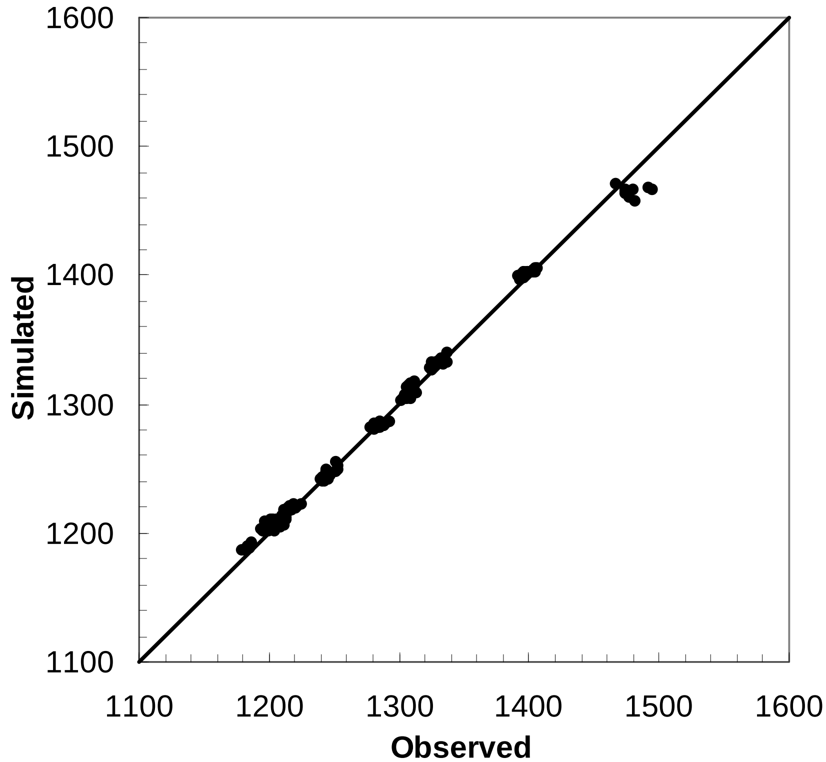


Figure 47- Simulated versus observed well hydrographs.

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 the Smoky Hill River model calibration was typically performed with relatively sparse 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. Figure 48 shows the simulated water level from the calibrated model as compared to the observed data in 1963, when precipitation was lower than average and the number of available water-level measurements was greater than average for the transient period. The overall agreement is deemed as reasonable between the simulated and observed water levels where there are actual measured wells to make comparisons.

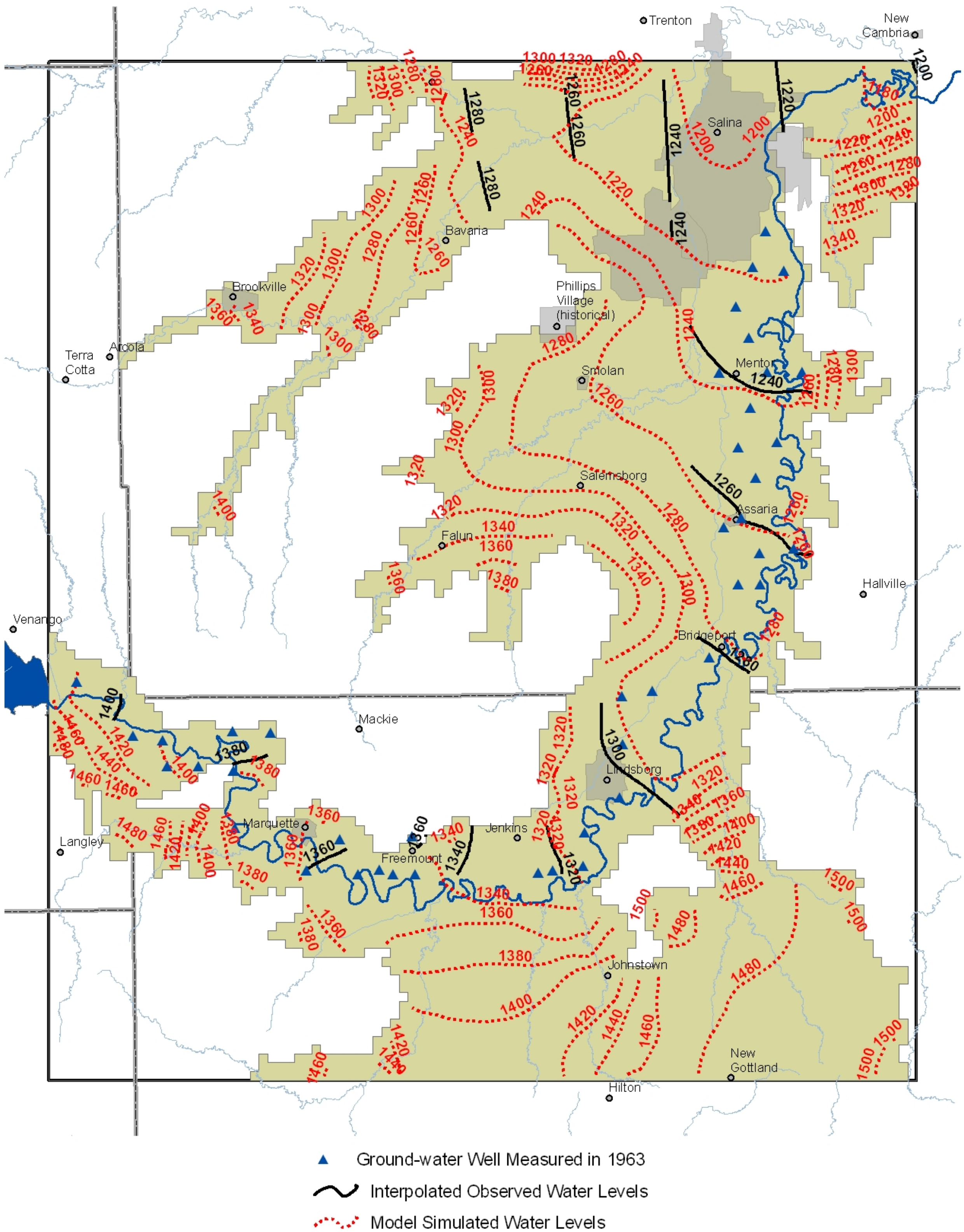


Figure 48. Water-level contours for simulated (dotted red lines) versus observed (solid black lines) water levels for 1963.

Sensitivity Analysis

Table 8 lists the sensitivities of the recharge parameters that are used to define the segmented precipitation-recharge curves in different zones in the growing season. The sensitivities are relatively small for all the different parameters, indicating that the calibrated model is stable (and thus robust in making model predictions) with respect to the calibrated recharge zonation and rates.

Table 8
Sensitivities of the parameters of segmented recharge curves in the growing season. The recharge curve in zone I (main alluvium) is defined by a11, a21, a31 and a41; the curve in zone II (High Plains) is defined by a12, a22, a32 and a42; and so forth.

Parameter	Calibrated Value	Relative Sensitivity
a11	0.60	0.030
a12	0.50	0.120
a13	0.55	0.068
a14	0.45	0.015
a21	1.50	0.081
a22	1.10	0.539
a23	1.30	0.090
a24	1.00	0.026
a31	2.00	0.045
a32	1.50	0.284
a33	1.75	0.021
a34	1.35	0.017
a41	2.45	0.007
a42	1.90	0.034
a43	2.25	0.028
a44	1.75	0.004

Transient Model Results

<u>Water Levels</u>

Finding adequate data for calibration of the model simulations of the water-table elevations was challenging. The Smoky Hill River valley lacks monitoring wells with long-term depth-to-water measurements covering the entire transient period. In addition, the available measurements are often scattered both spatially and temporally. Ground-water wells along the Smoky Hill River and into the Equus Beds aquifer were selected to compare the model estimates of water-table elevations (Figure 45). If two wells close to each other provided a longer period of record (e.g., one was measured early in the time period while the other was measured later) they were grouped together and compared as a single entity.

The transient model best matches simulated water levels with observed values in areas closer to the Smoky Hill River where the aquifer has a substantial permeable zone and water rights have been developed. This is even true in the well groups or two well pairs. The well closest to the river (often where the thickest sediment deposits are located) provides the best overall match to the simulated water levels. The absolute match of the model to observed data is not as good in areas where the aquifer is thin, both vertically and horizontally, or in areas along the edges of the alluvial deposits. However, in most cases, the model still mimics the same hydrograph trends in these fringe areas.

Hydrographs showing both observed and model simulated water levels are shown in Figures 49 to 55. Each graph displays the well identification number referenced by the map in Figure 44 and the model zone in which the well is located.

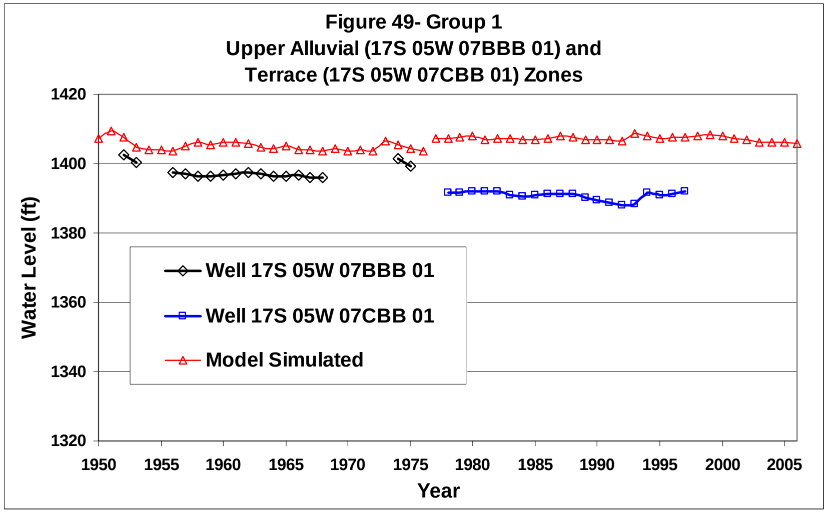


Figure 49- Group 1
Upper Alluvial (17S 05W 07BBB 01) and
Terrace (17S 05W 07CBB 01) Zones
Water Level (ft)
Year
Well 17S 05W 07BBB 01
Well 17S 05W 07CBB 01
Model Simulated

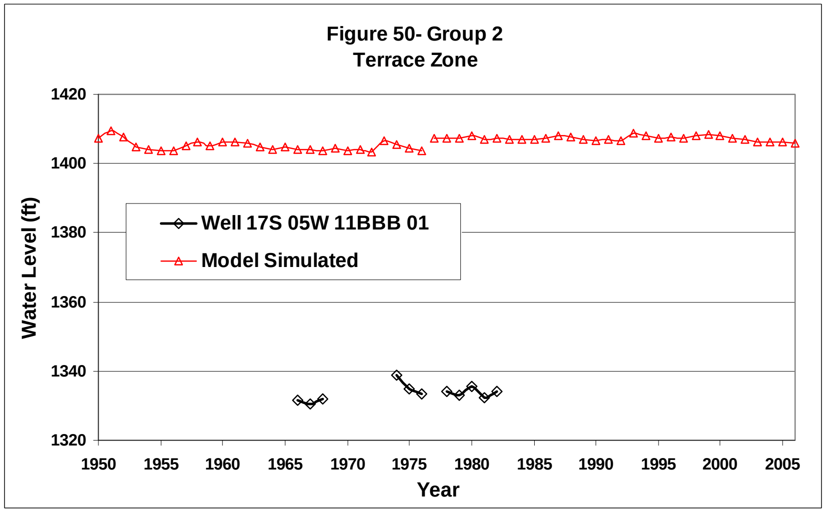


Figure 50- Group 2
Terrace Zone
Water Level (ft)
Year
Well 17S 05W 11BBB 01
Model Simulated

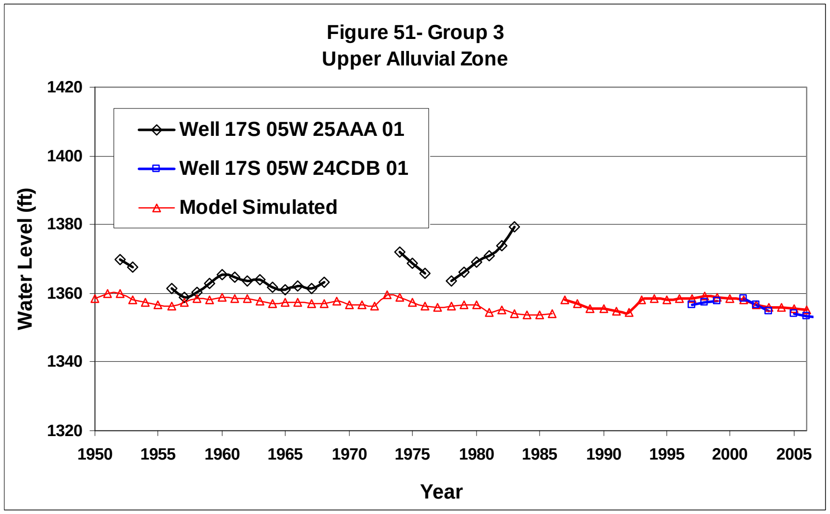


Figure 51- Group 3
Upper Alluvial Zone
Water Level (ft)
Year
Well 17S 05W 25AAA 01
Well 17S 05W 24CDB 01
Model Simulated

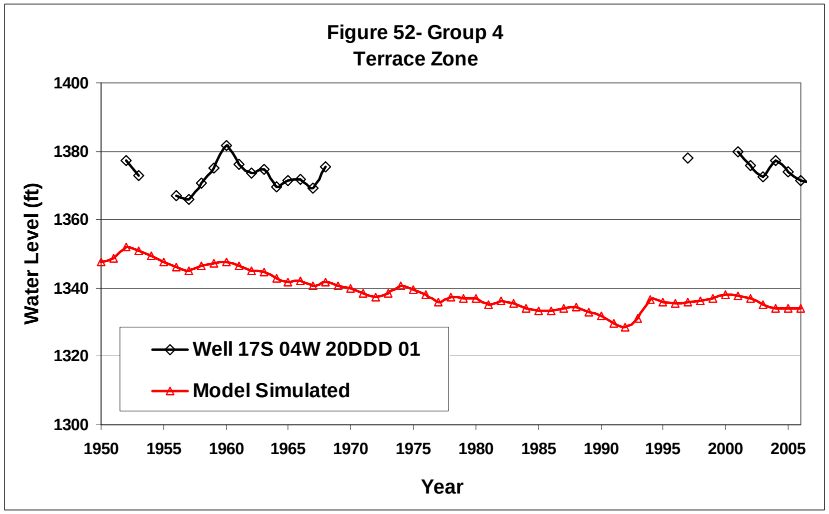


Figure 52- Group 4
Terrace Zone
Water Level (ft)
Year
Well 17S 04W 20DDD 01
Model Simulated

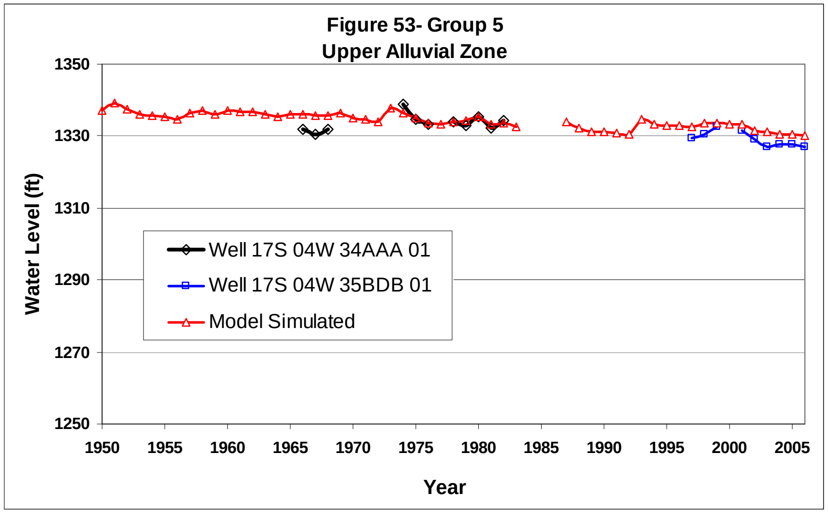


Figure 53- Group 5
Upper Alluvial Zone
Water Level (ft)
1350
1330
1310
1290
1270
1250
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year
Well 17S 04W 34AAA 01
Well 17S 04W 35BDB 01
Model Simulated

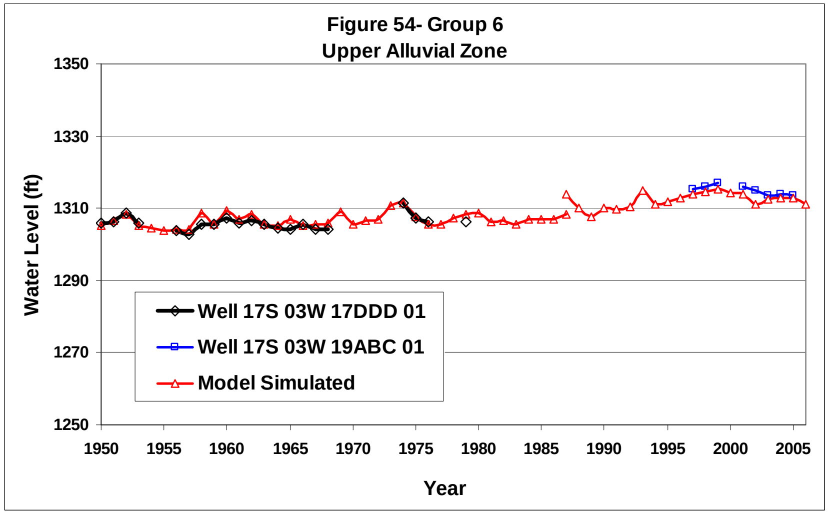


Figure 54- Group 6
Upper Alluvial Zone
Water Level (ft)
1350
1330
1310
1290
1270
1250
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year
Well 17S 03W 17DDD 01
Well 17S 03W 19ABC 01
Model Simulated

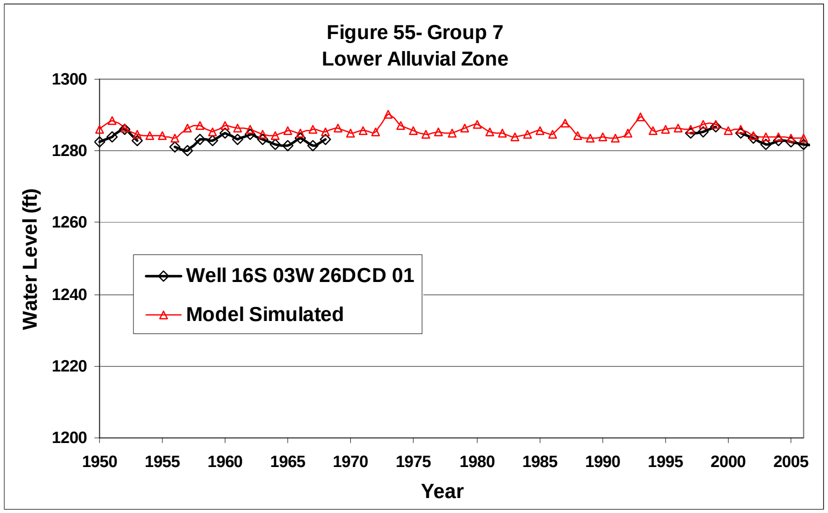


Figure 55- Group 7
Lower Alluvial Zone
Water Level (ft)
1300
1280
1260
1240
1220
1200
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year
Well 16S 03W 26DCD 01
Model Simulated

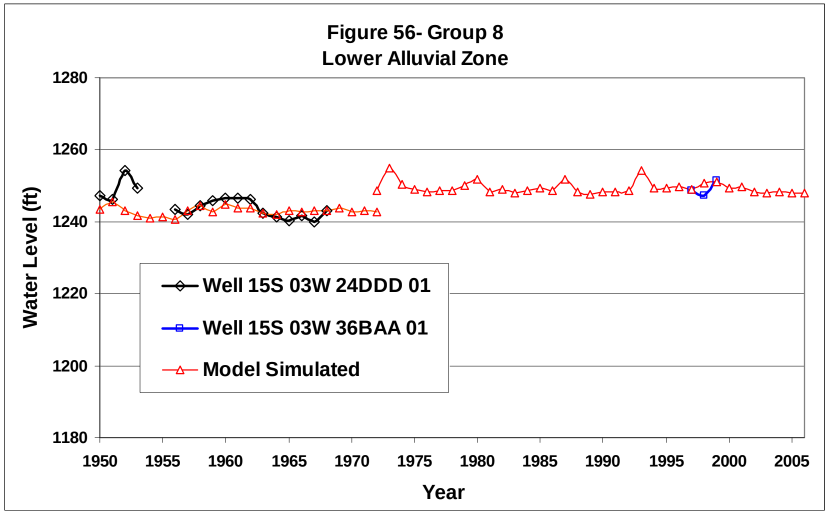


Figure 56- Group 8
Lower Alluvial Zone
Water Level (ft)
1280
1260
1240
1220
1200
1180
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year
Well 15S 03W 24DDD 01
Well 15S 03W 36BAA 01
Model Simulated

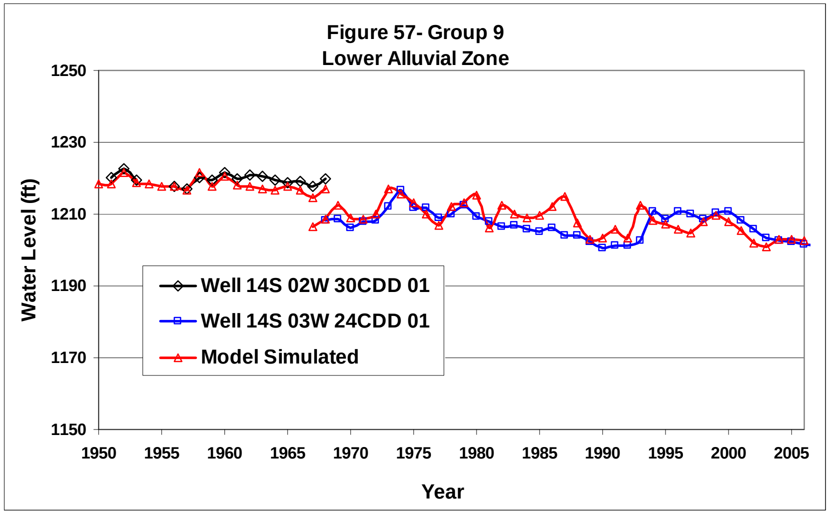


Figure 57- Group 9
Lower Alluvial Zone
Water Level (ft)
1250
1230
1210
1190
1170
1150
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year
Well 14S 02W 30CDD 01
Well 14S 03W 24CDD 01
Model Simulated

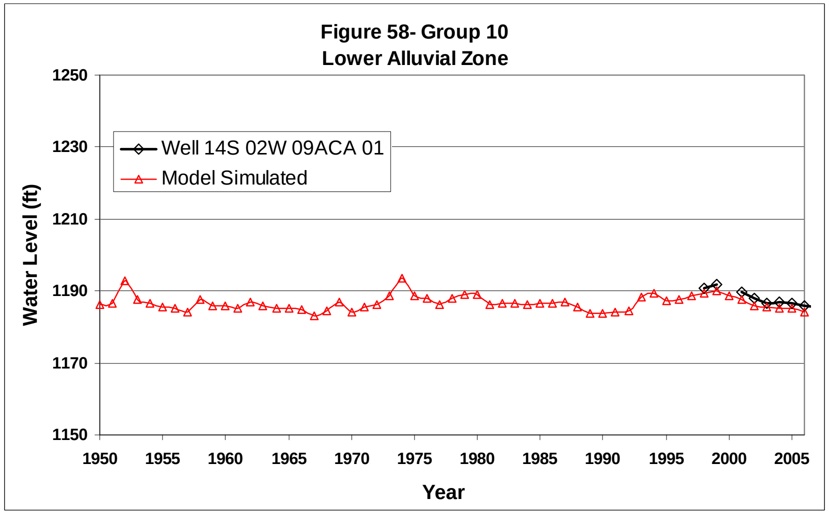


Figure 58- Group 10
Lower Alluvial Zone
Water Level (ft)
1250
1230
1210
1190
1170
1150
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year
Well 14S 02W 09ACA 01
Model Simulated

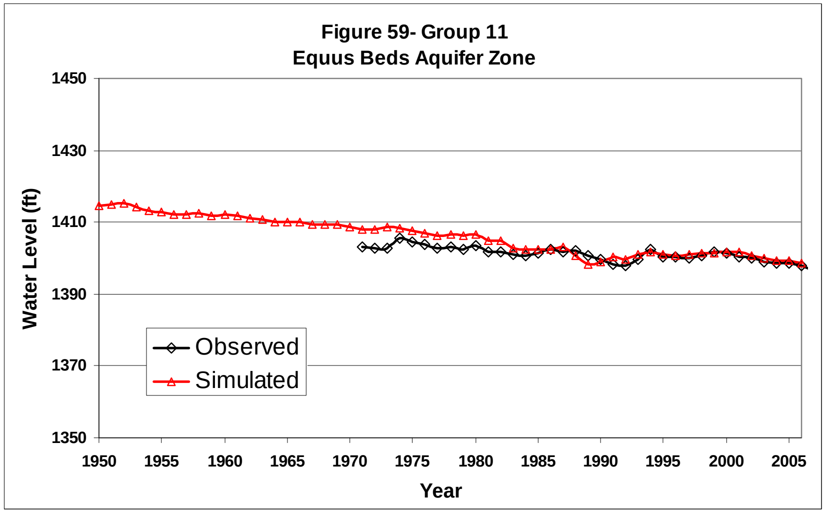


Figure 59- Group 11
Equus Beds Aquifer Zone
Water Level (ft)
1450
1430
1410
1390
1370
1350
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year
Observed
Simulated

Domestic Well Development In and Around Salina

One of the challenges during the calibration phase of the transient model was matching the simulated water levels with the observed water levels in Salina, Group 9 wells. The model compared very favorably with well 14S 02W 30CDD 01. Observed measurements for this well run from the 1950s and ended in 1968. A replacement well, 14S 03W 24CDD 01, is located within the city limits of Salina and measurements started in 1968 and continue to this day. Early versions of the model, however, were not simulating the observed declining trends that occurred in the late 1970s and early 2000s at this well. Model simulations kept the water levels near the 1210-foot elevation without any declines (Figure 60).

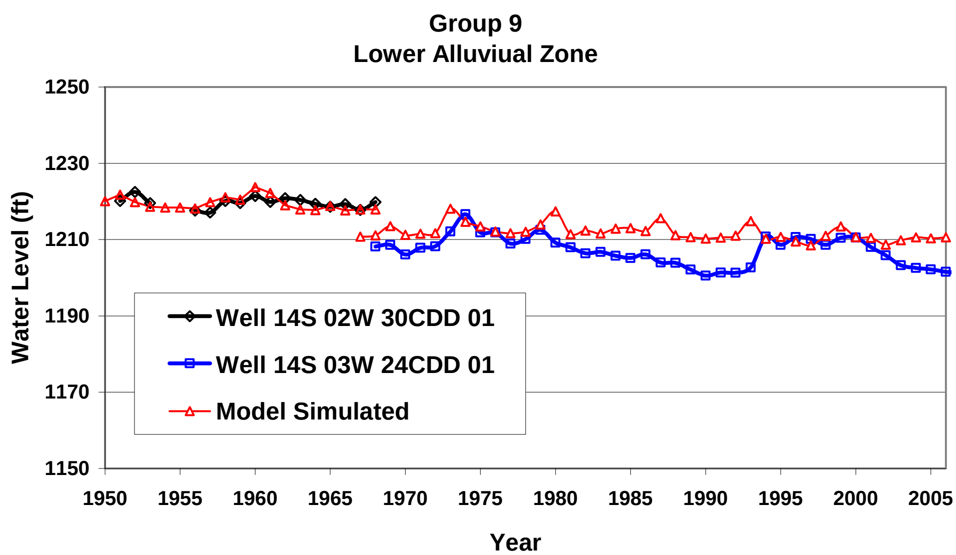


Figure 60. Observed and simulated water levels at the Group 9 wells in Salina before model adjustment for domestic well pumping.

This lack of simulated ground-water decline indicates that either the model is not accounting for all the potential ground-water pumping occurring throughout the year or the estimated recharge values are too high in this area of the model. Given the relatively strong hydrograph comparisons throughout the rest of the lower alluvial model zone, the recharge estimates are probably satisfactory and the model was lacking additional pumping in the Salina area.

Historic non-traditional water rights do occur in the model area but were not initially considered due to their small volumes. A review of these types of water rights in the Salina area show them to be “Temporary” or “Term” water rights, generally used for smaller, time-dependent projects such as a site specific contamination remediation or construction activities. The inclusion of this additional non-traditional pumping did not improve the hydrograph comparison of simulated-versus-observed water levels for the Group 9 wells.

Another possible source of additional pumping could come from domestic well development. Like non-traditional water rights, domestic or privately owned wells were not considered in the model due to the small water usage of an individual well. Domestic well usage is so small that they do not require a water right. The State of Kansas maintains records on ground-water well development in the Water Well Completion Records Database (WWC-5) of the Kansas Department of Health and Environments. Since 1974, Kansas drilling companies have been required to submit a WWC-5 form to the State whenever a well is drilled, re-constructed, or plugged. Records are available for over 1,400 private wells drilled in and around the Salina area for domestic and lawn/garden applications (Figure 61).

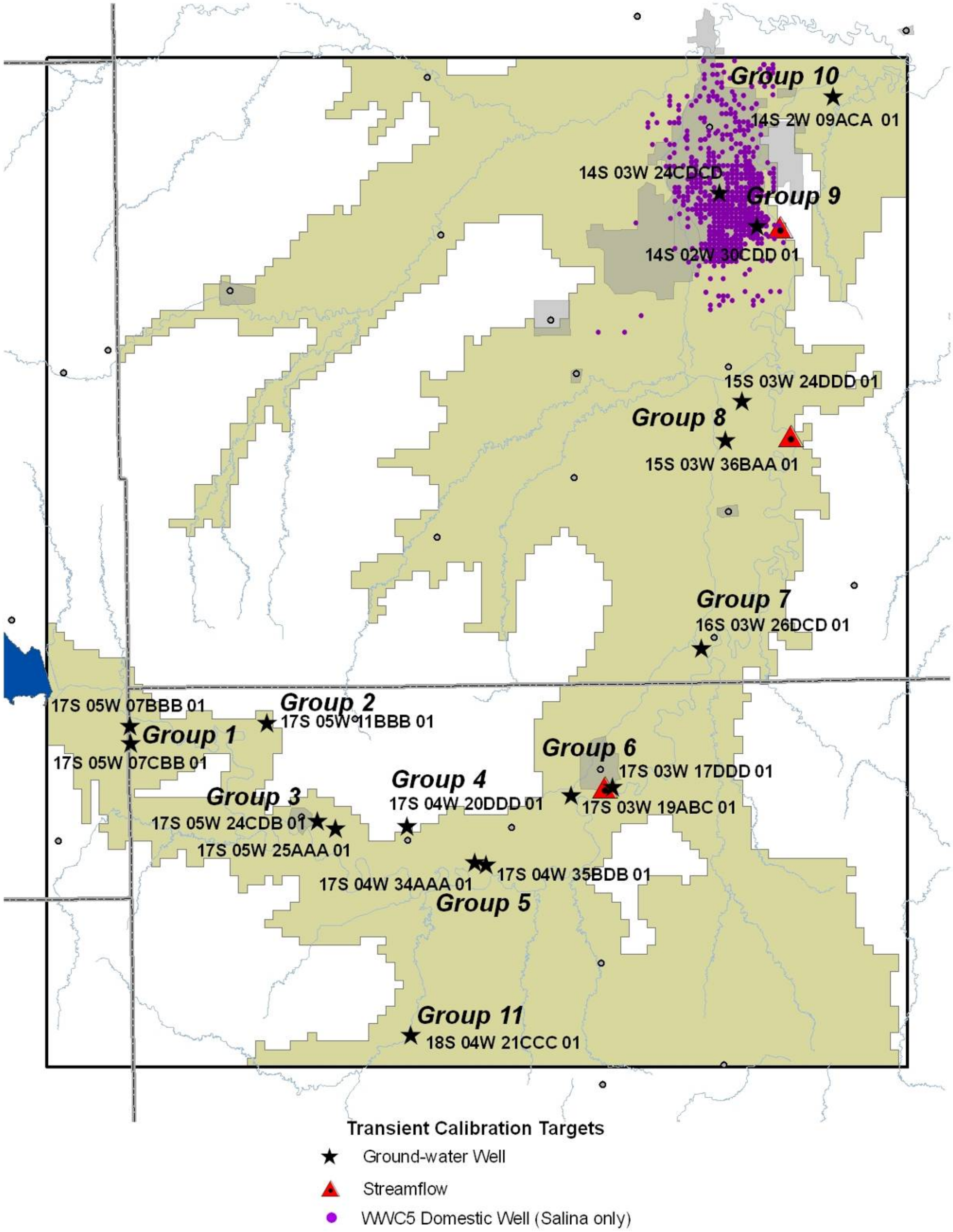


Figure 61. Private domestic and lawn/garden ground-water well development in and around Salina.

The vast majority of these private wells are for lawn and garden purposes. A plot of the number of private wells drilled over time shows an increasing trend starting in the early 1980s (Figure 62), which is the same time period for which the model-simulated water levels begin to deviate from the observed values taken at well 14S 03W 24CDD 01.

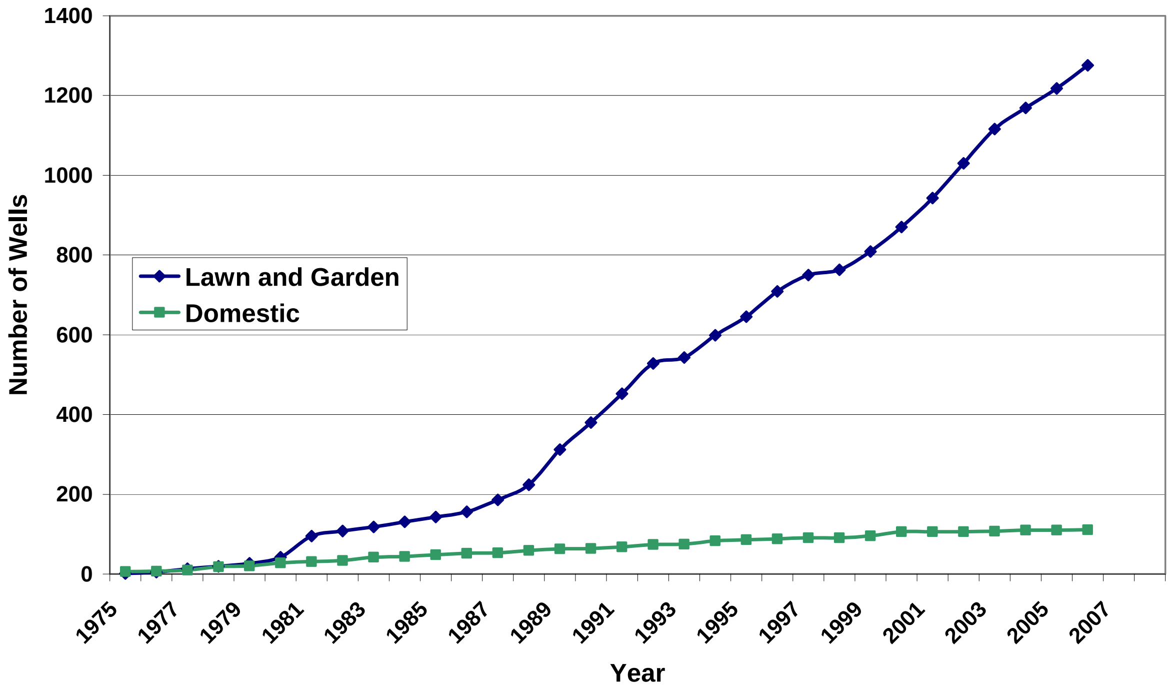


Figure 62. Private domestic and lawn/garden ground-water well development in and around Salina

The water-use estimates applied to the model for wells designated in the WWC-5 records as lawn and garden wells are based on a watered area of 1/3 of an acre. The estimated water use varies based on the precipitation during the growing season and the non-growing season; most of the water use was assumed to occur during April-September but a little water use was assumed for the early spring (March) and fall (October-November). The April-September estimates are based on a maximum application rate of 3 ft of water during the year with the least April-September rainfall (1956) to one tenth of that (0.3 ft) during the wettest year (1993). This gives an application rate of about 2.1 ft (25 inches) and a water use of 0.7 acre-ft during the growing season for an average precipitation of 21.4 inches for April-September. For the October-March period, a maximum application rate of 0.6 ft (7 inches) was assumed for the driest year (1967) and zero for the wettest (1973), giving an application rate of 0.17 ft (4.6 inches) for an average October-March.

Water use by wells designated as domestic in the WWC-5 records was estimated as 0.67 acre-ft per year based on three people consuming 200 gallons/day through the year to which water used for lawn and gardens was added for the growing season. During October-March, the total water use was assumed as a constant 0.3 acre-ft. During April-September, the maximum water use was a combination of the house use and lawn and garden use based on a slightly smaller watered area of 0.3 acre than for the lawn and garden wells, and a maximum application rate of 2.5 ft of water during the driest year (1956) and about one tenth of that for the wettest year

(1993). This gave a range of 1.1 acre-ft to 0.4 acre-ft during April-September for the driest and wettest April-September, respectively. The April-September water use for an average summer season was 0.88 acre-ft.

This relationship between model time step (six months) to water use for a single lawn and garden well (LG) and domestic well (DOM) is shown in Figure 63. Applying this relationship to the number of wells constructed each year and the amount of precipitation indicates that a substantial amount of water is used each year by private wells, especially during periods of low precipitation (Figure 64).

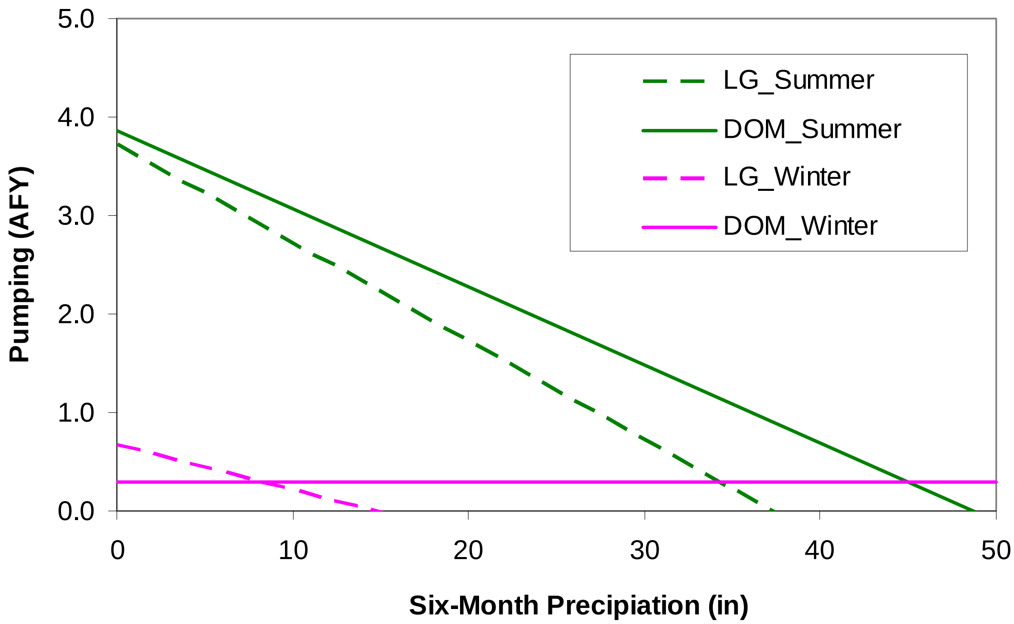


Figure 63. Single well water use / precipitation ratio

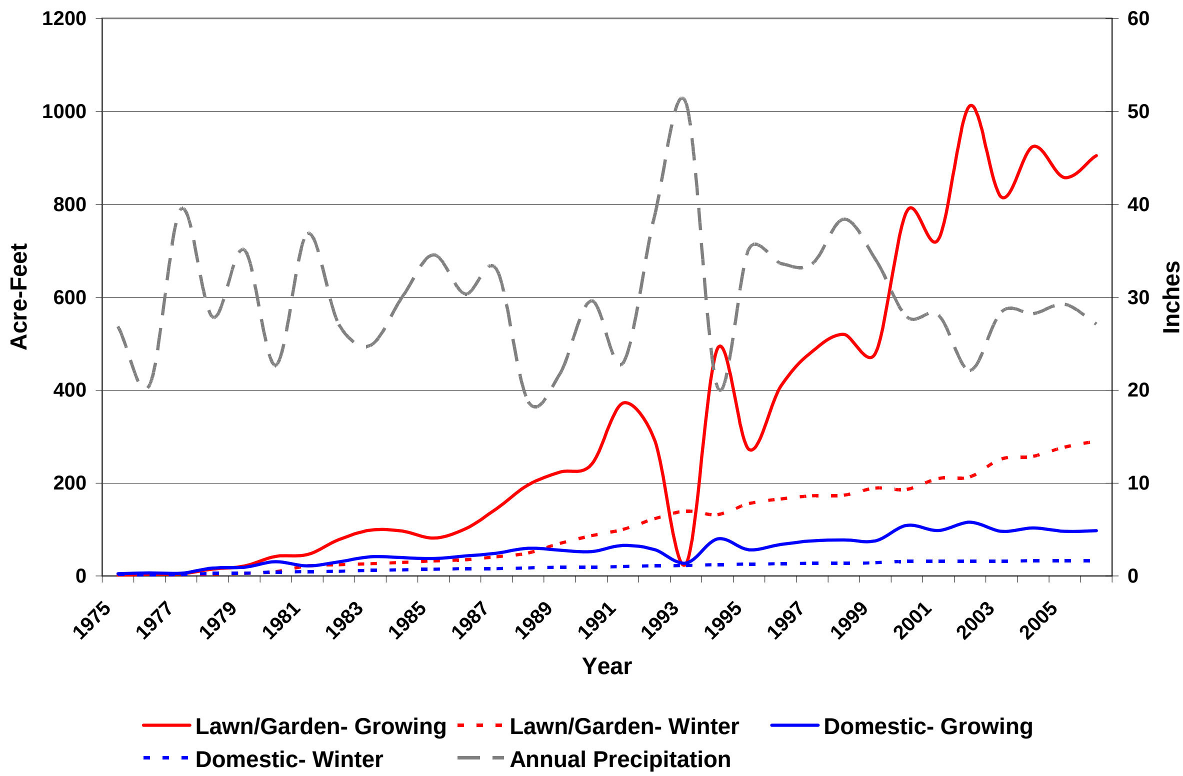


Figure 64. Estimated private domestic and lawn/garden ground-water pumping.

The inclusion of the estimated ground-water pumping from privately owned domestic and lawn/garden wells in and the around the Salina area adds close to 800 to 1,000 acre-feet of withdrawals each year since 2000. This is the equivalent of having three to four center pivot irrigation systems typical for a quarter section operating within the city limits of Salina. Accounting for this additional pumping improved the model's water-level simulations in this area (Figure 57 above).

Streamflow

The model was also calibrated to streamflow at the Lindsborg and Mentor gaging stations, especially during low-flow events. Figures 65 and 66 plot the model simulations versus observed values from the Lindsborg and Mentor gages. Figures 67 and 68 display the residual (simulated minus observed values) for each gage, which indicates the model underestimates streamflow more times than it over estimates flow.

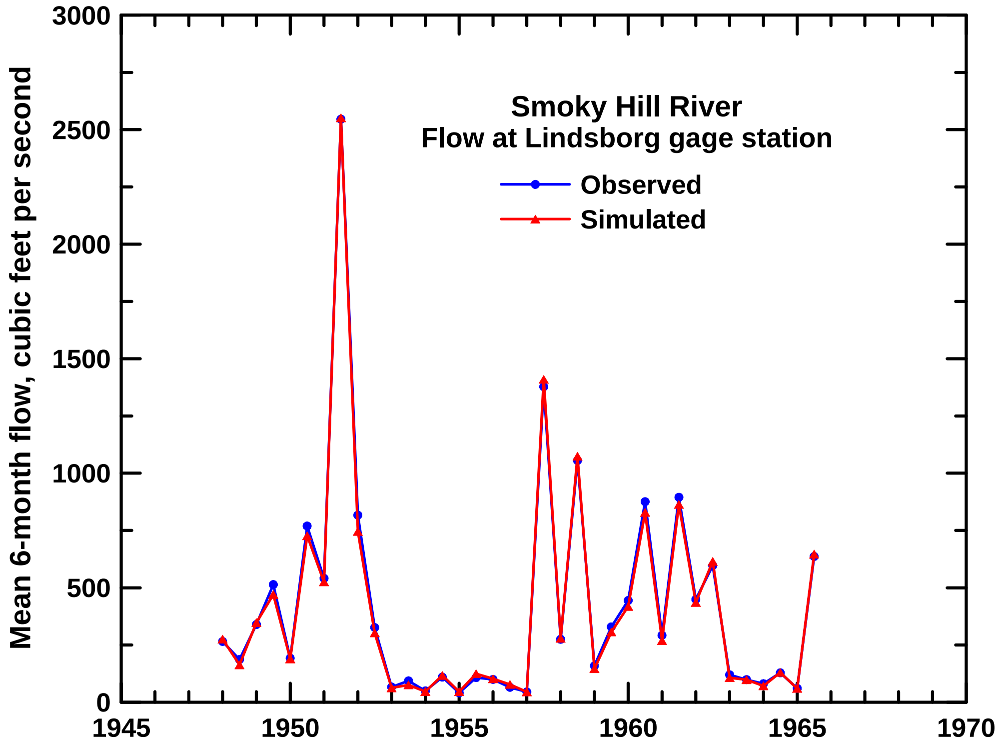


Figure 65. Calibrated Streamflow at Lindsborg

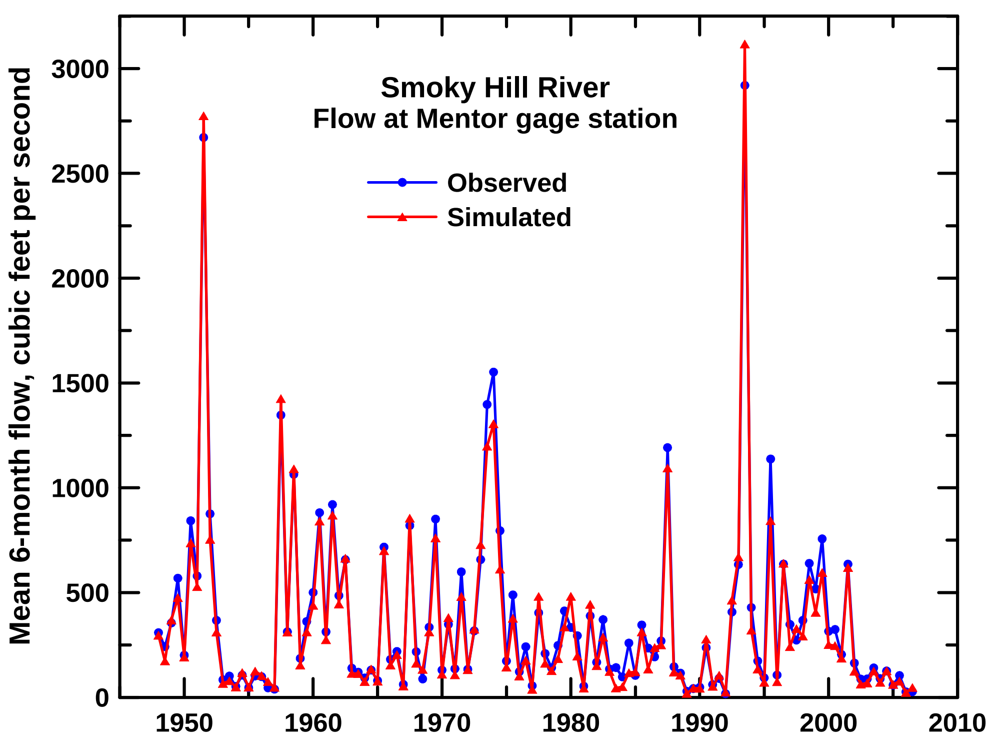


Figure 66. Calibrated Streamflow at Mentor

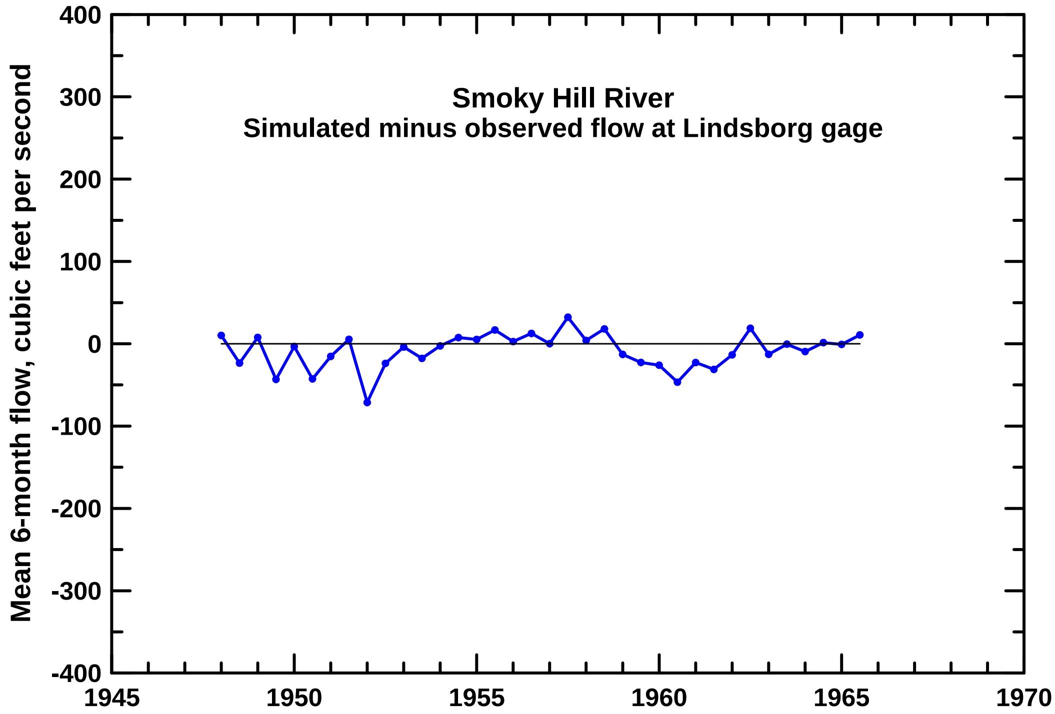


Figure 67. Residual plot, Lindsborg Gage

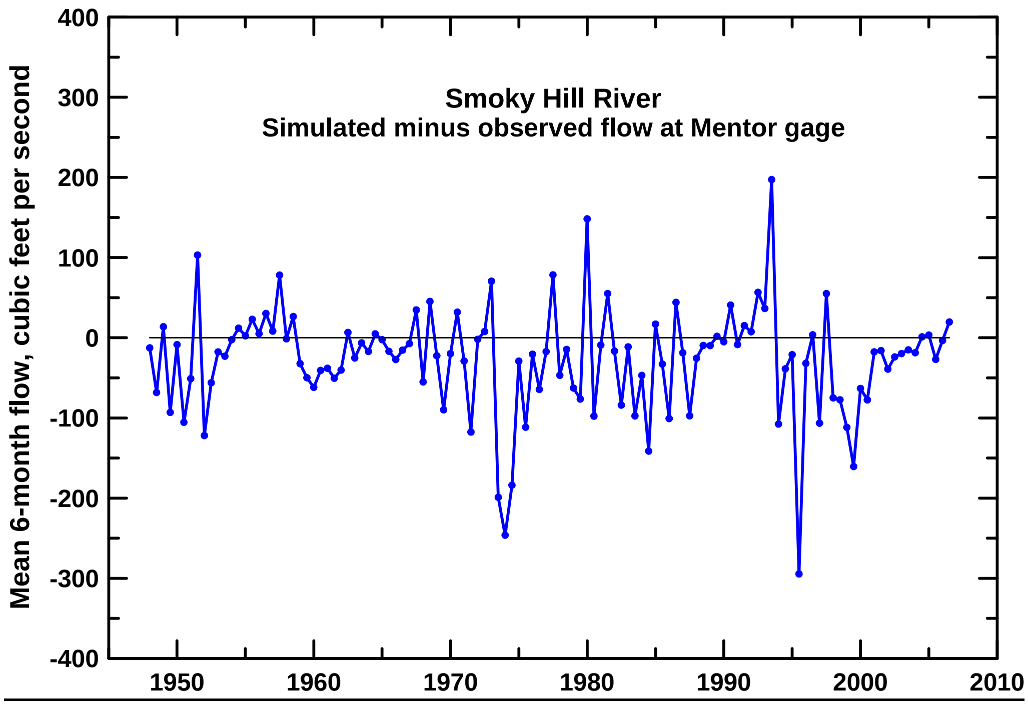


Figure 68. Residual plot, Mentor Gage

Water Budgets

Streamflow

An average annual streamflow budget from 1962 (post construction of the Dry Creek surface-water diversion works) to 2006 was constructed to give an overview of the Smoky Hill River within the model area during the transient period (Figure 69). On average, the river is a gaining stream, meaning it increases in flow as it moves down gradient, until it reaches the Salina area. At this point, it starts to lose water to the underlying aquifer. The river becomes a gaining stream again just east of the city.

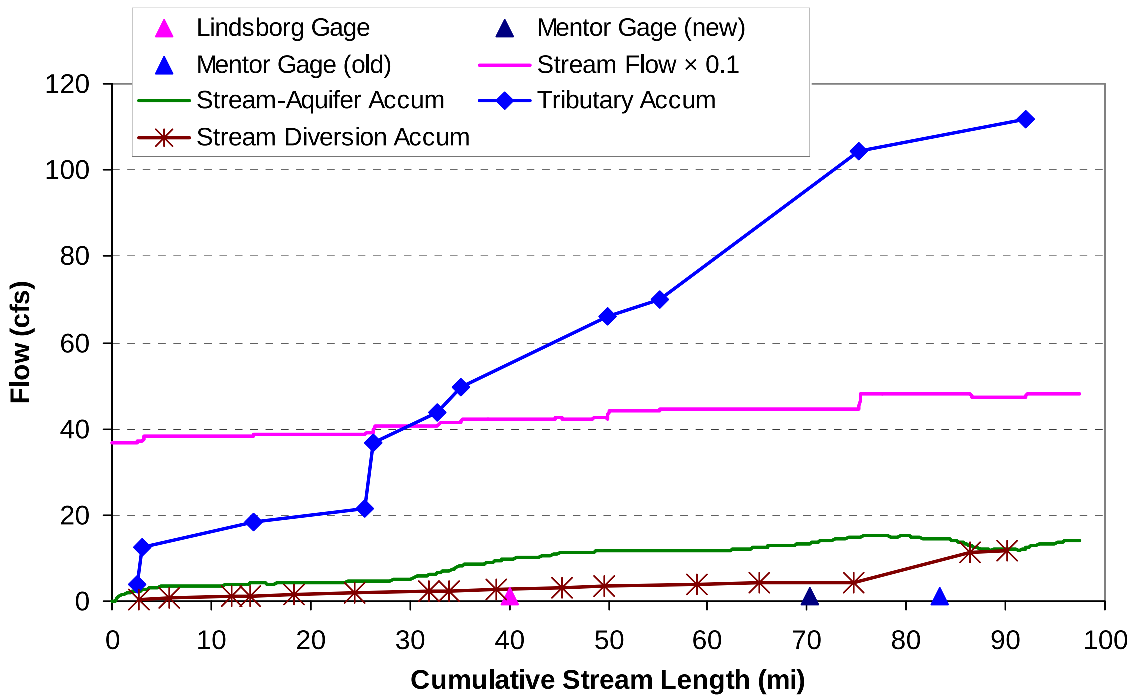


Figure 69. Average annual streamflow budget for the Smoky Hill River, 1962 to 2006. The triangles indicate the locations of the gaging stations. The red, green, and blue lines represent the cumulative stream diversions, stream-aquifer interactions and tributary inflows along the Smoky Hill River. The magenta line shows that total river flow, the amount entering the model plus the accumulative flows from tributaries and stream-aquifer interactions minus the stream diversions.

The stream-aquifer interactions for each model cell also show that the Smoky Hill River is a gaining stream throughout much of its course (Figure 70). The surface-water diversion works on Dry Creek, which diverts flow into the Smoky Hill River, is the largest inflow point for the tributary systems (the point on Figure 71 between mile 70 and 80). Sharps Creek and Kentucky Creek represent the next largest inflows to the river. Surface-water diversions occur along the entire stretch of the river in the model area; the largest is associated with the water rights of the City of Salina at the lower end of the model area (Figure 72).

Figure 73 displays the average annual values cumulative values during 1948 to 2006 for tributary inflow, stream-aquifer interactions, and stream diversions. There has been little change in slope of the stream-aquifer interactions and diversions indicating they are relatively constant. The figure shows the model simulation of tributary inflows for the major flood events in 1951, 1973, and 1993 as major step increases in flow for those particular events.

Figure 74 shows the average annual budget components of tributary inflow, stream-aquifer interactions, and stream diversions for the Smoky Hill River during 1948-2006. The plot for stream-aquifer interactions crosses the zero line several times from the late 1980s to 2006. This indicates the Smoky Hill River becomes a losing stream with water seeping into the underlying alluvial aquifer for certain years. The periods during which the river becomes a losing stream have increased in frequency in the later years of the transient period starting in 1987. These losing periods also occur during the growing season model step (April to September) when the surface and ground water diverted for irrigation and municipal uses are at their highest.

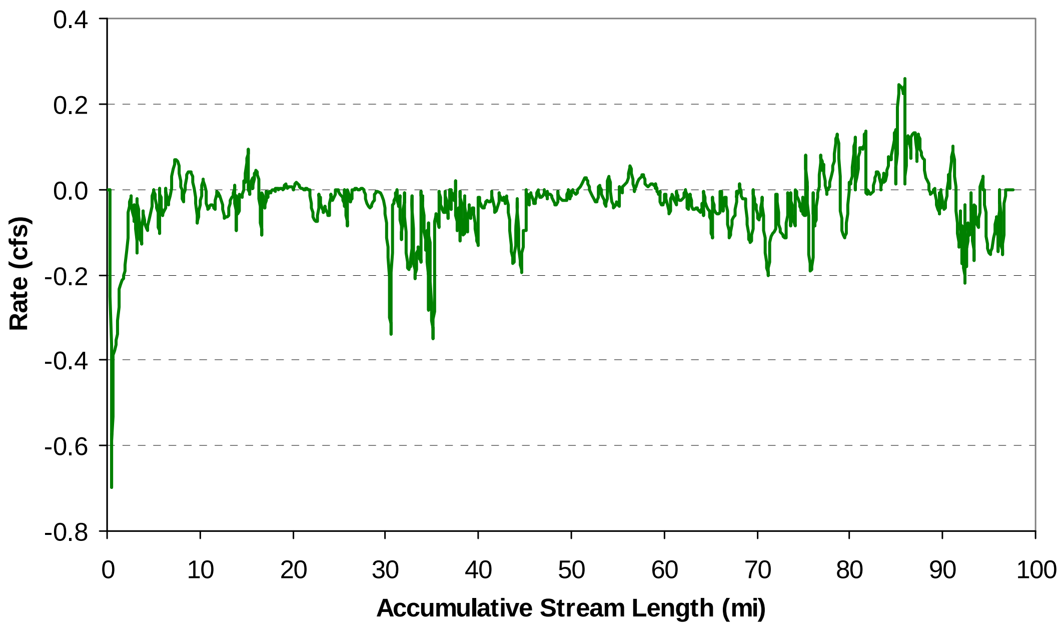


Figure 70. Stream-Aquifer Interactions, Average 1962 to 2006

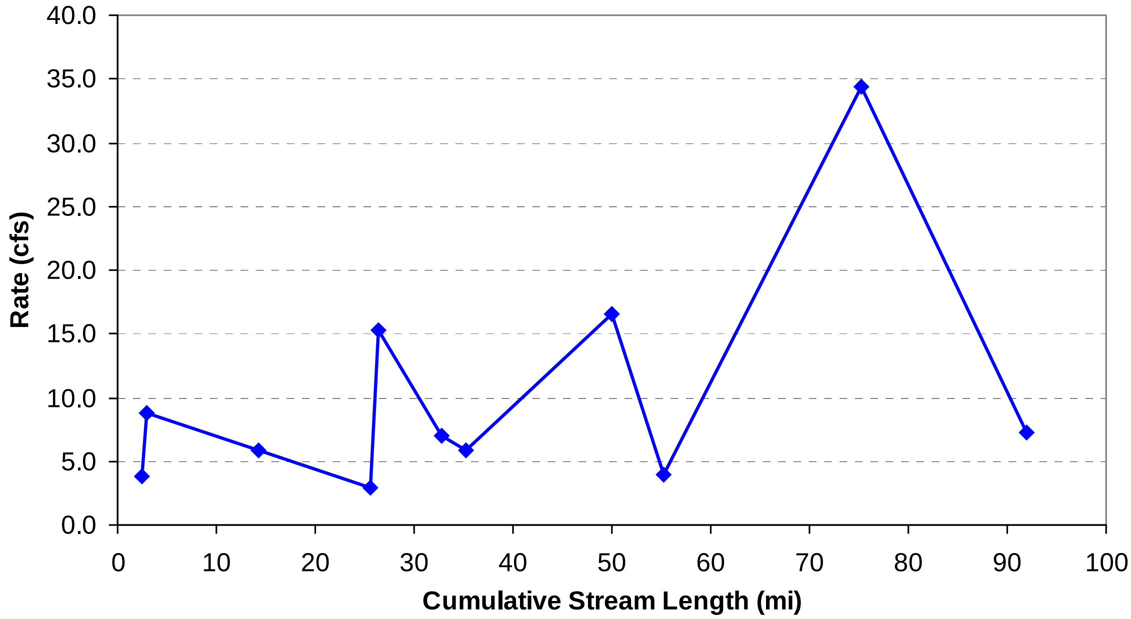


Figure 71. Tributary Inflows, Average 1962 to 2006

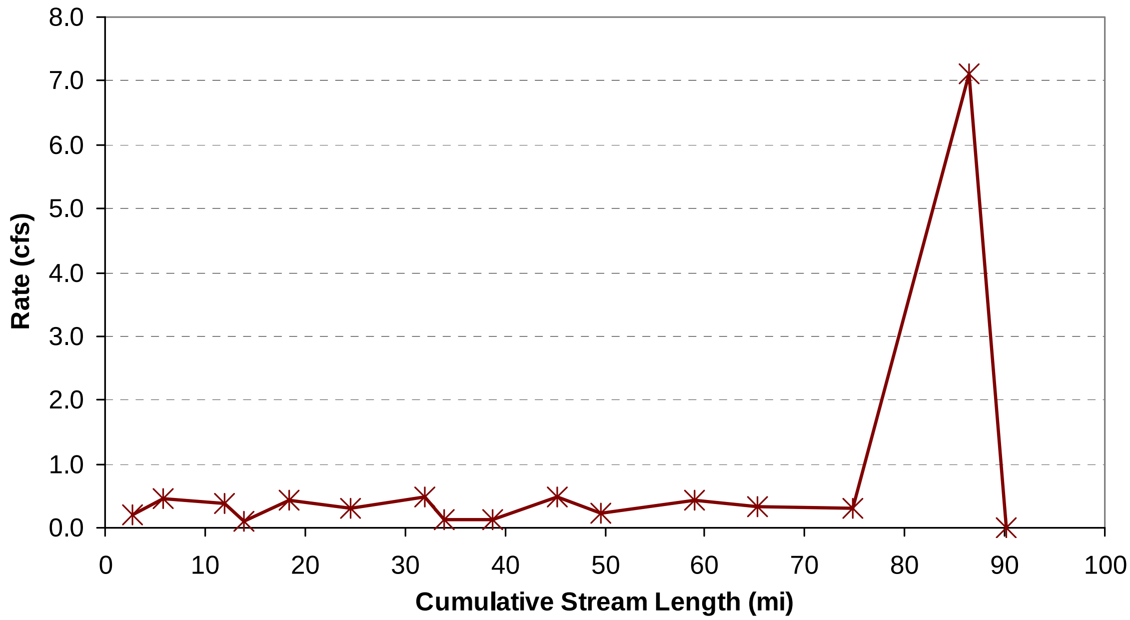


Figure 72. Stream Diversions, Average 1962 to 2006

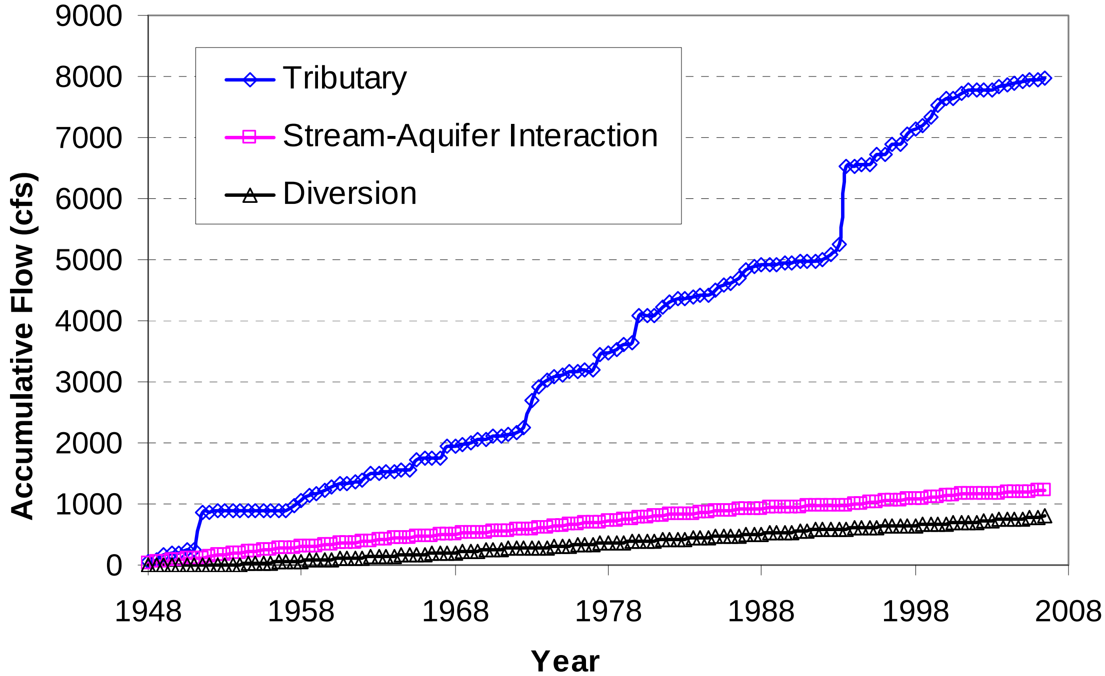


Figure 73. Yearly Streamflow Budget

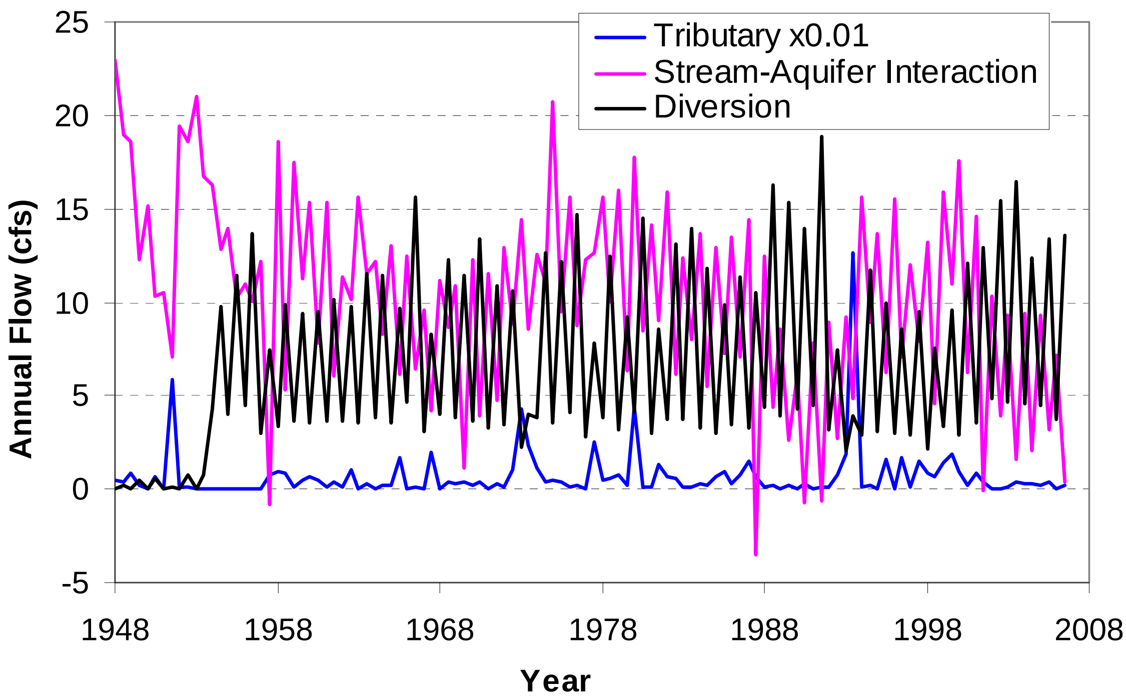


Figure 74. Yearly Streamflow Budget

Ground Water

The ground-water portion of the model budget includes the change in net storage, head boundaries (lateral flow), well pumping, evapotranspiration, areal recharge, and stream leakage (stream-aquifer interactions). Figure 75 shows the cumulative change in the budget over the transient period. Positive values indicate water is going into the aquifer system, specifically from recharge and lateral flow in the subsurface. Negative numbers indicate outflow from the aquifer. The migration of ground water to the stream system (base flow) and pumping from ground-water wells represent the largest outflows.

The cumulative change in net storage of the aquifer shows a gradual decline since the start of the transient period (1948). The change in storage varies slightly over time with an accumulated total loss estimated by the model of over 100,000 acre-feet, which is in the same magnitude of the ET losses from the aquifer.

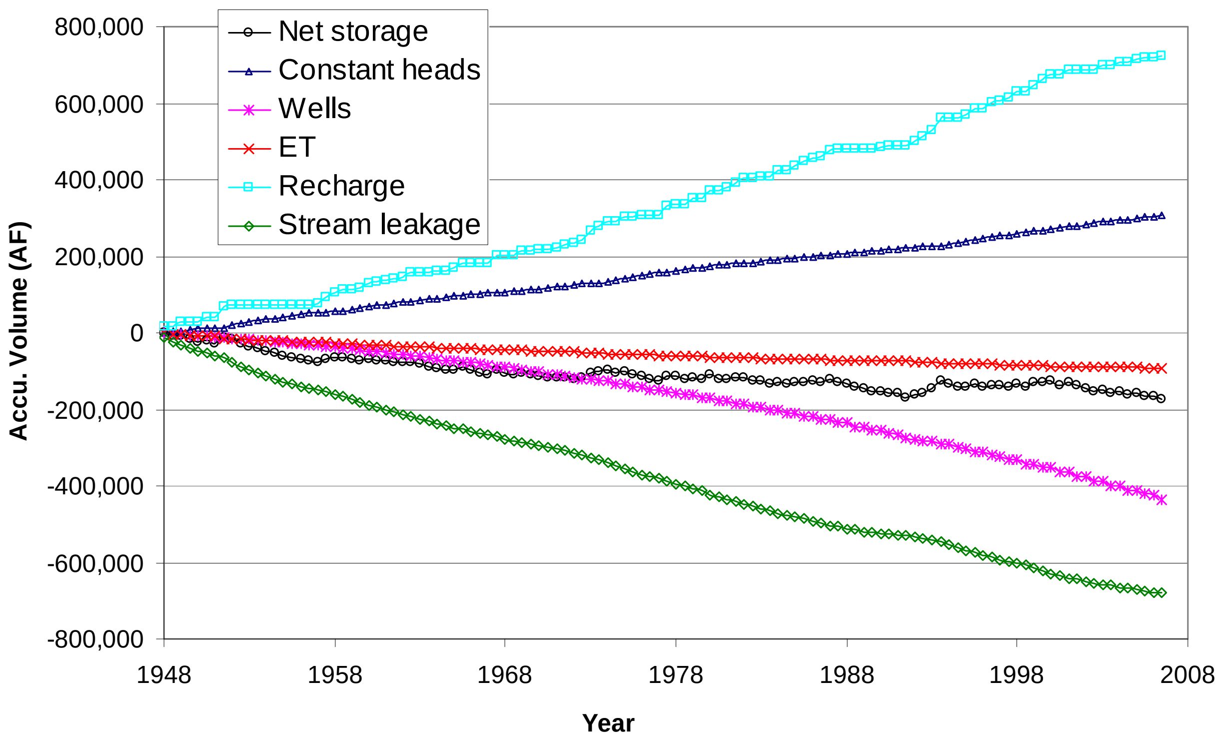


Figure 75. Accumulated ground-water budget, 1948 to 2006

Figure 76 shows the average annual components of the ground-water budget for individual years over the transient period. Figure 77 displays the same information with a two-year moving average trend applied to each variable in order to better visually illustrate changes over time. Positive values indicate water is going into the aquifer system while negative numbers indicate outflow from the aquifer.

The annual plots indicate the strong influence of precipitation on many of the model parameters (recharge, pumping). The amount of water pumped from the aquifer to wells shows the most notable increasing trend over time.

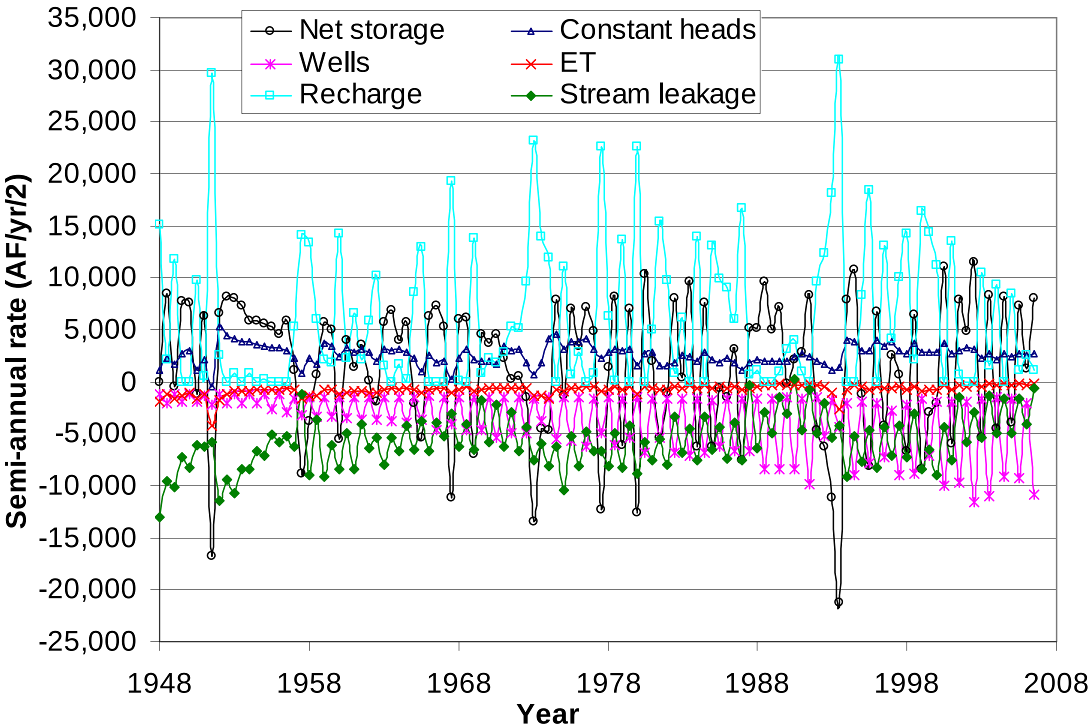


Figure 76. Yearly ground-water budget, 1948 to 2006

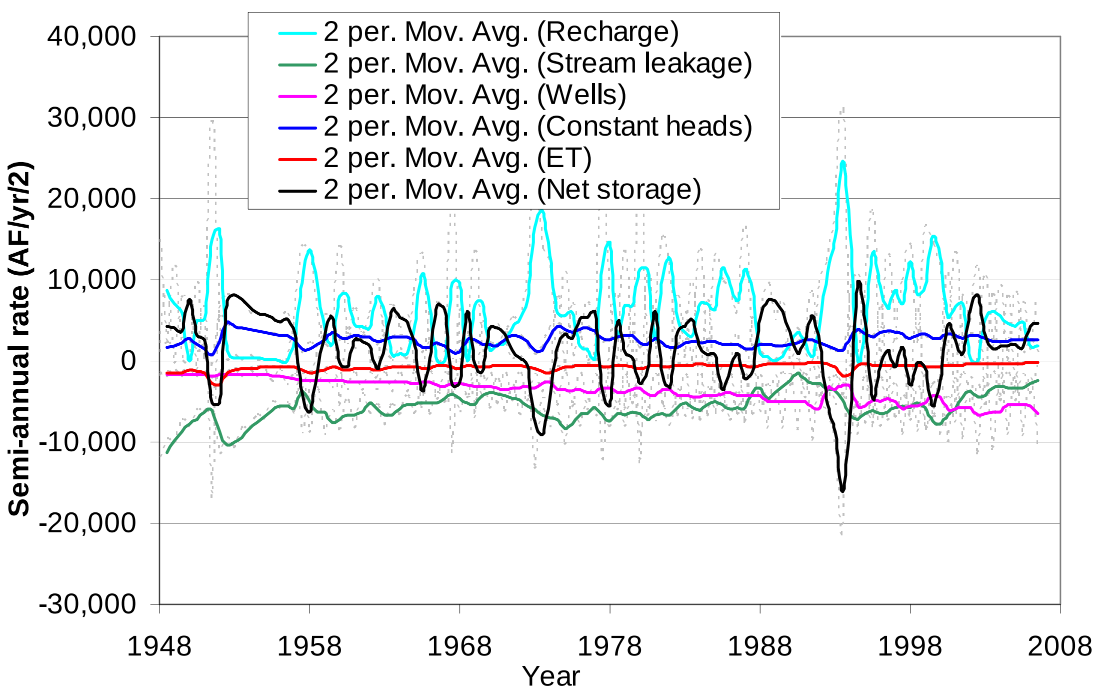


Figure 77. Two-Year moving averaged yearly ground-water budget, 1948 to 2006

MODEL SCENARIOS

Once a numerical model has been constructed and adequately replicates past hydrologic conditions, it becomes a powerful management and planning tool by allowing the computation of "What if…." scenarios. Traditional scenarios involve changing certain model parameters, such as increasing or decreasing ground-water pumping demands, to see how the water levels and streamflow in the river respond. However, the KWO determined that another type of scenario would fit better for the management of water releases from Kanopolis Reservoir, requiring a non-traditional but innovative approach to using the model.

The first scenario is a type of back calculation that focuses on determining the minimum flow of the Smoky Hill River into the model domain (releases from Kanopolis Reservoir) in order to achieve a particular river flow rate at Salina. This flow was specified and provided by the KWO as the 7Q10 flow (the lowest seven-day average flow that occurs on average once every 10 years) calculated from measurements for the Mentor gage. For this scenario, the model repeats the past climatic conditions from 1948 to 2006 again into the future. Surface- and ground-water pumping demands are computed from the linear water-use regressions applied to each climatic period but always based on the 2006 level of water right development. This means all uses and all sources divert water; the amount diverted depends on the level of precipitation. The initial ground-water level, head boundaries, and stream properties (depth, width) are also based on 2006 conditions.

Inflow from the start of each model computational run is zero (no releases from Kanopolis). The model is then run and the flow near Salina computed. If the streamflow is not within 18 to 22 ft^3/sec (plus or minus 10 percent of the 20 ft^3/sec 7Q10 benchmark) the model is run again with an increase or decrease of 80 percent of the difference between the simulated and 20 ft^3/sec 7Q10 benchmark. Model runs are repeated and the flow rate again checked until the target flow range is satisfied. For each 6-month time step, the model repeats the process to incrementally increase or decrease the amount of outflow from Kanopolis until the targeted 7Q10 flow is met. When this scenario was run, the back calculation process took approximately two days for a high-end personal computer to complete the automated process.

The end goal of the scenario is the number of six-month time steps in the 59-year period and the amount of water required to be released from Kanopolis to meet the 7Q10 flow at Salina under current water demands. Reservoir yield models for Kanopolis Reservoir could then be compared with the scenario results to determine the probability the lake can meet those water demands.

Figure 78 shows the results of the back-calculation minimum release, 7Q10 flow target scenario. Out of the 118 six-month model steps, 63 required some amount of flow to be released from Kanopolis Reservoir in order to maintain the 2006 level of water right development and also to achieve the 20 ft^3/sec 7Q10 flow near Salina. Thirty of those simulated events occurred during the growing seasons while 35 occurred during the winter period of October to March.

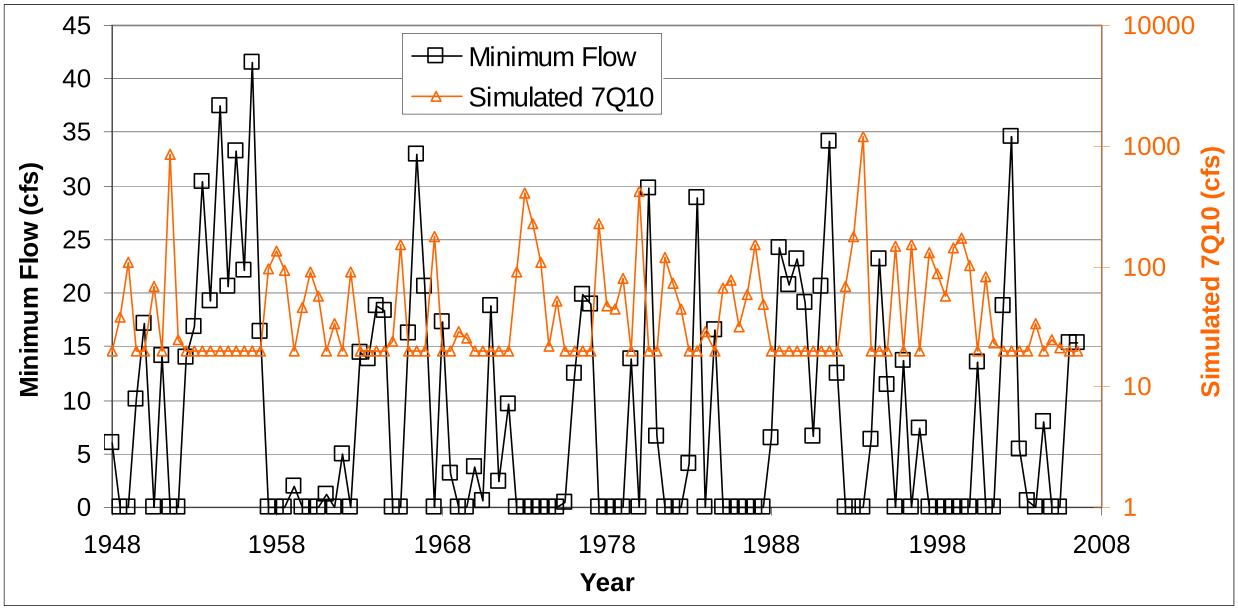


Figure 78 . Simulated mean six-month flow in the Smoky Hill River at Salina and the back-calculated minimum lake flows needed to achieve the 7Q10 flow of 20 ft^3/sec at Salina in model scenario 1.

The second model scenario requested by the KWO is a modification to the first back-calculation scenario in which there is never any outflow from Kanopolis into the model and no ground-water pumping and stream diversions occur from water rights. All other conditions remain the same as for the first scenario – 2006 hydrogeologic conditions and a repeat of climatic conditions from 1948 to 2006. The model is then run to compute the flows for each year in the Smoky Hill River at Salina.

The results for the second scenario are shown in Figure 79. Under this scenario, the 7Q10 benchmark flow of 20 ft^3/sec near Salina was not achieved in 30 of the 118 time steps in the model (Figure 79). Twenty-two (73.3%) of those 30 events occurred during a winter time step.

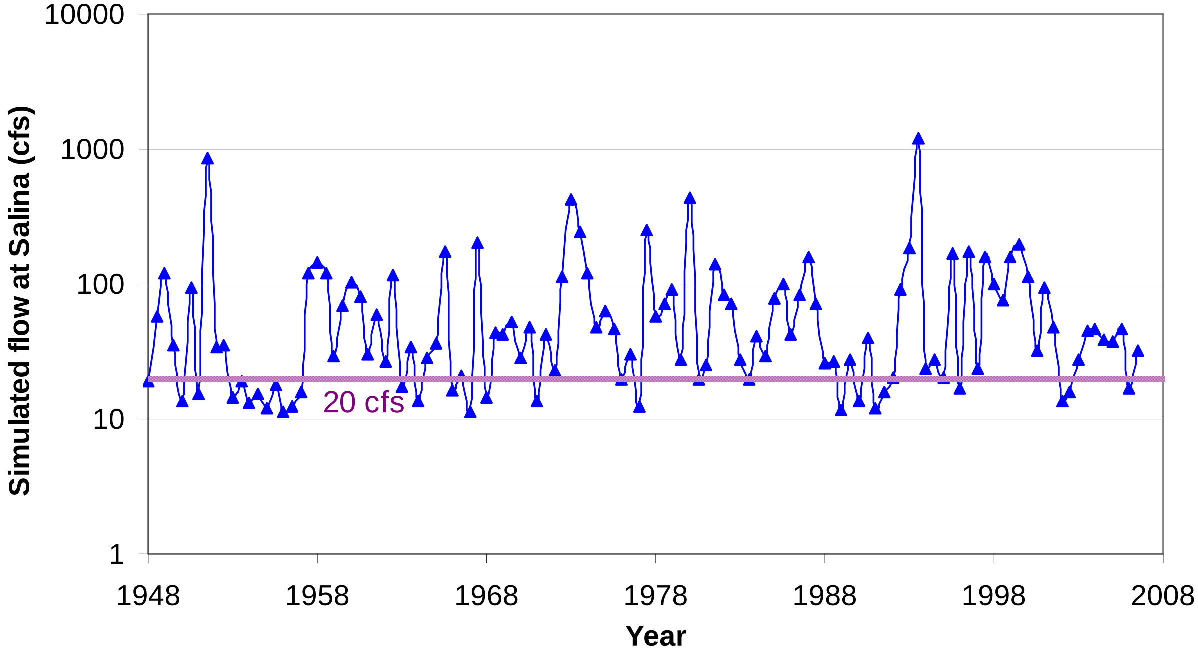


Figure 79. Scenario 2 results, no Kanopolis outflow, no water right diversions.

REFERENCES

Anderson, M.P., and W.W. Woessner, 1992, Applied Groundwater Modeling. Academic Press, 381 p.

Barker, W.L. and Dodge D.A., 1989, Soil Survey of Ellsworth County, Kansas. U.S. Department of Agriculture, Soil Conservation Service, 100 p.

Bayne, C.K., Franks, P.C., and Ives Jr, W., 1971, Geology and Ground-water Resources of Ellsworth County, Central Kansas. Kansas Geological Survey, Bulletin 201, 84 p.

Doherty, J., 2004, PEST—Model-Independent Parameter Estimation. User Manual, 5th Edition, Watermark Numerical Computing.

Egbert, S.L., Peterson, D.L., Stewart, A.M., Lauver, C.L., Blodgett, C.F., Price, K.P., and Martinko, E.A. 2001. The Kansas Gap Land Cover Map: Final Report. Kansas Biological Survey Report #98. Lawrence, Kansas.

Gillespie, J. B. and G. D. Hargadine, 1981, Saline ground-water discharge to the Smoky Hill River between Salina and Abilene, Central Kansas, U.S. Geological Survey, Water-resources Investigations Report 81-43, 71 p.

Gillespie, J. B. and G. D. Hargadine, 1986, Geohydrology of the Wellington-alluvial aquifer system and evaluation of possible locations of relief wells to decrease saline ground-water discharge to the Smoky Hill and Solomon rivers, Central Kansas, U.S. Geological Survey, Water-resources Investigations Report 86-4110, 31 p.

Hansen, C. V., 1991, Estimates of freshwater storage and potential natural recharge for principal aquifers in Kansas: U.S. Geological Survey, Water Resources Investigations Report 87-4230, 100 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to modularization concepts and the Ground-Water Flow Process. U.S. Geological Survey, Open-File Report 00- 92, 121 p.

Juracek, K.E., 2001, Channel-Bed Elevation Changes Downstream From Large Reservoirs in Kansas, U.S. Geological Survey Water-Resources Investigations Report 01-4205, 24p.

Kansas Water Authority, 2005, Kansas Water Plan. Available from Kansas Water Office, Topeka, KS and online at http://www.kwo.org.

Latta, B.F., 1949, Ground-water conditions in the Smoky Hill valley in Saline, Dickinson, and Geary counties, Kansas: Kansas Geological Survey, Bulletin 84, 152 p.

Macfarlane, P.A., Doveton, J.H., and Whittemore, D.O., 1998, User's guide to the Dakota aquifer in Kansas: Kansas Geological Survey, Technical Series 2, 56 p.

National Oceanic and Atmospheric Administration, 2007, National Climatic Data Center data available on the World Wide Web, accessed April 24, 2007, at http://lwf.ncdc.noaa.gov/oa/ncdc.html

Palmer, C.D., Hamilton, V.L., Hoffman, B.R., Fahnestock, P.B., and Barker, W.L., 1992, Soil Survey of Saline County, Kansas. U.S. Department of Agriculture, Soil Conservation Service, 122 p.

Perry, D.A., Wolock, D.M., and Artman, J.C., 2004, Estimates of flow duration, mean flow, and peak-discharge frequency values for Kansas stream locations: U.S. Geological Survey, Scientific Investigations Report 2004-5033, 651 p.

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model. U.S. Geological Survey, Open-File Report 88-729, 113 p.

Sadeghipour, J., P. A. Macfarlane, C. D. McElwee and M. W. Kemblowski, 1987, Saltwater intrusion into alluvial aquifers: an evaluation of field methods and ground-water modeling techniques, Kansas Geological Survey, 208 pp.

U.S. Department of Agriculture, Natural Resources Conservation Service, 2007, Soil Data Mart data available on the World Wide Web, accessed March 3, 2007 at http://soildatamart.nrcs.usda.gov

Whittemore, D.O., Sphocleous, M.A., Butler, J.J., Wilson, B.B., Tsou, M.S., Zhan, X., Young, D.P., McGlashan, 2006, Numerical Model of the Middle Arkansas River Subbasin. Kansas Geological Survey Open-file Report 2006-25, 122 p.

Williams, C.C., and Lohman, S.W., 1959, Geology and ground-water resources of a part of south-central Kansas: Kansas Geological Survey, Bulletin 79, 455 p.

Wilson, B.B., and Bohling, G.C., 2003, Assessment of Reported Water Use and Total Annual Precipitation, State of Kansas, Kansas Geological Survey, Open-file Report 2003-55C, 39 p.