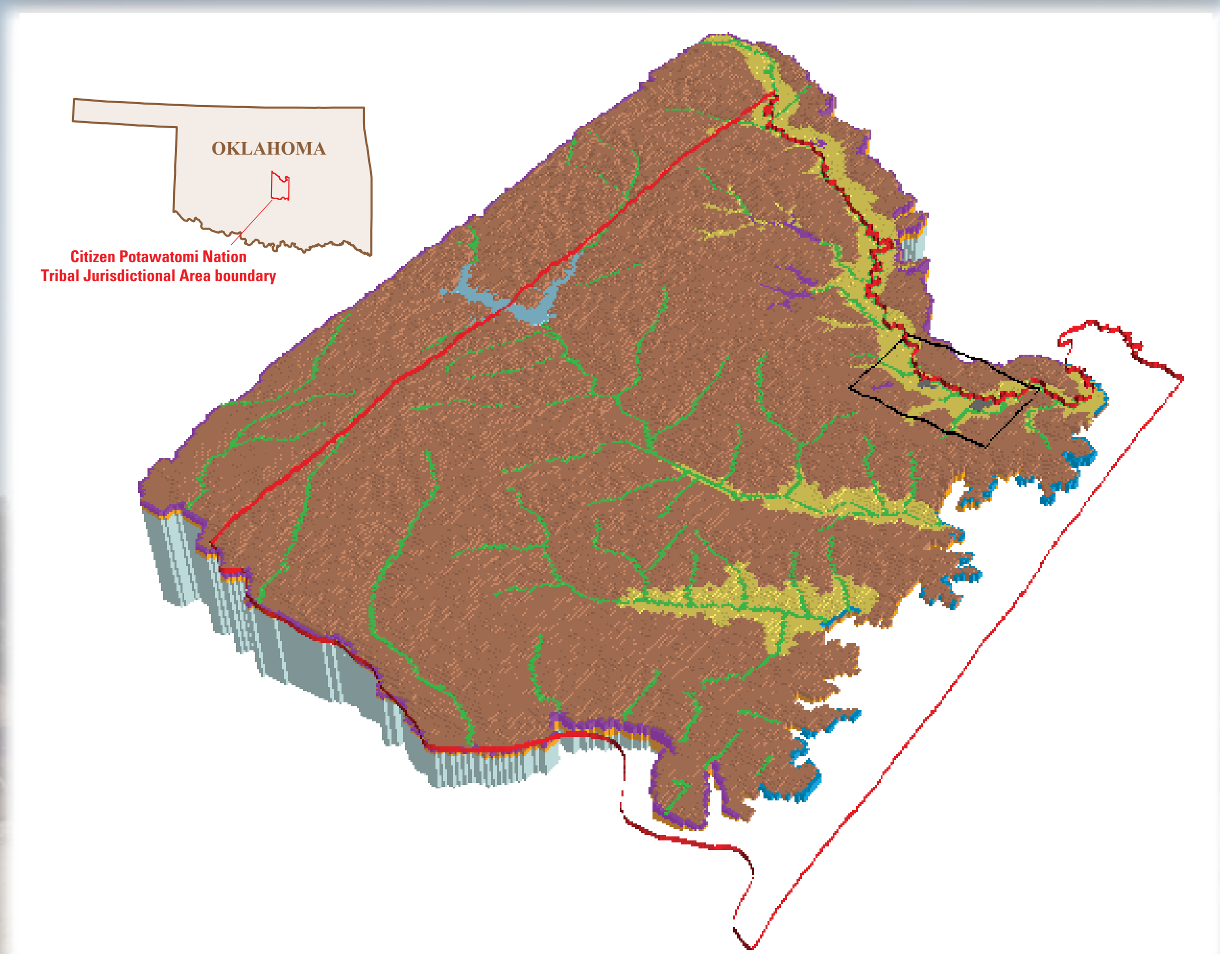
Prepared in cooperation with the Citizen Potawatomi Nation

Numerical Simulation of Groundwater Flow, Resource Optimization, and Potential Effects of Prolonged Drought for the Citizen Potawatomi Nation Tribal Jurisdictional Area, Central Oklahoma



Scientific Investigations Report 2014–5167

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

Cover:

Front and back cover background, North Canadian River at Harrah, Oklahoma, 2014 (photograph by James R. Hanlon, U.S. Geological Survey).

Front cover, Block diagram of Citizen Potawatomi Nation numerical groundwater-flow model and the inset model domain for the Citizen Potawatomi Nation Tribal Jurisdictional Area groundwater study, central Oklahoma. Perspective is looking northwest.

Back cover, North (left) and south (right) water-supply wells along the North Canadian River near the streamflow-gaging station at Harrah, Oklahoma, January 2015 (photograph by William J. Andrews, U.S. Geological Survey).

Numerical Simulation of Groundwater Flow, Resource Optimization, and Potential Effects of Prolonged Drought for the Citizen Potawatomi Nation Tribal Jurisdictional Area, Central Oklahoma

By Derek W. Ryter, Christopher D. Kunkel, Steven M. Peterson, and Jonathan P. Traylor

Prepared in cooperation with the Citizen Potawatomi Nation

Scientific Investigations Report 2014–5167

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

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod/.

Suggested citation:
Ryter, D.R., Kunkel, C.D., Peterson, S.M., and Traylor, J.P., 2015, Numerical simulation of groundwater flow, resource optimization, and potential effects of prolonged drought for the Citizen Potawatomi Nation Tribal Jurisdictional Area, central Oklahoma, U.S. Geological Survey Scientific Investigations Report 2014–5167, 27 p., http://dx.doi.org/10.3133/sir20145167.

ISSN 2328-031X (print)
ISSN 2328-0328 (online)

Acknowledgments

The authors would like to thank the Citizen Potawatomi Nation for support and cooperation with the scope and direction of the project and for providing geographic information pertinent to the analyses. They would also like to thank Paul Barlow and Edward Banta for valuable assistance with the resource optimization. Joseph Nadolski and Robert Frye provided help in the preparation of the numerical groundwater-flow model and datasets. Thanks to Paul Barlow and Randal Hanson for reviews of the manuscript and the numerical groundwater-flow model.

Contents

Figures

Tables

Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile	259.0	hectare (ha)
square mile	2.590	square kilometer (km^2)
	Volume	
acre-foot	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second (ft^3/s)	2446.576	cubic meter per day (m^3/d)
gallon per minute (gal/min)	5.451	cubic meter per day (m^3/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

BFI	A computer program that uses daily streamflow records with a hydrograph recession method to separate base flow from runoff; base-flow index
CPN	Citizen Potawatomi Nation
EDZ	Economic development zones
ET	Evapotranspiration
GHB	General Head Boundary
GWM	Groundwater Management Process for MODFLOW
GWM–VI	Groundwater Management Process, Version Independent, for MODFLOW
GTW	Geothermal well
IHW	Iron Horse well
Kh	Horizontal hydraulic conductivity
MNW	Multi-node well
OWRB	Oklahoma Water Resources Board
R^2	Coefficient of determination
SFR2	Streamflow-Routing Package version 2
SWB	Soil-Water Balance
Sy	Specific yield
USGS	U.S. Geological Survey

Numerical Simulation of Groundwater Flow, Resource Optimization, and Potential Effects of Prolonged Drought for the Citizen Potawatomi Nation Tribal Jurisdictional Area, Central Oklahoma

By Derek W. Ryter, Christopher D. Kunkel, Steven M. Peterson, and Jonathan P. Traylor

Abstract

A hydrogeological study including two numerical groundwater-flow models was completed for the Citizen Potawatomi Nation Tribal Jurisdictional Area of central Oklahoma. One numerical groundwater-flow model, the Citizen Potawatomi Nation model, encompassed the jurisdictional area and was based on the results of a regional-scale hydrogeological study and numerical groundwater-flow model of the Central Oklahoma aquifer, which had a geographic extent that included the Citizen Potawatomi Nation Tribal Jurisdictional Area. The Citizen Potawatomi Nation numerical groundwater-flow model included alluvial aquifers not in the original model and improved calibration using automated parameter-estimation techniques. The Citizen Potawatomi Nation numerical groundwater-flow model was used to analyze the groundwater-flow system and the effects of drought on the volume of groundwater in storage and streamflow in the North Canadian River. A more detailed, local-scale inset model was constructed from the Citizen Potawatomi Nation model to estimate available groundwater resources for two Citizen Potawatomi Nation economic development zones near the North Canadian River, the geothermal supply area and the Iron Horse Industrial Park.

Groundwater pumping rates at potential well locations were optimized using the most recent version of the U.S. Geological Survey Groundwater-Management Process for MODFLOW. The objectives of optimization were to determine if a total pumping rate of 500 gallons per minute could be pumped from 5 wells at the geothermal supply area and to maximize discharge from 16 wells at the Iron Horse Industrial Park without exceeding specified head drawdown constraints at the pumping wells and thus prevent groundwater depletion.

The inset model was used to estimate North Canadian River streamflow depletion caused by optimized pumping at the Iron Horse Industrial Park because water quality was a concern, and the river may have degraded water quality compared to water in other parts of the alluvial aquifer. The fate of streamflow that infiltrates into groundwater because of pumping was not directly determined, but it was assumed that this water could end up in the well discharge, and was considered to be a maximum proportion of well discharge derived from the North Canadian River.

The total optimized continuous pumping rate from five managed wells at the geothermal supply area was 638 gallons per minute, which exceeded the target pumping rate of 500 gallons per minute. The total continuous pumping rate from 16 wells at the Iron Horse Industrial Park was 1,472 gallons per minute, which induced stream infiltration of approximately 4.1 gallons per minute (approximately 0.3 percent of the total well discharge) from the North Canadian River.

To estimate the effects of drought on water resources in the Citizen Potawatomi Nation Tribal Jurisdictional Area, a hypothetical 10-year drought during which precipitation would decrease by 50 percent was simulated by decreasing model groundwater recharge by the same proportion for the period 1990–2000 of the transient model. The effects of the drought were estimated by calculating the change in the volume of groundwater storage and groundwater flow to streams at the end of the drought period, and the change in simulated streamflow in the North Canadian River at the streamflow-gaging station at Shawnee, Okla., during and after the drought.

The hypothetical decrease in recharge during the simulated drought caused groundwater in storage over the entire model in the study area to decrease by 351,500 acre-feet (14,100 acre-feet in the North Canadian River alluvial aquifer and 346,400 acre-feet in the Central Oklahoma aquifer), or approximately 0.2 percent of the total groundwater in storage over the drought period. This small percentage of groundwater loss showed that the Central Oklahoma aquifer as a bedrock aquifer has relatively low rates of recharge from the surface relative to the approximate storage. The budget for base flow to the North Canadian River indicated that the change in groundwater flow to the North Canadian River decreased during the 10-year drought by 386,500 acre-feet, or 37 percent. In all other parts of the Citizen Potawatomi

Nation Tribal Jurisdictional Area, base flow decreased by 292,000 acre-feet, or 28 percent. Streamflow in the North Canadian River at the streamflow-gaging station at Shawnee, Okla., decreased during the hypothetical drought by as much as 28 percent, and the mean change in streamflow decreased as much as 16 percent. Streamflow at the Shawnee streamflow-gaging station did not recover to nondrought conditions until about 3 years after the simulated drought ended, during the relatively wet year of 2007.

Introduction

Commercial development has grown in recent years in the Citizen Potawatomi Nation (CPN) Economic Development Zones (EDZs) in the CPN Tribal Jurisdictional Area (fig. 1). The EDZs require dependable sources of surface water and groundwater—some with specific water-quality requirements—as water demands increase. The study described in this report was a cooperative effort between the U.S. Geological Survey (USGS) and the CPN to evaluate the available groundwater resources for resource management in the CPN Tribal Jurisdictional Area by performing a detailed analysis of the integrated hydrological system and water use in areas of development, including numerical groundwater-flow models.

Part of the numerical groundwater-flow model of the Central Oklahoma aquifer described in Mashburn and others (2013), referred to in this report as the Central Oklahoma aquifer model, was refined and improved to produce a subregional-scale numerical groundwater-flow model, referred to here as the CPN model. The CPN model was used to describe the groundwater-flow system and to estimate the effects of future droughts on the water resources in the CPN Tribal Jurisdictional Area (fig. 1). A high-resolution numerical groundwater-flow model—termed the inset model—was constructed in the CPN model active area as a stand-alone model for local-scale analysis. The inset model was used to optimize use of groundwater resources in two EDZs using state-of-the-art applications, including the Groundwater Management Process (Banta and Ahlfeld, 2013).

Purpose and Scope

The purpose of this report is to describe the construction, calibration, and analyses performed with two numerical groundwater-flow models for the Central Oklahoma aquifer and alluvial aquifers in the CPN Tribal Jurisdictional Area in central Oklahoma. Analyses include optimization of groundwater-resource use at two locations and estimating the effects of a prolonged severe drought on the total amount of groundwater in storage and streamflow at selected locations. The scope of this study includes the geographic extent of the CPN Tribal Jurisdictional Area where it overlies the Central Oklahoma aquifer (fig. 1). The time period of the analysis of the groundwater-flow system includes the period 1987–2009.

Location and Description of Study Area

The CPN Tribal Jurisdictional Area is in central Oklahoma, east of Oklahoma City on the southeastern part of the Central Oklahoma aquifer between the North Canadian River on the north and the Canadian River on the south (fig. 1). The study area was defined as the CPN Tribal Jurisdictional Area that overlies the Central Oklahoma aquifer, and the numerical groundwater-flow model, as defined by the CPN, included an area approximately 20 miles (mi) beyond the western boundary of this area and approximately 5 mi north of the North Canadian River to minimize external boundary effects. The study area is approximately 1,100 square miles (mi^2) (704,000 acres).

Large lakes in the study area include Lake Thunderbird, the Shawnee Reservoir 1 and Shawnee Reservoir 2, Wes Watkins Reservoir, and Tecumseh Lake (fig. 1). Land use in the area is mostly rural with cultivated agricultural practices restricted to river valleys, and other areas characterized as ranchland or forests (Mashburn and others, 2013).

Previous Investigations

Mashburn and others (2013) describes the hydrogeology, surface water, and a regional-scale transient numerical groundwater-flow model that included the entire Central Oklahoma aquifer. Havens (1989) describes the hydrogeology of the North Canadian alluvial and terrace deposits in the study area, and Adams and others (1997) is a collection of digital geographic data that includes the extents and generalized hydraulic properties and groundwater altitudes of aquifers in this area.

Water Use

Groundwater demands in the CPN Tribal Jurisdictional Area are predominantly from municipal and domestic wells (Mashburn and others, 2013). Water use is regulated by the Oklahoma Water Resources Board (OWRB) and reported by water-use permit holders as total annual pumping. For this report, monthly time increments of water pumping amounts were used. To convert annual water use from the Central Oklahoma aquifer model to monthly time periods, the OWRB estimate of the monthly percentage of the annual water discharge for different categories of wells pumped by county (Oklahoma Water Resources Board, 2012) was used. Other municipal demands were met through surface-water storage in reservoirs and were not included in this analysis.

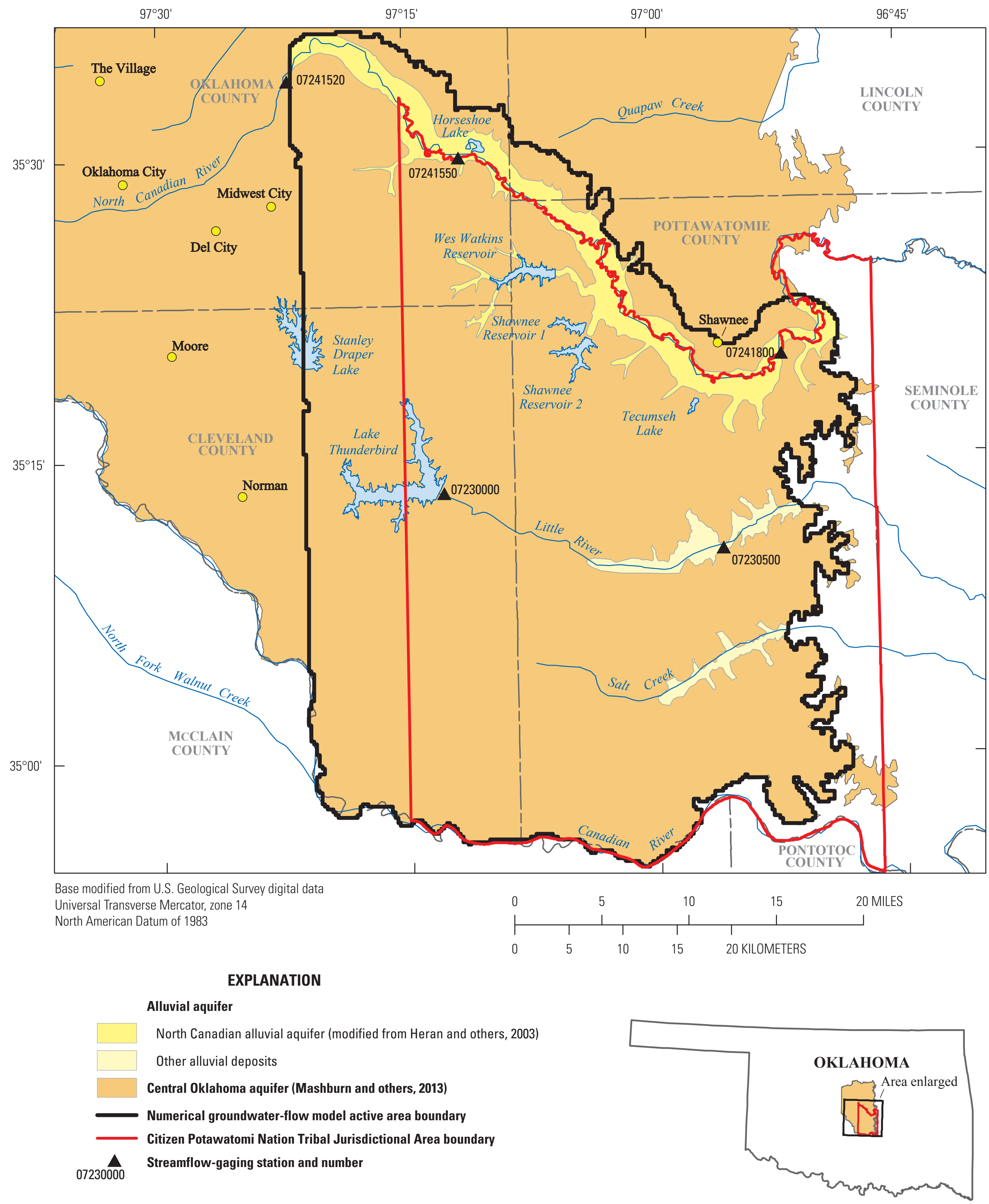


Figure 1. Location of the Citizen Potawatomi Nation Tribal Jurisdictional Area, hydrological features, and the Central Oklahoma and alluvial aquifers, central Oklahoma.

Hydrogeological Framework

The hydrogeological framework of the Central Oklahoma aquifer described in Mashburn and others (2013) was modified in the CPN model. Alluvial aquifers are composed of Quaternary-age alluvial-valley deposits along major streams (fig. 1) and were included as an additional discontinuous hydrogeologic unit in the CPN model to better simulate the flow between streams and groundwater. The lower boundary of the Central Oklahoma aquifer model was defined as the transition from overlying freshwater to saline water, and it was assumed that there was not substantial flow across this boundary (Mashburn and others, 2013). Although there is no physical hydrologic boundary and there was not expected to be substantial flow in the saline part of the aquifer, the CPN model includes the saline groundwater to the base of the Wellington Formation. The base of the Wellington Formation is a physical boundary where hydraulic conductivity greatly decreases (Mashburn and others, 2013). In this report, the saline zones of the Wellington Formation are referred to as the "saline unit."

Alluvial deposits along the North Canadian River (Havens, 1989) and reaches of Little River and Salt Creek (Heran and others, 2003) were included as a discontinuous hydrogeologic unit (fig. 1). The OWRB designated the North Canadian River alluvium as the North Canadian River alluvial and terrace aquifer (Oklahoma Water Resources Board, 2012) and is referred to in this report as the North Canadian River alluvial aquifer. The alluvial deposits along the Little River and Salt Creek were not extensive or thick enough to be named as aquifers in this study. Other surficial deposits such as upland terrace deposits were not considered to contain substantial groundwater resources and were not included in the CPN model as a separate unit.

The base and thickness of alluvial deposits were estimated from borehole logs submitted to the OWRB (Oklahoma Water Resources Board, 2013). Lithological logs that included a depth of the base of alluvial deposits were selected and used to construct the bedrock surface. Between locations where the base of the alluvial deposits was estimated, the base was assumed to be an east-draining erosional surface similar to the configuration of modern drainages. The North Canadian alluvial aquifer was estimated to have a mean thickness of 29 feet (ft) and maximum thickness of 77 ft in the study area. The Little River alluvial deposit mean thickness was approximately 24 ft with a maximum of 107 ft, and the Salt Creek alluvium mean thickness was approximately 27 ft with a maximum of 82 ft in the study area.

Aquifer Hydraulic Properties

Initial hydraulic properties of the freshwater part of the Central Oklahoma aquifer were taken directly from Mashburn and others (2013). Horizontal hydraulic conductivity (Kh) ranged from 0.3 to 6.6 feet per day (ft/d) and locally is highly variable because of lenticular beds of fine sand surrounded by claystone and shale. The saline unit was assumed to be composed of silt and silty fine sand and was assigned an initial Kh value of 0.2 ft/d for this lithology from Fetter (1994). The values for Kh and vertical anisotropy used in the Central Oklahoma aquifer model were used as initial values in the CPN model and were adjusted during model calibration. There were, however, no available direct measurements of hydraulic properties in the Central Oklahoma aquifer, saline unit, or North Canadian alluvial aquifer in the study area.

Adams and others (1997) is a digital dataset of the hydrogeology of the North Canadian alluvial aquifer, but that dataset is limited to the average properties of the entire deposits as single values for the entire aquifer. Thus, to include an estimate of spatial variation for the CPN model, hydraulic properties of textural classes from Fetter (1994) were assigned to textural descriptions in lithological borehole logs, and the thickness-weighted mean Kh was calculated at each log location. The Kh values for the alluvial deposits from individual logs were estimated to range from 0.3 to 120.0 ft/d with a mean of 38.0 ft/d. Mean Kh values from each lithological borehole log were used to interpolate Kh from various locations across the alluvial aquifer using the inverse-distance weighted function in ArcGIS version 10, Spatial Analyst (Esri, 2015). As with Kh values of the Central Oklahoma aquifer, estimated hydraulic properties of the alluvium were changed during numerical model calibration. Initial hydraulic properties were used to assign conductance values to aquifer boundary conditions.

The Kh of the alluvial material was estimated to be much greater than the Kh of the Central Oklahoma aquifer; thus, groundwater in the alluvial material is much more responsive to stresses such as seasonal recharge, and has a substantial hydraulic connection with streams such as the North Canadian River. The lesser Kh of the Central Oklahoma aquifer is assumed to limit the hydraulic connection between these two aquifers.

Potentiometric Surface

The potentiometric surface of the Central Oklahoma aquifer in 1986-7 from Mashburn and others (2013) was used for this study (fig. 2). The potentiometric surface of the saline unit was assumed to be the same as the Central Oklahoma aquifer. Detail for the potentiometric surface in the North Canadian River alluvial aquifer and Little River and Salt Creek alluvial deposits was added using water levels from the National Water Information System (U.S. Geological Survey, 2012) and the altitude of surface-water bodies, such as stream channel altitudes derived from digital elevation models (not shown on fig. 2).

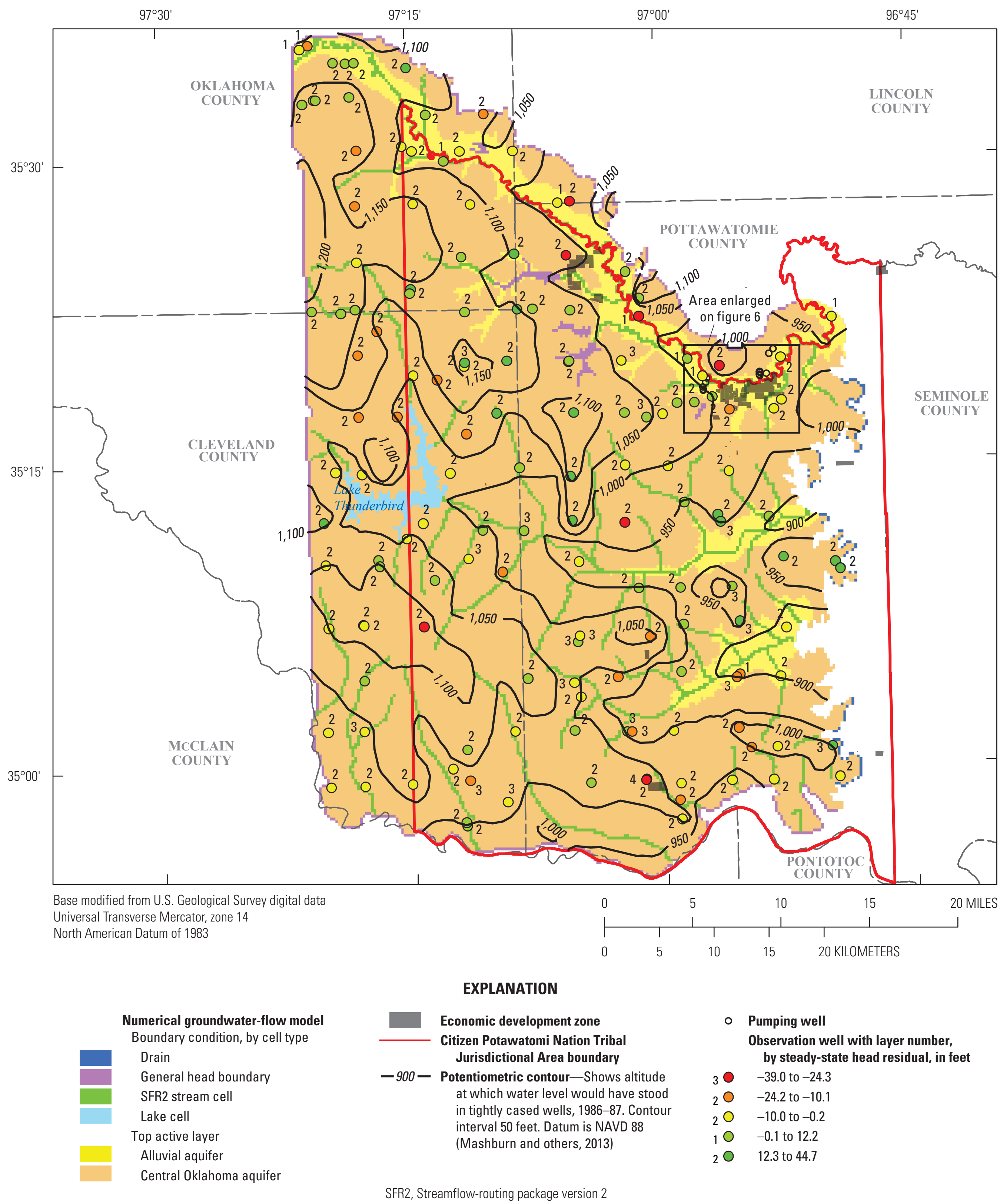


Figure 2. Citizen Potawatomi Nation numerical groundwater-flow model active area with the 1987 potentiometric surface, steady-state head residuals, locations of model features, and the inset model domain for the Citizen Potawatomi Nation Tribal Jurisdictional Area groundwater study, central Oklahoma.

As shown in Mashburn and others (2013) and figure 2, groundwater in the Central Oklahoma aquifer flows to the east away from recharge areas in the central and western parts of the aquifer and discharges to streams across the aquifer. Streams are generally considered to be gaining streams that receive groundwater discharge along their lengths. The total flow to all lakes and streams has not been calculated by previous studies or estimated in this study; however, base flow for the North Canadian River was estimated and used to calibrate the numerical groundwater-flow model.

Conceptual Flow Model

A conceptual flow model is a schematic description of a groundwater system including water inflows and outflows that take place at aquifer boundaries. Stream base flow and gaining and losing stream reaches are also described in this section.

Aquifer Boundaries

Aquifer boundaries include locations, linear features, and areas. Location boundaries in this study included pumping wells used for agriculture or public water supply and seeps or springs. Linear boundaries were stream channels that, in most cases in the study area, are sinks where groundwater flows to streams, and the margins of the area where groundwater moves laterally into or out of the aquifer. Areal boundaries include the land surface where recharge from precipitation and plant consumption takes place, and lakebeds through which groundwater flows to or from the lake.

The boundary condition with the largest area in the model is the land surface through which water enters the groundwater system from precipitation and leaves the system through plant uptake and evapotranspiration (ET). Based on the potentiometric surface in Mashburn and others (2013), the water table of the Central Oklahoma aquifer was located within bedrock and well below the typical deciduous forest and grassland root zone depth (Thornthwaite and Mather, 1957). Thus, plant uptake from groundwater through ET was not simulated where the Central Oklahoma aquifer was present at the land surface. On alluvial deposits and near surface-water bodies where the water table is very shallow, recharge was decreased during model calibration to offset groundwater discharged to ET. The largest discharges of the Central Oklahoma aquifer groundwater occur along stream-channel boundaries as stream base flow (Mashburn and others, 2013). Stream channels also were determined to be the largest discharge boundaries for the North Canadian alluvial aquifer.

Stream Base Flow

The objective of stream base flow analysis was to estimate the mean daily base flow during the study period (1987–2009) and the monthly stream base flow for the period of the transient model (1988-2009) as described in the “Model Configuration and Boundary Conditions” section of this report for the North Canadian River in the study area. Stream base flow, defined in Barlow and Leake (2012) as the flow of groundwater into streams, was estimated along the North Canadian River in the study area to provide flow values for numerical groundwater-flow-model calibration. Stream reaches receiving base flow are referred to as gaining, and those with infiltration to the aquifer are referred to as losing. The North Canadian River reaches studied were between the USGS streamflow-gaging stations just upstream from the model domain at Britton Road in Oklahoma City, Okla. (USGS station 07241520), near Harrah, Okla. (USGS station 07241550), and at Shawnee, Okla. (USGS station 07241800) (fig. 1). Streamflow measurements for all stations were accessed from the National Water Information System (U.S. Geological Survey, 2012). The period of record for the streamflow-gaging station at Harrah was from 1968 to 2009, but the period of record for the streamflow-gaging station at Shawnee was from 2001 to 2009 and did not include the complete period of study (U .S. Geological Survey, 2012). For the available periods, base flow was estimated using base-flow index (BFI), a computer program that uses daily streamflow records with a hydrograph recession method to separate base flow from runoff (Wahl and Wahl, 2007).

During the 84 months for the period from 2001 to 2009 during which all three streamflow-gaging stations recorded streamflow, the North Canadian River between the streamflow-gaging stations at Britton and Shawnee was a gaining stream during 70 months and a losing stream for 14 months. From 2001 to 2009, the mean daily North Canadian River base flow calculated using BFI at the streamflow-gaging station at Britton was 99 cubic feet per second (ft^3/s), at Harrah was 185 ft^3/s, and at Shawnee was 226 ft^3/s.

To estimate base flow for the reach between the Harrah and Shawnee streamflow-gaging stations when streamflow observations were not available at the Shawnee station (1988–2001) during the model simulation period, the base flow upstream from the streamflow-gaging station at Harrah was assumed to change by a characteristic amount calculated for the period when streamflow data were available at both stations. The BFI results indicate that the base flow between the streamflow-gaging station at Harrah and the streamflow-gaging station at Shawnee was affected by the precipitation measured at the National Weather Service cooperative observer station in Shawnee, Okla. (USC00348110; National Climatic Data Center, 2013). Months were classified based on precipitation as being wet (greater than 4.65 inches), average (between 4.65 and 1.53 inches), or dry (less than 1.53 inches). During wet months, mean base flow at the streamflow-gaging station at Shawnee increased 77 ft^3/s relative to flow at the streamflow-gaging station at Harrah; mean base flow increased 36 ft^3/s during months with average precipitation, and mean base flow increased 44 ft^3/s during dry months. Streamflow for months without streamflow data at the Shawnee streamflow-gaging station was added by classifying each month as wet, average, or dry and adding the characteristic change in base flow to the measured flow at Harrah.

The BFI program was used to calculate base flows for the Little River streamflow-gaging station near Tecumseh, Okla. (USGS station 07230500), although these data were not used as values for model calibration. Because of effects from streamflow releases from Lake Thunderbird, the streamflow input to BFI was estimated to be the difference between Little River streamflow near Tecumseh and streamflow just downstream from the lake measured at the streamflow-gaging station at Little River below Lake Thunderbird near Norman, Okla. (USGS station 07230000). The long-term mean base flow at that streamflow-gaging station on the Little River from 1968 to 2009 was 2.69 ft^3/s.

Citizen Potawatomi Nation Numerical Groundwater-Flow Model

The CPN model was a simulation of the groundwater-flow system using MODFLOW-NWT, a Newton formulation for MODFLOW-2005 (Niswonger and others, 2011) that included both a steady-state and transient model. The potentiometric heads produced by the steady-state model were used as the starting heads for the transient model. The calibrated transient model was used to estimate the effects of drought on water resources of the study area. A transient inset model was constructed using calibrated parameters from the CPN model for groundwater-pumping optimization.

The numerical groundwater-flow models described in this report were based on the assumption that groundwater flows through the aquifers according to Darcian flow principles, that the variation in the hydraulic properties of the aquifers modeled can be resolved with the chosen cell sizes, and that the variations in water flux can be simulated with monthly stress periods. It was assumed that the water lost to plant ET can be simulated by adjusting recharge to the aquifer. It was assumed that during 1987 the groundwater-flow system was at an approximate equilibrium and could represent a steady-state period as used in Mashburn and others (2013). Lastly, the head and base-flow observations and estimates were assumed to be adequate to calibrate the models.

Model Configuration and Boundary Conditions

The CPN model objectives required more spatial detail than the Central Oklahoma aquifer model, which used cell dimensions of 3,280 ft on each side. More spatial detail was achieved by setting the CPN model cells to 820 ft on each side. One of the most important modifications to the Central Oklahoma aquifer model was the addition of the North Canadian alluvial aquifer and alluvial deposits along Little River and Salt Creek as layer 1 (fig. 2), which were not included as a separate layer in the Central Oklahoma aquifer model.

The CPN model did not require the same level of vertical detail included in the Central Oklahoma aquifer model, which used 100-ft thick horizontal layers and did not include distinct hydrogeologic units. In the CPN model, the Central Oklahoma aquifer was configured as two layers (layers 2 and 3) representing the upper and lower parts of the aquifer. The saline unit was assigned to layer 4. Where there was no alluvial deposit, the uppermost active model layer was the Central Oklahoma aquifer in layer 2 (fig. 2).

The CPN model time period including both steady-state and transient models was from 1987 to 2009, which was the same as the transient Central Oklahoma aquifer model of Mashburn and others (2013). The steady-state model represented mean conditions during 1987, and the transient model included the period from 1988 to 2009. The Central Oklahoma aquifer model used annual stress periods, which were too long to resolve the changes in head and flows in the alluvial aquifers used in the CPN model. Thus, the transient CPN model used 264 monthly stress periods to increase the temporal resolution.

Conceptual flow-model boundaries were simulated in the numerical groundwater-flow model by defining model cells as having boundary conditions. Boundary conditions included head-dependent flow boundaries such as streams, springs, and locations where groundwater enters or leaves the model; constant-rate flow boundaries such as wells or areas receiving recharge; and no-flow boundaries defined as inactive cells or the model extent. Flow-boundary conditions were simulated with several packages that function with the MODFLOW-NWT solver.

Streamflow was routed through the model using the Streamflow-Routing Package version 2 (SFR2) for MODFLOW (Niswonger and Prudic, 2005) (fig. 2). This package simulates water in stream channels and flow between streams and groundwater with specified parameters for stream channel dimensions, streambed thickness and hydraulic conductivity, and channel gradient. For the streams overlying the Central Oklahoma aquifer (layer 2), the parameter values derived in Mashburn and others (2013) were used as initial values. For stream segments overlying the Salt Creek, Little River, and North Canadian River alluvial deposits, initial streambed conductivity was estimated to be within the range of silty, fine sand in Fetter (1994), approximately 13 ft/d. Streambed conductivity in four segments of the North Canadian River was adjusted during automated parameter estimation.

The SFR2 Package was linked with the Lake Package for MODFLOW (Merritt and Konikow, 2000), which was used to simulate Lake Thunderbird (fig. 2). Stream segments simulated in SFR2 can discharge into lakes, and reservoirs can release water into stream segments. Streamflow from local base-flow fed streams was routed into Lake Thunderbird, and releases from Lake Thunderbird recorded by the U.S. Army

Corps of Engineers (2013) were routed to the adjacent downstream segment of the Little River. The Lake Package also simulated groundwater flow into and out of Lake Thunderbird.

Several other head-dependent flow boundary conditions in the steady-state and transient models were simulated using the General Head Boundary (GHB) Package for MODFLOW (Harbaugh and others, 2000). A GHB cell has a specified groundwater head for each stress period and a hydraulic conductance of the interface between the GHB and the adjacent aquifer cell, which governs groundwater flow between the GHB and adjacent cells. For GHB cells, the conductance was set at the initial hydraulic properties of the model at that cell and was adjusted only during the initial calibration.

Shawnee Reservoirs 1 and 2, Horseshoe Lake, Wes Watkins Reservoir, and Tecumseh Lake (fig. 2) did not release substantial water to streams and were simulated using GHB cells instead of the Lake Package. Approximate lake stages were taken from the National Hydrography Dataset (U.S. Geological Survey, 2013b) and held constant during the transient model period.

Groundwater entered the model from areas to the west and north where the edge of the CPN model did not coincide with a hydrological boundary in the Central Oklahoma aquifer model through GHB cells (fig. 2). In these areas, the heads at GHB cells were taken from the groundwater heads simulated by the Central Oklahoma aquifer model (Mashburn and others, 2013), and the extent of the CPN model was set beyond the CPN Tribal Jurisdictional Area to minimize any boundary effects from the GHBs. On the western upstream model margin, groundwater entering the North Canadian River alluvial aquifer was simulated using GHBs. Heads in GHBs were set at the estimated initial heads from groundwater observations and surface-water bodies. The GHB cells were held constant during the transient model period. As with the GHBs used to simulate lakes, conductance of the peripheral GHBs was approximately the same as the aquifer in which they were located.

Because of the increased detail of the CPN model, springs and seeps that discharge groundwater along the eastern margin of the Central Oklahoma aquifer were simulated with the Drain Package for MODFLOW (Harbaugh and others, 2000) as shown in figure 2. Seeps and springs were not simulated in the Central Oklahoma aquifer model (Mashburn and others, 2013). Where groundwater in alluvial deposits left the model on the eastern margin, drain cells were used instead of GHBs. The Drain Package is independent of other boundaries and only allows groundwater to leave the model based on the relative altitude of the drain and the aquifer head and drain conductance. Drain conductance was set equal to that of the aquifer at each drain cell, and the drain altitude was set to the land-surface altitude from a digital-elevation model of the area (U.S. Geological Survey, 2013a). Drain cell properties were only adjusted during initial model calibration.

Pumping wells are constant-rate flow boundaries and were simulated using the Multi-node Well (MNW) Package Version 2 for MODFLOW (Konikow and others, 2009), which allows wells to withdraw groundwater from multiple layers. Well depths reported to the OWRB were used with model layer thicknesses to determine from which layer each well pumped water (Oklahoma Water Resources Board, 2013). All of the well construction information was taken from Mashburn and others (2013) and was applied to the CPN model layers.

The land surface through which recharge flows is a constant-rate flow boundary. The Soil-Water-Balance (SWB) code of Westenbroek and others (2010) used in the Central Oklahoma aquifer model (Mashburn and others, 2013) was used in this study with increased spatial detail to estimate amounts and distribution of recharge to the aquifer from the land surface. This recharge estimate was applied to the CPN model using the Recharge Package for MODFLOW (Harbaugh and others, 2000). Mean daily recharge for 1987 from the SWB analysis was input to the steady-state model, and mean daily recharge for each month from 1988 to 2009 was input to each stress period of the transient model. Recharge was applied to the uppermost active layer in each model cell and scaled during model calibration.

Because SWB estimates recharge as deep percolation through the root zone of the landscape, this package does not provide an estimate of the seepage through the unsaturated zone and into bedrock. A substantial amount of the deep percolation can flow laterally through the soil and discharge into streams. Thus, where the Central Oklahoma aquifer was the top active model layer, recharge was decreased to adjust for losses between the land surface and the bedrock. During initial calibration, the scaling factor for recharge where the Central Oklahoma aquifer was the top active layer was determined to be 0.2, which was an estimate of the general fraction of the soil deep percolation that may enter the Central Oklahoma aquifer as recharge. Because of the spatial variability of the Central Oklahoma aquifer and plant evapotranspiration, recharge was further scaled locally during calibration, as described in the “Model Calibration Methods” section of this report.

Model Calibration Methods

Model calibration is the process by which certain model inputs are adjusted so that simulated potentiometric heads and base flows more closely match measured or estimated potentiometric heads and base flows. The difference between simulated heads and measured heads or base flows and estimated base flows is referred to as the residual. The residual is calculated as measured or estimated value minus the simulated value.

The initial aquifer hydraulic properties, boundary-control parameters, and recharge were adjusted manually using trial and error to minimize head residuals in the steady-state model. When the head residuals were manually minimized as much as possible, parameters were further adjusted using automated parameter estimation that also calibrated to estimated stream base-flow targets. This section describes inputs that were adjusted, manual and automated approaches to parameter estimation, and comparison of the observations to the final calibrated simulation.

Observations

To ensure that the groundwater-flow simulation accurately reproduced natural conditions and processes in the study area, simulation results were compared to field measurements or estimated values at specific locations (observations), also referred to as targets or calibration targets. For the study described in this report, observations include groundwater heads measured in wells retrieved from the National Water Information System (U.S. Geological Survey, 2012) and estimated base flows for the North Canadian River as described in the "Stream Base Flow" section of this report. Groundwater-head observations were placed in three groups: (1) 149 water-level measurements used for the steady-state model, (2) 126 Central Oklahoma aquifer water levels measured during the transient period, and (3) 5 water-level measurements in the North Canadian River alluvial aquifer during the transient period. Of the 149 head observations for the steady-state model, 9 observations were from wells open to layer 1, 121 were from wells open to layer 2, 18 were from wells open to layer 3, and 1 was from a well open to layer 4.

Similar to the steady-state model, head observations for the transient period were mostly available from layer 2 with a total of 97 head observations, 4 from wells open to layer 1, 80 from wells open to layer 2, 12 from wells open to layer 3, and 1 from a well open to layer 4. Many of the wells were measured multiple times with 5 of the head measurements being from wells open to layer 1, 113 from wells open to layer 2, 12 from wells open to layer 3, and 1 from a well open to layer 4. There was also a temporal bias with most of the measurements made as part of synoptic water-level measurements during the steady-state period of 1987 and during the last year of the transient model period of 2009. Only 35 of the 131 measurements were made between 1987 and 2009.

Estimated base flows of the North Canadian River consisted of 528 observations with 264 values each being used for the streamflow-gaging stations at Harrah and Shawnee. Estimated flows represented monthly mean streamflow values from 1988 through 2009 for the transient model.

Initial Trial-and-Error Calibration

An initial trial-and-error calibration was performed on the steady-state and transient models to estimate values and ranges for model parameters and help guide and constrain the automated parameter estimation. During the initial calibration, parameters for Kh, specific yield (Sy; the ratio of unit of water produced per unit of drawdown) in the uppermost active layer, specific storage in lower layers, and recharge were changed manually on a cell-by-cell basis to reduce head-observation residuals. Vertical hydraulic conductivity anisotropy (the ratio of horizontal to vertical hydraulic conductivity) for layers 2 and 3 was adjusted as a single value for each layer. The initial trial-and-error calibration reduced head residuals, and both head residuals and base-flow residuals were expected to improve during the automated parameter estimation.

From the initial calibration, the recharge entering the Central Oklahoma aquifer was determined to be highly variable across the aquifer. Instead of changing recharge estimates from SWB directly for each stress period, recharge arrays for all stress periods in the steady-state and transient models were adjusted using a multiplier array that included 16 different zones (12 of which are shown on fig. 3) with different multiplier values. This array preserved the seasonal recharge variability and some of the spatial recharge variability. The numerous recharge multiplier zones for part of the CPN model area in figure 3 show the spatial variability of the Central Oklahoma aquifer in contrast to the larger multiplier zones in the North Canadian alluvial aquifer. Multiplier zones were set up independently in the Central Oklahoma aquifer and the North Canadian alluvial aquifer to accommodate much higher recharge rates in the alluvial deposits. Each multiplier zone was adjusted to reduce residuals at groundwater-head observation locations and improve the calibration. When only minor improvement in head residuals was achieved by manually changing parameters between model runs, the manual calibration was terminated and the automated parameter estimation was used.

Parameters

Though a model simulation might consist of thousands of input values to represent groundwater flow in an area, only some of those inputs are adjusted to calibrate a model; these inputs are called parameters. After initial manual trial-and-error calibration, automated parameter estimation was used to further calibrate the model. For automated parameter estimation, the recharge multiplier zones used in the initial trial-and-error calibration were used and new parameters for Kh and streambed hydraulic conductivity were added. Vertical hydraulic conductivity anisotropy values for layers 2 and 3 were included as parameters. The same parameters were used for the steady-state and transient groundwater-flow models. For the sensitivity analysis, some parameters were also included in parameter groups. Recharge multiplier zone parameters in the initial calibration were included in the group *transrch*.

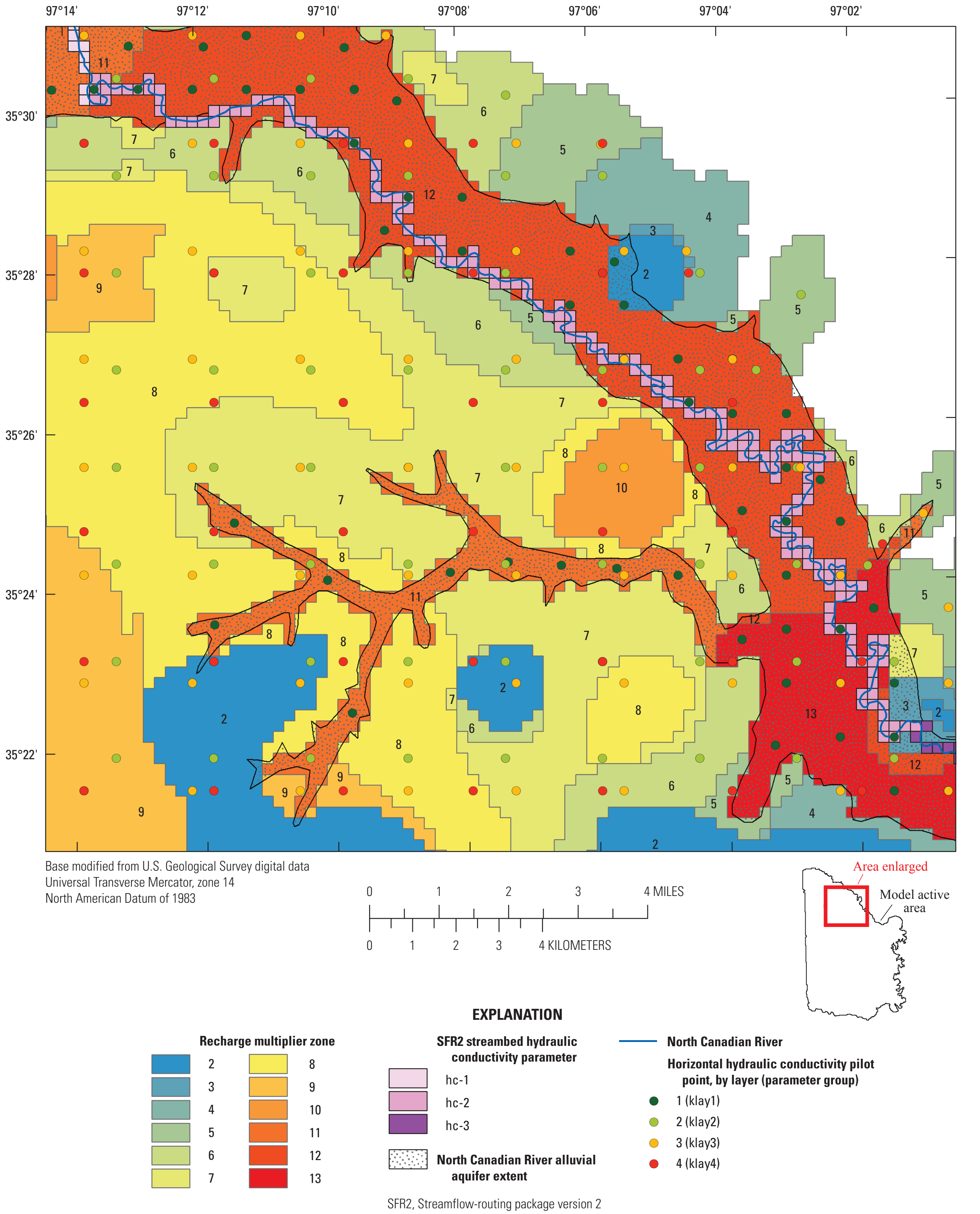


Figure 3. Recharge multiplier zones, horizontal hydraulic conductivity pilot points, and streambed hydraulic conductivity parameters used in the Citizen Potawatomi Nation numerical groundwater-flow model, Citizen Potawatomi Nation Tribal Jurisdictional Area, central Oklahoma.

Streambed hydraulic conductivity in the SFR2 Package was divided into four parameters (hc-1 through hc-4) for four reaches of the North Canadian River; parts of hc-1 through hc-3 are shown on figure 3. Parameter hc-1 included the North Canadian River in the model active area upstream from the streamflow-gaging station at Harrah (USGS station 07241520) (fig.1). Parameter hc-2 included the reach between hc-1 and the river near Shawnee Reservoir 2. Parameter hc-3 included the reach of the North Canadian River between hc-2 and just upstream from the streamflow-gaging station at Shawnee (USGS station 07241800), and parameter hc-4 included the reach of river in the model active area downstream from hc-3. All stream reaches in each parameter segment were assigned the same value for streambed hydraulic conductivity and were adjusted by the same amount during each iteration of the automated parameter estimation process. The four streambed hydraulic conductivity parameters were included in the model parameter group *sfrhc*.

The adjustment of Kh on a cell-by-cell basis in automated parameter estimation, as was done in the initial manual calibration, was not feasible because doing so would require determination of a Kh parameter at every cell. Although estimating Kh for large groups of cells or zones is feasible, such an approach can result in large changes and unrealistic contrasts in Kh at zone boundaries; also, there may not be sufficient data to delineate such zones. A preferable approach is to use pilot points, which are discrete points located within the active model cells, in this case grouped by each layer; Kh was estimated for each pilot point individually and subsequently interpolated to every active model cell using the kriging spatial interpolation algorithm (Doherty, 2010). Pilot points were placed where points used in Mashburn and others (2013) caused a distinct pattern in the Kh values for each layer and were manually placed where they were near inactive model cells. A subset of the pilot points symbolized by layer is shown in figure 3. This approach produces smooth variations in Kh during calibration and thus introduces fewer artifacts to the simulation. This procedure used a total of 1,473 pilot points that were assigned to four parameter groups by layer: 176 points for layer 1 in group *klay1*, 566 for layer 2 in group *klay2*, 448 for layer 3 in group *klay3*, and 283 for layer 4 in group *klay4*.

Automated Parameter Estimation

Automated parameter estimation was undertaken using the statistical techniques provided in the PEST suite of software (Doherty, 2010) after the initial trial-and-error calibration. PEST is a model-independent tool that at its simplest level, automatically adjusts parameters within predefined limits, reruns the model, checks the calibration, and continues until the calibration cannot be improved further. Complex algorithms integral to PEST allow a model to be improved efficiently and quickly, allowing a large number of parameters to be used, and enabling a more accurate representation of the intrinsic variability of natural hydrologic systems.

In addition to the efficiencies gained through automation and powerful statistical approaches, PEST also facilitates Tikhonov regularization, wherein a penalty is applied to the objective function when parameters deviate from their initial values (Doherty, 2010). The result of that regularization is a more stable parameter estimation process that allows for introduction of variability when necessary to improve calibration but preserves initial values that may be based upon the best data and reasoning available to the investigator. For this study, Tikhonov regularization was applied to Kh parameters of aquifer layers 1–4, with initial values determined during the trial-and-error calibration. Parameters for hydraulic properties were limited by end-member values estimated for aquifer properties in Mashburn and others (2013). This limiting of parameters prevented the automated process from choosing values that are not realistic for aquifers in this study to achieve a best match with observations.

Calibration Results

Figure 2 shows the distribution of steady-state head residuals for all observation wells and the associated model layer. The mean residual for groundwater heads in the steady-state model was -1.1 ft (table 1), indicating that on average, simulated groundwater heads were 1.1 ft higher than measured groundwater heads. For transient groundwater heads in the Central Oklahoma aquifer, the mean residual was -1.7 ft, indicating that on average, simulated groundwater heads were 1.7 ft higher than measured groundwater heads. The mean residual was -4.1 ft for transient groundwater heads in the North Canadian River alluvial aquifer (table 1). The root-mean-squared groundwater head residuals for steady-state, transient Central Oklahoma aquifer, and transient North Canadian River alluvial aquifer had a maximum value of about 3 percent of the total groundwater-level relief (450 ft) in the study area, indicating that errors or inaccuracies were only a small part of the total model response (Anderson and Woessner, 1992). Figure 4 shows the correlation between simulated and measured head observations. Scatter about the regression line was caused by local variations in the Central Oklahoma aquifer not included in the model, but there is a reasonable general correlation with a coefficient of determination (R^2) value of 0.98. There was no apparent characteristic of the simulated head accuracy associated with higher or lower altitudes.

Table 1. Statistical comparison of measured and simulated groundwater heads and stream base flows, numerical groundwater-flow model for the Citizen Potawatomi Nation Tribal Jurisdictional Area, central Oklahoma.

[Residual is calculated as the measured or estimated value minus the simulated value; thus, a negative residual for water levels or streamflows indicates that simulated values are larger than estimated or measured values]

Observation group	Steady-state groundwater head (feet)	Transient groundwater head (feet)		Transient streamflows (cubic feet per second)
		Central Oklahoma aquifer	North Canadian River alluvial aquifer	
Observation count	149	126	5	528
Minimum residual	-39.0	-45.7	-12.1	-2,853
Mean residual	-1.1	-1.7	-4.1	74
Maximum residual	44.7	28.8	7.3	9,122
Mean absolute residual	9.4	6.3	7.0	204
Root-mean-squared residual	13.0	9.0	7.6	576

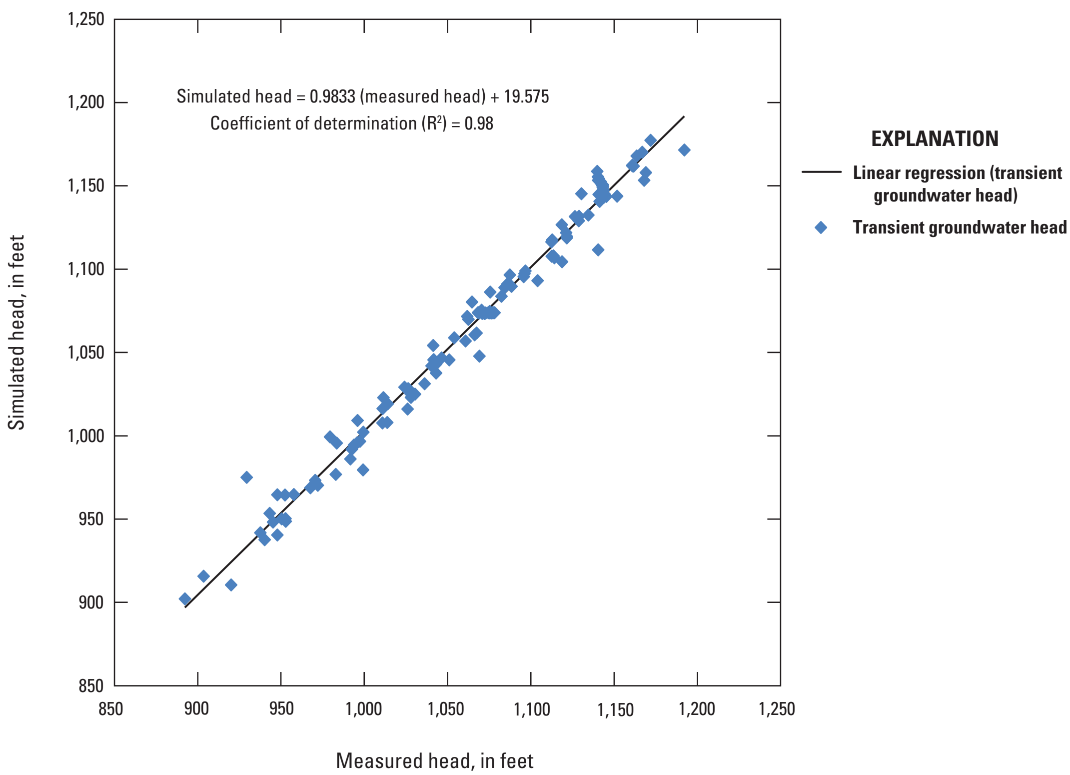


Figure 4. Transient measured groundwater heads plotted with simulated heads for the Citizen Potawatomi numerical groundwater-flow model, Citizen Potawatomi Nation Tribal Jurisdictional Area, central Oklahoma.

The CPN model provided reasonable matches between simulated stream base flow and estimated stream base flow at the Harrah streamflow-gaging station (fig. 5*A*) and the Shawnee streamflow-gaging station (fig. 5*B*). The mean estimated stream base flow used in the transient model was 604 ft^3/s. The mean residual for transient stream base flow was 74 ft^3/s (table 1), indicating that on average, simulated stream base flow was 74 ft^3/s, or about 12 percent, less than the mean estimated stream base flow. This difference was caused, at least in part, by runoff peaks coming into the model from upstream and no routing of runoff within the model area. The numerical flow model only affects the streamflow routed through the model by changes in base flow, which is a relatively small fraction of streamflow during peak-flow periods.

A statistical summary of the final calibrated values for Kh, Sy, and vertical anisotropy estimated during model calibration is listed in table 2, and the numerical groundwater-flow model annual flow budget and total flow for 1987–2009 are listed in table 3. The annual model flow budget includes the net flow—inflow minus outflow—for principal model boundaries, with positive flow indicating groundwater entering the model and negative flow leaving the model. The largest inflow was from recharge, which was nearly equal to the largest discharge, stream base flow (table 3). Negative volumes for change in storage represent adding groundwater to storage during wet years, and positive values represent water taken from storage during drier years.

Model Sensitivity

The PEST suite of software adjusts all parameters individually and determines the relative influence of parameters and parameter groups on the head and flow model observations. Figure 6 presents the relative magnitude of changes in residuals caused by a 1-percent change in the value of each parameter estimated during the initial trial-and-error calibration.

Changes in parameters for group *sfrhc* caused the largest change of residuals because of the direct influence on the residuals for streamflows in the North Canadian River, which had the largest contribution to the parameter estimation objective function. However, sensitivity to *sfrhc* was only approximately twice that of the least sensitive parameter group *klay1*. Parameter group *klay1* was the group that represented the North Canadian River alluvial aquifer hydraulic conductivity. This parameter group has more effect on head than on streamflow, but there were only nine head observations in layer 1 in the steady-state model and five in the transient model. Thus, changes in *klay1* may have caused a greater effect on residuals if there had been more head observations.

Simulated heads were sensitive to changes in parameter groups *klay2–4* and *transrch*. Because layer 2 was the uppermost active layer in the active model area that did not include alluvial deposits, it received recharge, and the majority of head observations in layer 2 were affected by *transrch* as well as *klay2*. Base flow was affected by *transrch* in areas where recharge was applied to the North Canadian alluvial aquifer.

The parameters to which model observations were most sensitive included streambed hydraulic conductivity, Kh, and recharge. Streambed hydraulic conductivity was limited to the North Canadian River overlying the North Canadian alluvial aquifer. Thus, model observations in the Central Oklahoma aquifer were only responding to changes in *klay2–4* and *transrch*.

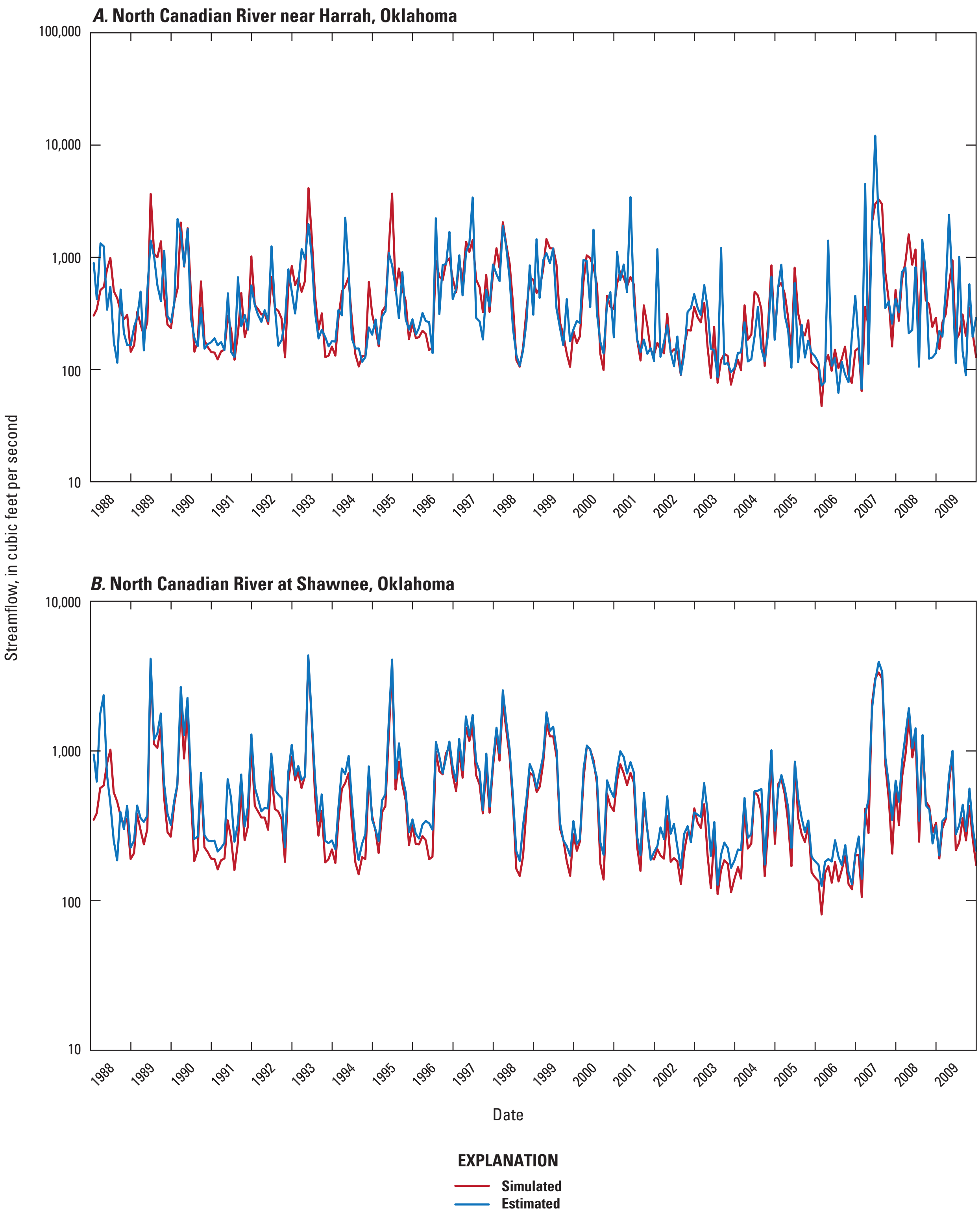


Figure 5. Simulated and estimated streamflows for North Canadian River streamflow-gaging stations *A*. near Harrah, Oklahoma, and *B*. at Shawnee, Okla., Citizen Potawatomi Nation Tribal Jurisdictional Area, central Oklahoma.

Table 2. Statistical summary for calibrated hydraulic parameters.

	Layer	Mean	Minimum	Maximum	Standard deviation
Horizontal hydraulic conductivity (feet per day)	1	43.42	0.04	315.53	151.39
	2	11.90	0.03	82.02	14.61
	3	1.79	0.03	16.40	1.20
	4	1.18	0.03	16.40	1.37
Specific yield	1	0.19	0.11	0.20	0.02
	2	0.12	0.07	0.20	0.01
	3	0.11	0.07	0.16	0.01
	4	0.10	0.10	0.10	0.00
Vertical anisotropy (vertical/ horizontal hydraulic conductivity)	1	19	4	20	67
	2	5	1	10	4
	3	516	100	960	395
	4	4	1	8	4

Table 3. Numerical groundwater-flow model annual flow budget, Citizen Potawatomi Nation Tribal Jurisdictional Area, central Oklahoma.

[1987*, is from the steady-state model; Positive flow is to the model and negative flow is from the model; all flows are net flow (balance of inflow and outflow) rounded to 100 acre-feet]

Annual model flow in acre-feet						
Year	**Recharge**	**Change in storage**	**General head boundaries and drains**	**Stream base flow**	**Lake**	**Wells**
1987*	170,000	0	4,000	-172,000	0	-2,000
1988	334,700	-60,900	3,500	-249,900	-24,700	-2,800
1989	306,600	-4,900	2,600	-285,300	-15,800	-3,100
1990	480,400	-114,700	1,400	-348,600	-15,400	-3,000
1991	452,600	-92,400	1,400	-344,100	-14,100	-3,400
1992	522,400	-97,300	-300	-406,500	-15,200	-3,000
1993	474,300	-33,000	-1,700	-420,500	-15,800	-3,300
1994	378,300	-3,700	-700	-356,600	-14,400	-2,900
1995	437,100	-30,400	-1,400	-385,900	-16,200	-3,300
1996	436,900	-46,200	-1,000	-373,200	-13,000	-3,500
1997	452,500	-44,500	-1,500	-390,800	-12,200	-3,400
1998	390,400	10,100	-1,600	-385,600	-10,600	-2,600
1999	331,700	34,100	-1,000	-348,000	-13,100	-3,700
2000	386,900	-19,900	-700	-348,900	-14,300	-3,100
2001	374,800	4,600	-1,000	-358,800	-15,800	-3,800
2002	381,000	-12,600	-700	-348,800	-15,600	-3,400
2003	183,900	111,800	200	-276,700	-16,100	-3,200
2004	423,600	-65,700	0	-337,700	-16,900	-3,300
2005	236,200	89,200	-100	-305,700	-16,300	-3,300
2006	204,000	60,200	1,300	-245,700	-16,400	-3,400
2007	550,900	-131,800	-500	-391,800	-22,400	-4,400
2008	298,100	53,400	-500	-329,200	-18,400	-3,500
2009	381,200	-25,700	-100	-332,000	-19,900	-3,600
Total	8,588,500	-420,300	1,600	-7,742,300	-352,600	-75,100

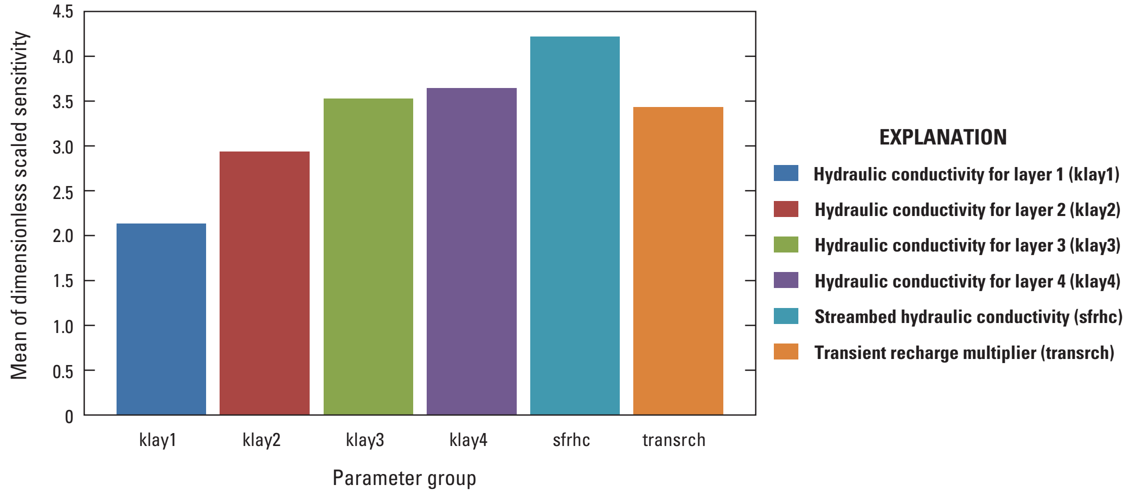


Figure 6. Scaled sensitivity of model observations in parameter groups, Citizen Potawatomi Nation numerical groundwater-flow model.

Inset Numerical Groundwater-Flow Model

A numerical groundwater-flow model was required to optimize groundwater pumping at two EDZs, the geothermal supply area and the Iron Horse Industrial Park just south of the city of Shawnee, Okla. (fig. 7). Because of the small area and increased detail required to analyze water resources in the EDZs, a detailed transient inset model with smaller cell sizes was constructed using the calibrated model inputs and layers from the CPN model. The inset model was constructed completely within the CPN model active area, on the North Canadian River near the northern margin (fig. 2) spanning 6.5 mi east to west and 5 mi north to south (fig. 7). The analysis performed using the inset model predominantly affected the North Canadian River alluvial aquifer, and the extent of the inset model is well beyond the extent of the alluvium to the north and south, and several stream miles upstream and downstream to eliminate boundary effects on the analysis.

The inset model also included heads calculated in the CPN model, and these heads were used in GHBs along the margin of the inset model. Like the CPN model, the inset model used the SFR2 Package to simulate routed streamflow, the MNW Package for wells, and the Recharge Package. The inset model provided a more efficient analysis of the optimized pumping and allowed simulation of local pumping effects on groundwater heads and North Canadian River streamflow depletion.

To provide more detail, the inset model cells were reduced to 164 ft on all sides from the 820-ft cells used in the CPN model. Properties such as recharge and Kh were transferred from the larger CPN model cells to the corresponding smaller cells. Pumping rates for groundwater-withdrawal wells in the inset model area were taken from the CPN model without further refinement. Simulated streamflow in the North Canadian River and tributaries in the CPN model were used as inflow to those streams that originated outside the inset model and crossed into the inset model active area (fig. 7). The inset model was not calibrated separately, and there were no head observations available within the inset model in the North Canadian River alluvial aquifer during the transient simulation period.

The starting head for all layers of the inset model was set equal to that of the CPN model. The external boundary of the inset model was composed of GHB cells with the head set to the starting head of the CPN model at each cell location. The head in GHB cells remained constant for the duration of the transient model simulation.

Optimization of Groundwater Withdrawals

Two EDZs along the North Canadian River were selected by the CPN for groundwater development: the geothermal supply area and the Iron Horse Industrial Park (fig. 7). Both areas are along the North Canadian River and are separated by about 2 mi. Both areas are underlain by the North Canadian River alluvial aquifer, and the groundwater resources in those areas are pumped from that aquifer. The areas are sufficiently distant from each other, and pumping at one site is assumed to have negligible effect on heads or water availability at the other.

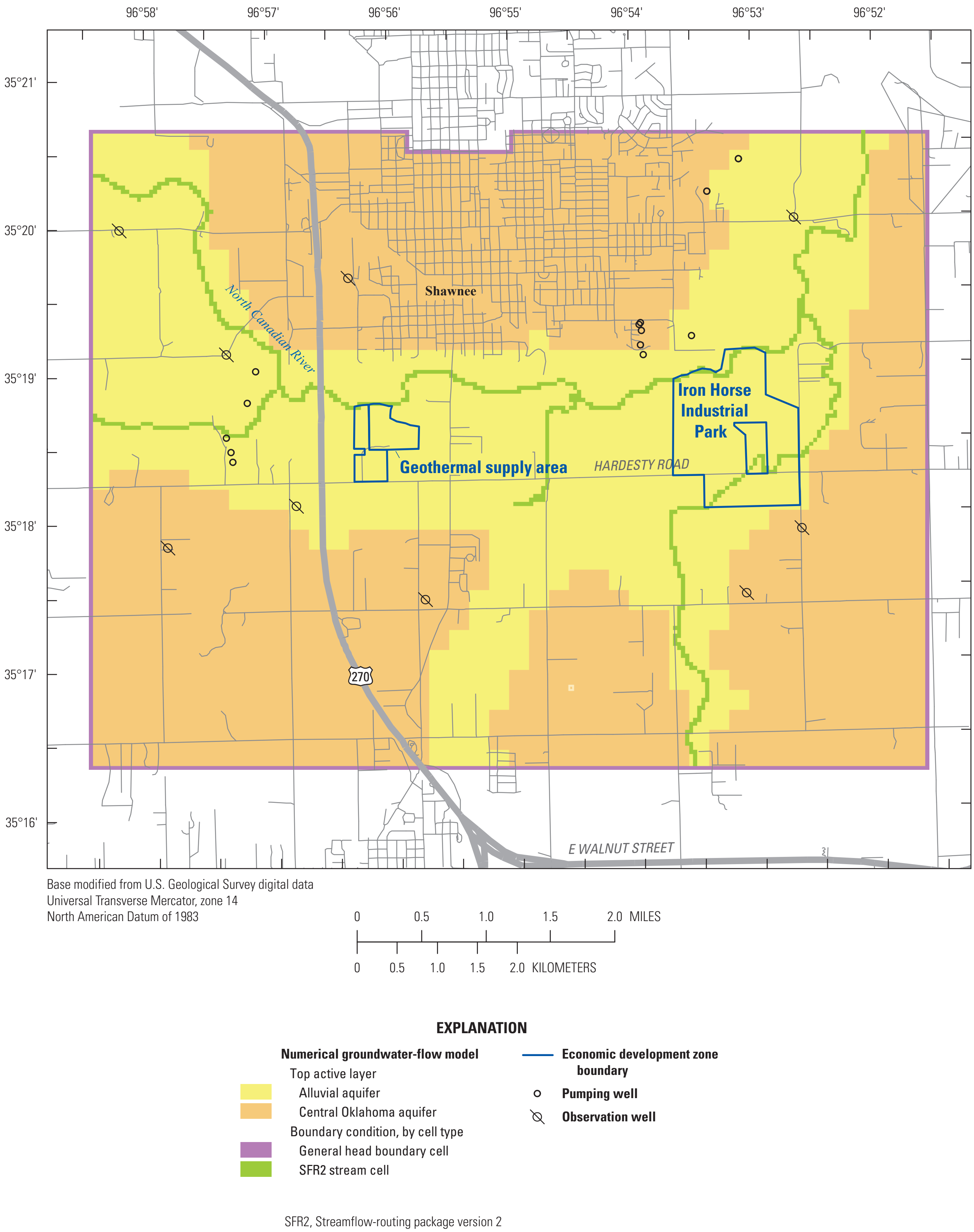


Figure 7. Inset model active area, top active layer, and boundary condition cells, and locations of economic-development zones included in the optimization analysis, Citizen Potawatomi Nation Tribal Jurisdictional Area, central Oklahoma.

Water Demands

The geothermal supply area required a continuous flow of 500 gallons per minute (gal/min) from one or more wells located within the geothermal supply area, just south of the North Canadian River (fig. 7). Plans for expansion of the Iron Horse Industrial Park have not set a specific water requirement, so the objective for that EDZ was to determine the total available groundwater at the site. Water quality was also an issue of concern for the Iron Horse Industrial Park, and stream water in this area has been found to contain more dissolved solids and chlorides, nitrogen, and organic compounds than the groundwater in alluvial deposits (Becker, 2014); thus, the amount of stream water entering the Iron Horse Industrial Park well field was a concern.

Streamflow Depletion by Wells

Streamflow depletion by a well takes place when a well reduces streamflow either by capturing groundwater that would otherwise discharge to the stream as base flow or by inducing streamflow to flow into the adjoining aquifer through induced infiltration, or both (Barlow and Leake, 2012). At a gaining reach, the aquifer head is higher than the stream stage, but if the aquifer head is drawn down below the stream stage by pumping, the head gradient is reversed, resulting in induced infiltration of streamflow to groundwater.

The SFR2 Package was used to determine the rates of base flow and streamflow depletion through induced infiltration of North Canadian River streamflow that could enter wells. The SFR2 Package determines rates of groundwater flow to or from each stream reach; a reach is defined as the length of stream channel in each model cell. The SFR2 results showed that before development of the Iron Horse Industrial Park well field, all adjacent North Canadian River stream reaches were gaining base flow during model simulations. If pumping caused gaining reaches to become losing reaches, the volume of induced infiltration of streamflow to the aquifer during well pumping was calculated using SFR2. Because the North Canadian River is a hydrologic groundwater boundary in the North Canadian alluvial aquifer and there were no other known groundwater withdrawals in the area, all water lost from the stream was assumed to enter the pumping wells. However, because the fate of induced infiltration was not confirmed in this study, this calculated flow is considered to be a maximum value.

As shown in figure 5, streamflow in the North Canadian River is highly variable. Flow in the reach adjacent to the Iron Horse Industrial Park was tracked with the SFR2 Package. The median streamflow in the North Canadian River adjacent to the Iron Horse Industrial Park was 302 ft^3/s during the transient model period.

Optimization Methods

Pumping optimization was performed by coupling the inset numerical groundwater-flow model with the most recent version of the USGS Groundwater-Management Process (GWM) for MODFLOW (Ahlfeld and others, 2005), which is referred to as GWM-VI, version 1.0.1 (Banta and Ahlfeld, 2013). Optimization determined whether the 500 gal/min required for the geothermal supply could be pumped from the geothermal supply area, and the maximum amount of water that could be pumped from wells in the Iron Horse Industrial Park. All of the pumping rates were constrained by limits on head drawdown to protect the alluvial aquifer from dewatering.

The GWM process uses managed wells, which are planned or existing wells, and determines pumping rates during optimization as flow variables. The optimization process determines the response at each constraint to pumping at each managed well independently and then uses an objective function method to determine the optimal pumping rate at each well that satisfies all constraints. The objective function at the geothermal supply area included a criterion that the total pumping from managed wells had to be at least 500 gal/min. At the Iron Horse Industrial Park, the maximum pumping rate that satisfied all head drawdown constraints was determined.

Optimization Design

Because of the presence of the North Canadian River adjacent to the well fields and the relatively thin alluvial aquifer, the response of heads to pumping was not entirely linear. To correct for this nonlinearity, the sequential linear programming algorithm in GWM was used to linearize nonlinear processes and calculate the response at constraints (Ahlfeld and others, 2005).

The mean thickness of the alluvial aquifer is approximately 43 ft in the parts of the EDZs where optimization was performed and the drawdown in managed wells could cause loss of well yield. The MNW package calculates loss of yield and adjusts the flow rate to simulate the net flow from the well. To prevent loss of yield, preliminary model runs were used to determine the pumping rate at which loss of yield takes place at each well without regard to other constraints. This flow rate was used in GWM as the maximum allowable pumping rate for each managed well.

Pumping rates at all managed wells were considered to be the optimal continuous flow rates with all wells pumping simultaneously. The drawdown and effects on streamflow in the North Canadian River were evaluated over the entire transient model period of 21 years; thus, the pumping rates were conservative and will be less than short-term pumping rates that could be achieved by cycling pumping rates from several wells.

Managed Wells

Five proposed managed wells were placed in the geothermal supply area (GTW1–5; fig. 8). A total of 16 managed wells were placed in the northern part of the Iron Horse Industrial Park (IHW01–16; fig. 9). A minimum well spacing of 650 ft was chosen based on the estimated drawdown cone at each pumping well observed during preliminary model runs. Similar to recently developed wells in the local area, all of the planned wells were open only to the North Canadian alluvial aquifer (layer 1) and did not penetrate the Central Oklahoma aquifer.

Pumping Constraints

The principal concern at the geothermal supply area and the Iron Horse Industrial Park was that head drawdown would deplete groundwater in the alluvial aquifer and could be unsustainable. Head constraints were placed on all wells to limit the head drawdown. The maximum head drawdown at each of the geothermal supply managed wells was set at 16.4 ft, which was estimated to be the maximum drawdown that would not cause loss of well yield. The head constraints at the Iron Horse Industrial Park well field allowed the head to drop as much as one-half of the predevelopment saturated thickness (starting head relative to the base of layer 1) at each well.

Streamflow depletion was expected to take place under pumping conditions at both EDZs. However, preliminary runs of the inset model showed that streamflow depletion and induced infiltration were a very small fraction of the total streamflow in the North Canadian River and total pumping. Thus, the streamflow depletion was not used as a pumping constraint, but induced infiltration was calculated to estimate the total streamflow that could end up in the pumped water at the Iron Horse Industrial Park well field.

Optimization Results

Optimized pumping rates for wells at the geothermal supply area ranged from 98 to 201 gal/min (fig. 8). The combined optimized pumping rate was approximately 638 gal/min, which exceeded the goal of 500 gal/min pumping for the five managed wells. Managed wells located in areas where the aquifer is relatively thin or little water is taken from the North Canadian River had lower optimized pumping rates. The total pumping rate might be increased by increasing well spacing or adding wells outside of the well field, or both, although these changes would require the wells to be located outside the geothermal EDZ boundary.

Optimized pumping rates for the 16 managed wells at the Iron Horse Industrial Park ranged from 62 to 141 gal/min (fig. 9). The total estimated optimized pumping rate at the Iron Horse Industrial Park was estimated to be 1,472 gal/min. Wells closer to the North Canadian River and those to the southwest generally produced more water as shown in figure 9, in part because the stream provided a hydrologic boundary that reduced head drawdown under pumping conditions, and the aquifer is slightly thicker to the southwest.

Under pumping conditions, the base flow to the North Canadian River adjacent to the Iron Horse well field was decreased, and groundwater head declined to the point where streamflow began to infiltrate to groundwater. Flow into and out of each stream reach defined in the inset model was calculated by the SFR2 package, and rates of induced infiltration that resulted from the optimal pumping scheme at the Iron Horse Industrial Park are shown for each stream reach numbered upstream to downstream on figure 9. The total rate of induced infiltration from the North Canadian River for the optimal pumping scheme was approximately 4.1 gal/min, which was approximately 0.3 percent of the total pumping of 1,472 gal/min.

A graph of the distribution of predevelopment base flow and induced infiltration from each inset model reach adjacent to the Iron Horse Industrial Park is shown in figure 10. The reaches are shown in map view on figure 9. This figure shows the change in base flow and amount of induced infiltration in each short section of the river that may be captured by the Iron Horse wells. The green line in figure 10 shows the predevelopment base flow for each stream reach. After development, the yellow line shows that all reaches have induced infiltration caused by pumping. The greatest loss of water occurred in reaches 27 and 29 (fig. 10). The wells closest to the reaches that lost the most water were IHW01, 03, 05, and 06 (fig. 9).

Effects of Prolonged Drought

The effects of drought on a groundwater system can be manifested in changes in inflow from decreased precipitation-related recharge, which can result in decreased groundwater discharge to streams and wells. Decreases in recharge also can cause a deficit that is balanced by loss of groundwater from aquifer storage. To estimate the effects of drought on the streamflow and groundwater storage, the CPN model was altered to simulate estimated drought conditions.

The CPN Tribal Jurisdictional Area in central Oklahoma has had several severe hydrologic droughts since recordkeeping began in 1925, including the Dust Bowl drought (1929–41) and the droughts of 1952–6, 1961–72, and 1976–81 (Shivers and Andrews, 2013). The duration of these drought periods ranged from 4 years in the 1950s to the 13-yearlong Dust Bowl. The period of this study does not include any of these historical droughts, so hypothetical drought conditions were estimated based on hydrologic characteristics of recorded droughts.

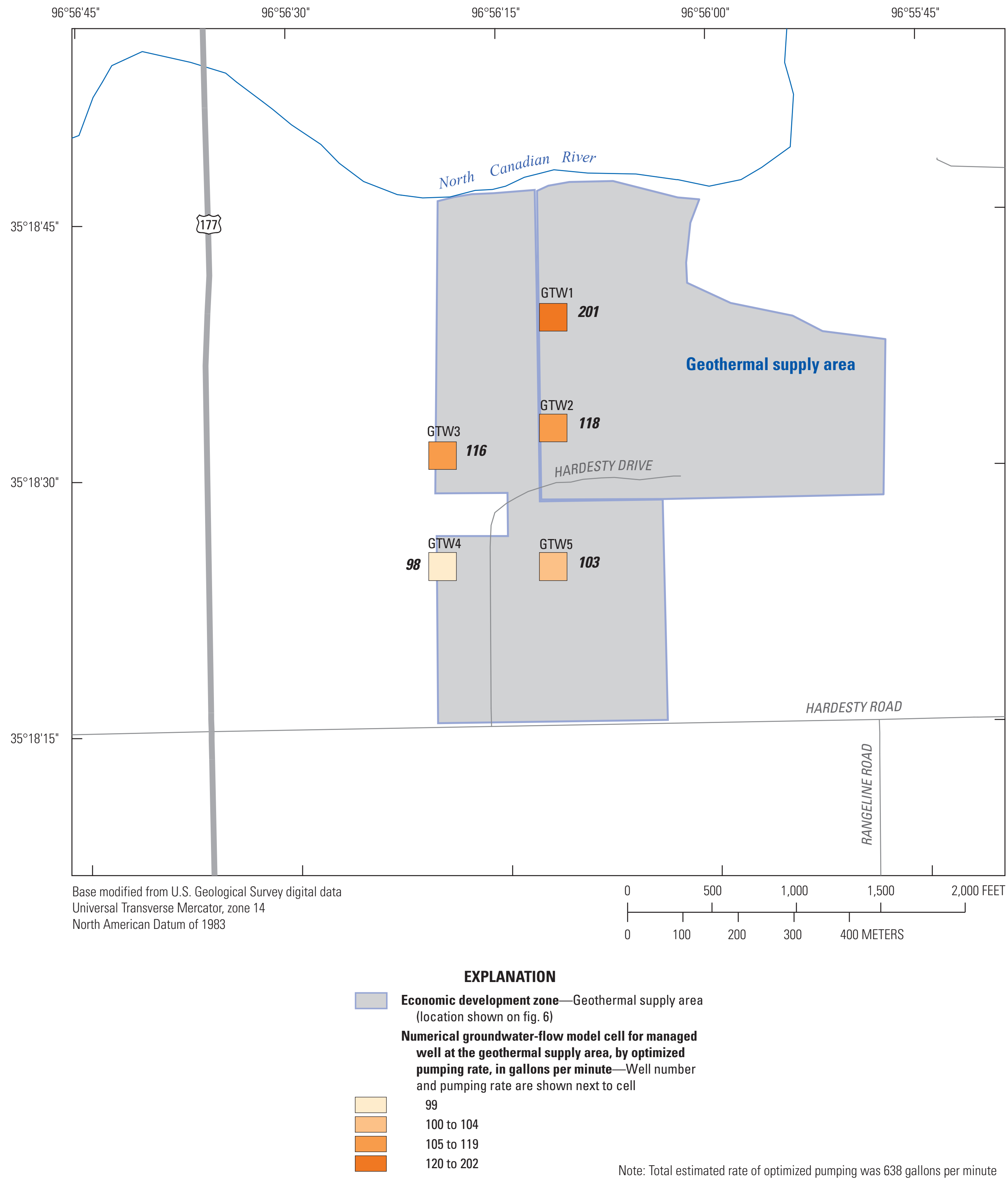


Figure 8. Groundwater Management Process managed wells with optimized pumping rates at the geothermal supply area, Citizen Potawatomi Nation Tribal Jurisdictional Area, central Oklahoma.

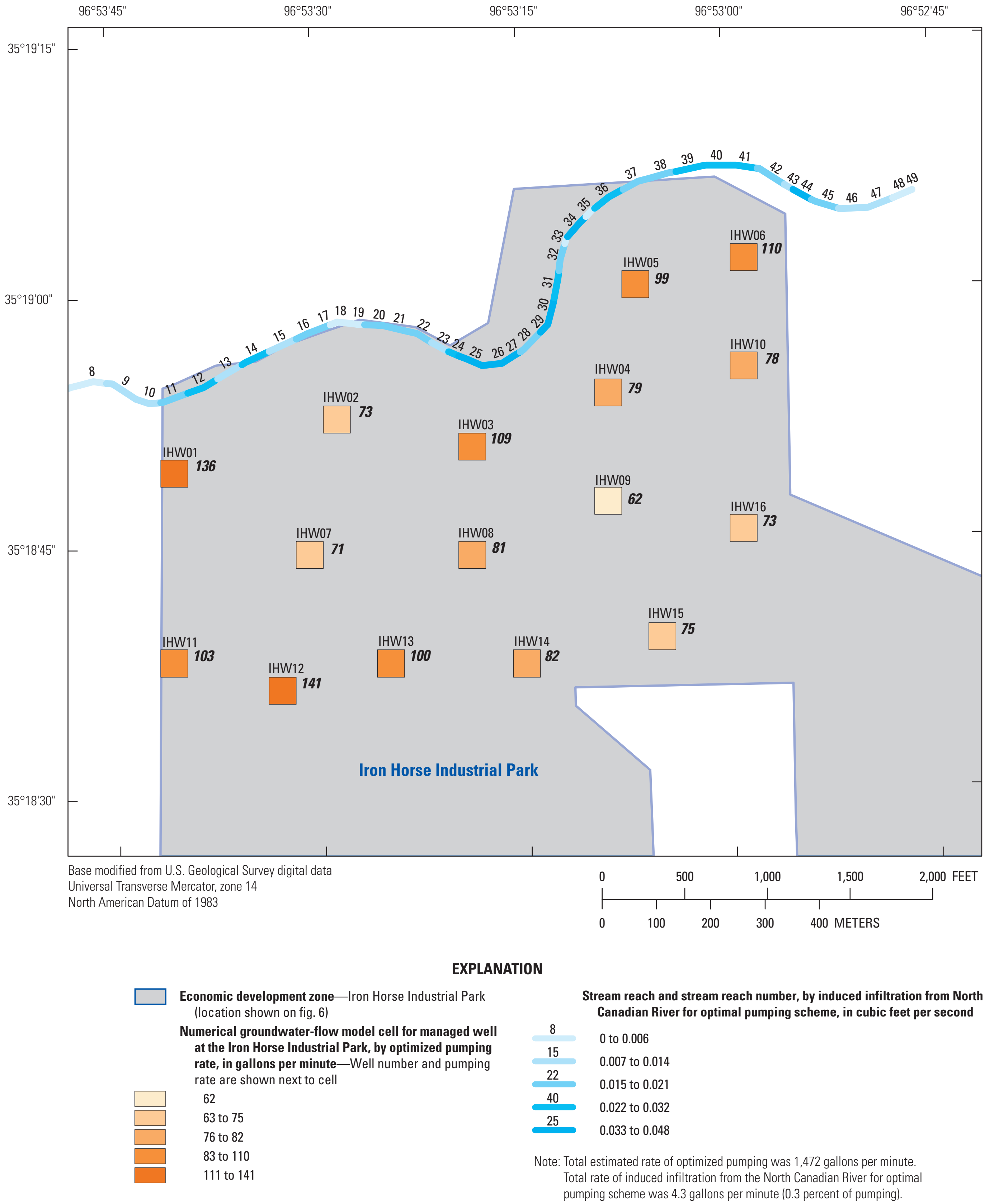


Figure 9. Groundwater Management Process managed wells, optimized pumping rates, and resulting effect on induced infiltration by stream reach number at the Iron Horse Industrial Park, Citizen Potawatomi Nation Tribal Jurisdictional Area, central Oklahoma.

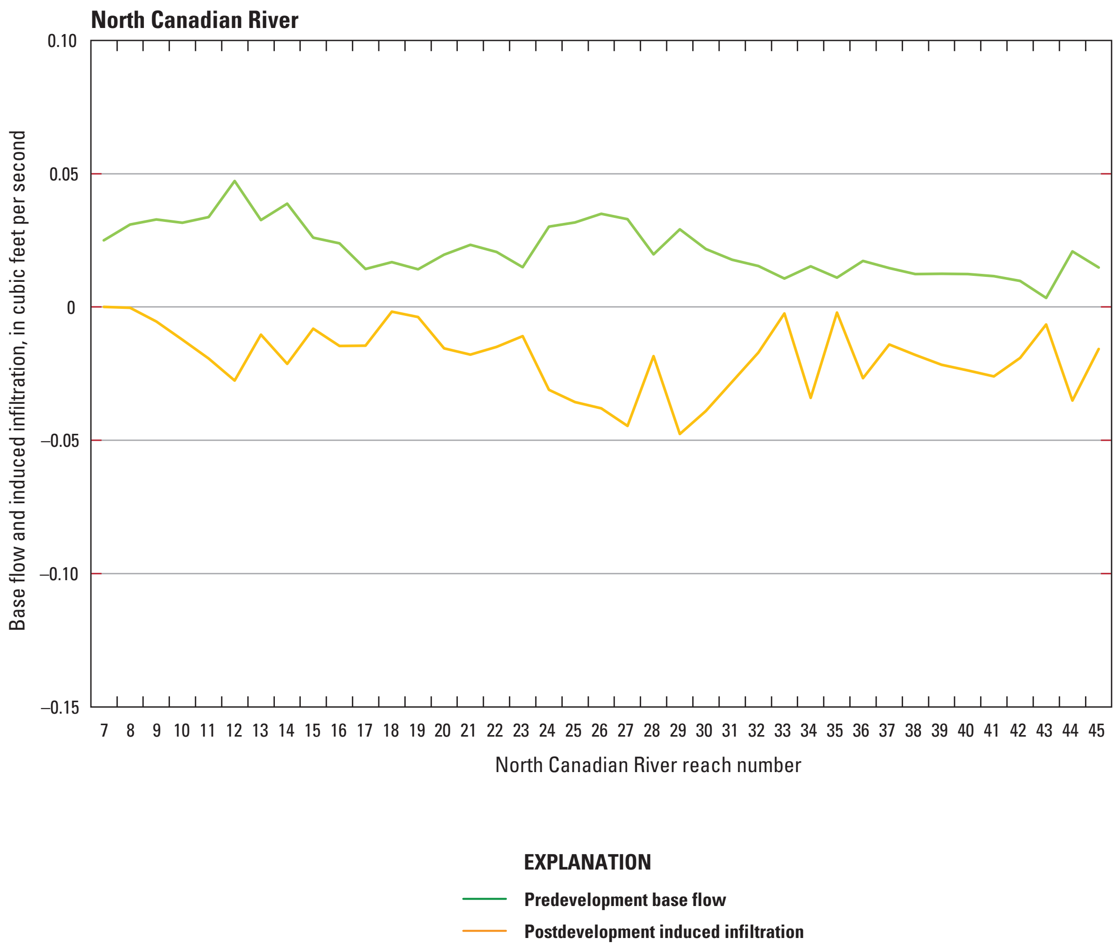


Figure 10. Predevelopment base flow and postdevelopment induced infiltration for the North Canadian River caused by optimized pumping at the Iron Horse Industrial Park, Citizen Potawatomi Nation Tribal Jurisdictional Area, central Oklahoma.

Years in the historical record that had the largest negative departure from the median precipitation were 1953 and 2011; both were nearly a 50-percent decrease in annual precipitation (Shivers and Andrews, 2013). Because groundwater recharge is tied to precipitation and in many areas estimated to be a percentage of precipitation, drought was approximated by decreasing recharge over the entire CPN model for each stress period by 50 percent for a 10-year period from 1990 to 2000. The results are approximate because changes in other flows such as runoff and streamflow entering the model and processes such as plant consumption were not changed during the hypothetical drought.

Changes to the volume of groundwater in storage in the CPN Tribal Jurisdictional Area were estimated by comparing the model run under calibrated recharge conditions to the model run with hypothetical drought recharge conditions using the “ZONEBUDGET” program (Harbaugh, 1990). The total water in storage was estimated using the saturated thickness in the model and the Sy of the aquifer in each cell. The Central Oklahoma aquifer (layers 2-4) had a mean Sy of 0.11 and the North Canadian alluvial aquifer (layer 1) had a mean Sy of 0.19 after model calibration (table 2). The total calibrated model groundwater in storage at the end of the hypothetical drought period (2000) without the hypothetical drought conditions was approximately 148 million acre-feet (acre-ft) in the Central Oklahoma aquifer (table 4), and 163,100 acre-ft in the North Canadian River alluvial aquifer.

During the hypothetical drought, model recharge to the North Canadian River alluvial aquifer decreased by 441,000 acre-ft and to the Central Oklahoma aquifer by 696,000 acre-ft (table 4). This decrease in recharge caused a decrease of 351,500 acre-ft of groundwater in storage (14,100 acre-ft or 8.6 percent in the North Canadian alluvial aquifer and 346,400 acre-ft or 0.2 percent in the Central Oklahoma aquifer) at the end of the hypothetical drought. The total change was approximately 0.2 percent of all groundwater in storage at the end of the drought period. This volume of groundwater storage loss shows that the rate of recharge to the Central Oklahoma aquifer over a 10-year period is much less than the total water in storage.

Table 4. Water budget for a simulation of decrease in recharge during a hypothetical 10-year drought and effects on groundwater in storage and base flow to streams, Citizen Potawatomi Nation Tribal Jurisdictional Area, central Oklahoma.

[Volumes in acre-feet]

Aquifer	Change in recharge during drought	Total groundwater in storage in 2000 with no drought	Net change in groundwater storage during drought	Percent change in total aquifer storage	Net change in base flow during drought	Percent change in base flow
North Canadian alluvial aquifer	-441,000	163,100	-14,100	-8.6	-386,500	-37
Central Oklahoma aquifer	-696,000	147,910,000	-346,400	-0.2	-292,000	-28
Total	-1,137,000	148,073,000	-351,500	-0.2	-678,500	-33

The budget for base flow in the model during the 10-year simulated drought decreased by 678,500 acre-ft (33 percent); base flow to the North Canadian River decreased by 386,500 acre-ft (37 percent), and for all other parts of the CPN Tribal Jurisdictional Area base flow decreased by 292,000 acre-ft (28 percent). Approximately 11 percent of the decrease in recharge to the North Canadian alluvial aquifer, and 66 percent of the change in recharge to the Central Oklahoma aquifer were offset by change in storage and base flow to streams. The balance of the change in recharge was due to decreases in discharge to GHBs, drains, and lakes.

The CPN model also was used to simulate changes to streamflow in the North Canadian River routed through the model during and after the drought period. Immediately after the start of the hypothetical drought, simulated streamflow in the North Canadian River at the Shawnee streamflow-gaging station decreased because of decreased base flow and continued to decrease until the end of the simulated drought in 2000 (fig. 11). Routed streamflow slowly recovered through 2008 as recharge restored the amount of groundwater in storage. The largest estimated decrease in mean streamflow was 28 percent during September of 1994, and the percent decrease approximated by a 50-month moving average was approximately 16 percent in 1994. Streamflow did not recover to near nondrought streamflow conditions until the wet year of 2007, which was 7 years after the end of the hypothetical drought. The delay in streamflow recovery was caused by the aquifer recharge replenishing groundwater storage that had been depleted during the drought.

Model Limitations

All models are based on limited amounts of data and thus are necessarily simplifications of actual systems. Model limitations are a consequence of uncertainty in three basic aspects of the model, including inadequacies, inaccuracies, or simplifications in observations used in the model; the representation of geologic complexity in the hydrogeologic framework; and the representation of the groundwater system in the model. It is important to understand how these characteristics limit the use of the model.

Layer 2 in the model had many more head observations than other layers, and there were many more observations in 1987 and 2009 than in the intervening years. Base flow in the North Canadian River was estimated throughout the transient model period but there were few head observations in layer 1. These biases in observation introduce uncertainty in the results of model simulations.

Although the CPN and inset models were refined from the numerical groundwater-flow model of the Central Oklahoma aquifer in Mashburn and others (2013), they do not include any more detailed hydraulic or hydrogeologic information, and local analyses can be improved by additional detailed hydrogeological characterization. The Central Oklahoma aquifer and alluvial aquifer hydraulic parameters were highly generalized and could not include the substantial local variations in hydraulic properties. Thus, the results of the simulations presented in this report are approximate mean values of local conditions. Furthermore, the Central Oklahoma aquifer is not composed of geologic layers that can be defined individually or grouped as hydrogeologic units, which introduces uncertainty in the model because model layers do not have unique hydraulic properties.

Recharge was applied only to layer 2 (Central Oklahoma aquifer) and to layer 1 (alluvial units). The Central Oklahoma aquifer was calibrated to head observations using Kh for all layers and recharge. Kh and recharge are correlated, which limits the ability to uniquely estimate parameter values because the same result could be achieved with multiple combinations of the parameter values. The North Canadian alluvial aquifer was calibrated to head observations and base-flow estimates using recharge, Kh, and streambed hydraulic conductivity parameters. However, the small number of head observations and having data from only two streamflow-gaging stations in the model active area introduces uncertainty, and again, different combinations of parameter values could provide the same calibrated model result.

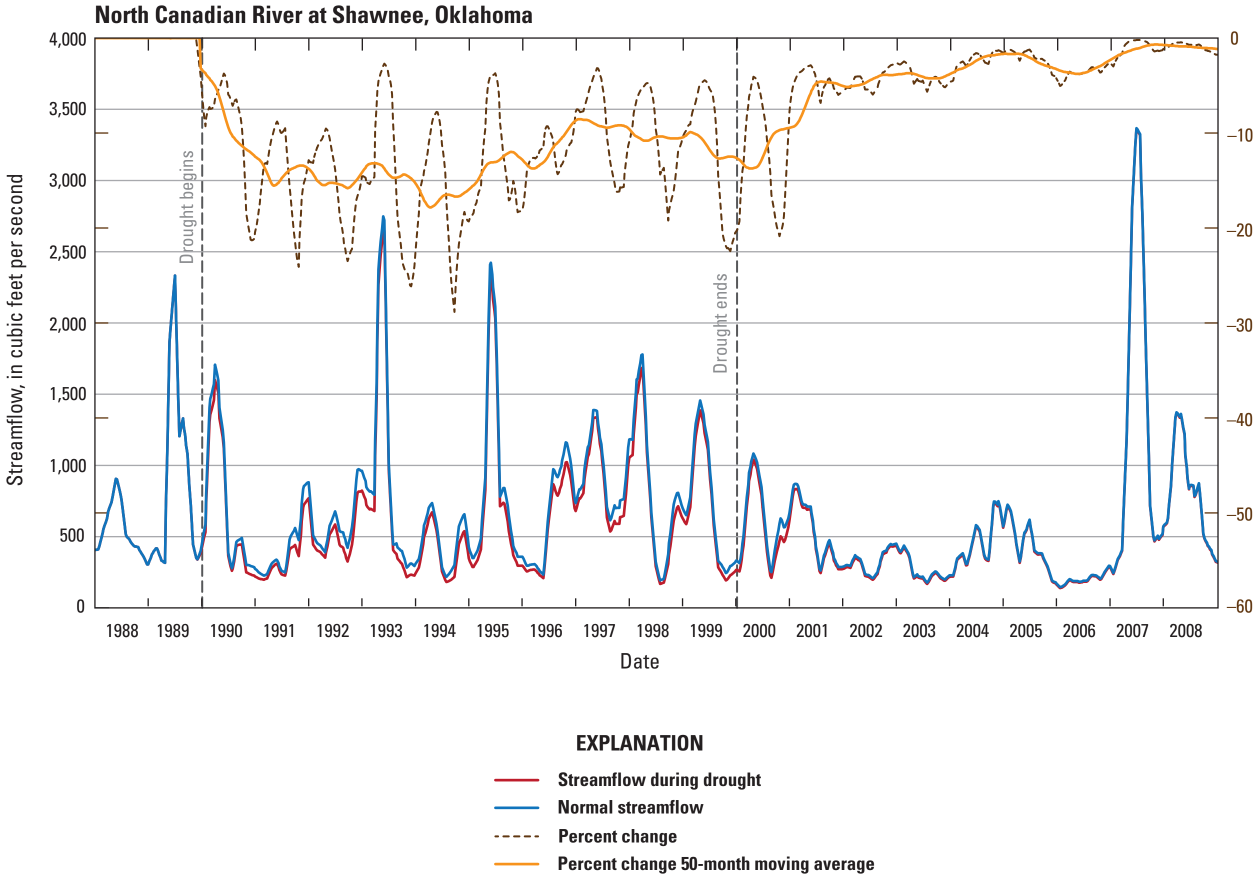


Figure 11. Observed North Canadian River streamflow at the Shawnee, Oklahoma, streamflow-gaging station and simulated flow with percent change during and after a hypothetical 10-year drought from 1990 to 2000.

Representation of the groundwater-flow system in the transient model was difficult because of the lack of stresses in the aquifers such as pumping and a dearth of observations of the system response to stresses. This lack of data introduces uncertainty to estimates of aquifer storage parameters and was seen in the low sensitivity of model observations to storage parameters.

Analyses of available groundwater at EDZs in this study are approximate and are limited by the size of model cells and limited available subsurface hydrogeological data. The inset model used calibrated hydraulic values estimated by the CPN model and did not include local variation in the Iron Horse Industrial Park or the geothermal supply area. The GWM analysis could be improved by obtaining additional subsurface data such as direct measurements of the alluvium thickness, aquifer properties, and water levels from the local area. The continuous pumping rates presented in this report are approximate, and additional subsurface and aquifer test data could be acquired to verify available water.

The simulation of a hypothetical 10-year drought is limited to local changes in recharge and there are no data available for how the system responded to previous droughts. The analysis presented in this report did not include changes in runoff within the model area, flow entering the model in the North Canadian River, or pumping and diversions that may take place under drought conditions. Although recharge is estimated to be the greatest inflow to the aquifers, a more detailed analysis of drought-related flow changes in the North Canadian River and changes in water consumption by humans and plants may reduce the uncertainty of drought effects.

Summary

A numerical groundwater-flow model was constructed using hydrogeologic information from the Central Oklahoma aquifer model that covered the Citizen Potawatomi Nation (CPN) Tribal Jurisdictional Area. The new model, termed the CPN model, estimated available groundwater resources and the effects of groundwater development and prolonged drought. The CPN model used a cell size of 820 feet (ft) on each side, which was substantially smaller than the cells in the Central Oklahoma aquifer model, which were 3,280 ft on each side. The CPN model also included alluvial deposits as hydrogeological units not differentiated in the Central Oklahoma aquifer model. Because of increased resolution and simulation of detailed flow on the eastern model margin, the CPN model also included drain cells to allow groundwater to discharge to the east. The CPN model simplified Central Oklahoma aquifer model layers to include only two layers in the Central Oklahoma aquifer—the upper and lower parts—and added an additional layer representing the part of the Wellington Formation that contains saline groundwater, referred to as the “saline unit.” The CPN model was calibrated using trial-and-error and automated parameter-estimation techniques to refine the calibration of the subregional Central Oklahoma aquifer model.

To optimize the use of water resources at two economic development zones (EDZs) just south of the city of Shawnee, Okla., the U.S. Geological Survey Groundwater-Management Process (GWM) for MODFLOW, referred to as the GWM-VI version, was used with an inset model constructed from a part of the CPN model. Model cells in the inset model were reduced to 164 ft on all sides to analyze local-scale groundwater flow and interactions between pumping wells and the North Canadian River. Model layers and hydraulic properties were transferred directly from the calibrated CPN numerical groundwater-flow model. Groundwater withdrawal amounts were optimized using GWM at the geothermal supply area and the Iron Horse Industrial Park. The target combined pumping rate for all wells at the geothermal supply area was 500 gallons per minute (gal/min). The Iron Horse Industrial Park required an estimate of the maximum groundwater development and the amount of North Canadian River water that may enter the wells. There were 5 managed wells used at the geothermal supply area and 16 managed wells used at the Iron Horse Industrial Park.

Because the estimated mean thickness of the North Canadian River alluvial aquifer was approximately 43 ft, streamflow depletion was less of a concern than local well drawdown, and pumping was constrained by head drawdown controls at managed wells at both EDZ areas. Induced infiltration of streamflow was calculated to determine the potential for lower-quality river water entering the water pumped for the Iron Horse Industrial Park. At the geothermal supply area, maximum allowed drawdown was set at 16.4 ft, which was estimated to be the maximum drawdown that would not cause loss of well yield. The head constraints at the Iron Horse Industrial Park well field allowed the head to drop as much as one-half of the predevelopment saturated thickness at each well.

Five managed wells at the geothermal supply area produced a maximum combined simulated flow of 638 gallons per minute (gal/min) of continuous pumping, which exceeded the goal of 500 gal/min. At the Iron Horse Industrial Park, the 16 managed wells had a combined withdrawal rate of 1,472 gal/min. Only 4.1 gal/min (0.3 percent) of the pumped water was estimated to come from induced infiltration of the North Canadian River streamflow

The effects of a hypothetical 10-year drought on groundwater in the CPN Tribal Jurisdictional Area and streamflow at the Shawnee, Okla., streamflow-gaging station were estimated using the CPN numerical groundwater-flow model. The drought was assumed to reduce precipitation and, in turn, recharge by 50 percent for the period 1990–2000. The model was run with recharge scaled down during the drought period and the resulting changes in total groundwater in storage and simulated streamflow at the Shawnee streamflow-gaging station were estimated.

The decrease in recharge during the hypothetical drought caused groundwater in storage over the entire model to decrease by 351,500 acre-feet (acre-ft) (14,100 acre-ft or 8.6 percent in the North Canadian River alluvial aquifer and 346,400 acre-ft or 0.2 percent in the Central Oklahoma aquifer), or approximately 0.2 percent of all groundwater in storage at the end of the drought period. This volume of groundwater loss showed that the Central Oklahoma aquifer is a bedrock aquifer that has relatively low rates of recharge from the land surface. The budget for base flow to the North Canadian River estimated that the change in groundwater flow to the North Canadian River decreased during the 10-year drought by 386,500 acre-ft (37 percent). In all other parts of the CPN Tribal Jurisdictional Area, base flow decreased by 292,000 acre-ft (28 percent). The total change in base flow to streams in the model was a decrease of 678,500 acre-ft (33 percent).

Streamflow in the North Canadian River was also analyzed during the hypothetical drought. The decrease of recharge to the North Canadian River alluvial aquifer was 441,000 acre-ft, which caused streamflow in the North Canadian River at the streamflow-gaging station at Shawnee to decrease by as much as 28 percent, and a 50-month moving average of simulated streamflow decreased by 16 percent. Simulated streamflow returned to nondrought streamflow rates approximately 7 years after the end of the drought.

References Cited

Adams, G.P., Runkle, D., Rea, A., and Becker, C.J., 1997, Digital datasets that describe aquifer characteristics of the alluvial and terrace deposits along the North Canadian River from Oklahoma City to Eufala Lake in East-Central Oklahoma: U.S. Geological Survey Open-File Report 96–448. [Also available at: http://pubs.usgs.gov/of/1996/ofr96-448/].

Ahlfeld, D.P., Barlow, P.M., and Mulligan, A.E., 2005, GWM—A ground-water management process for the U.S. Geological Survey modular ground-water model (MODFLOW-2000): U.S. Geological Survey Open-File Report 2005-1072, 124 p. [Also available at http://pubs.usgs.gov/of/2005/1072/pdf/ofr2005_1072.pdf.]

Anderson, M. P. and W. W. Woessner, 1992, Applied groundwater modeling: simulation of flow and advective transport; San Diego, London, Academic Press Inc., 381 p.

Banta, E.R., and Ahlfeld, D.P., 2013, GWM–VI—Groundwater management with parallel processing for multiple MODFLOW versions: U.S. Geological Survey Techniques and Methods, book 6, chap. A48, 33 p. [Also available at http://dx.doi.org/10.3133/tm6a48/.]

Barlow, P.M., and Leake, S.A., 2012, Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey Circular 1376, 84 p. [Also available at http://pubs.usgs.gov/circ/1376/.]

Becker, C.J., 2014, Stream-water and groundwater quality in and near the Citizen Potawatomi Nation Tribal Jurisdictional Area, Pottawatomie County, Oklahoma, 2012–13: U.S. Geological Survey Scientific Investigations Report 2014–5178, 102 p., [Also available at http://dx.doi.org/10.3133/sir20145178.]

Doherty, J., 2010, PEST, model independent parameter estimation user manual (5th ed.): Brisbane, Australia, Watermark Numerical Computing, accessed October 2, 2008, at http://pesthomepage.org/.

Esri, 2015, An overview of the Spatial Analyst Toolbox, accessed January 28, 2015, at http://resources.arcgis.com/en/help/main/10.2/index.html#/An_overview_of_the_Spatial_Analyst_toolbox/009z00000003000000/.

Fetter, C.W., 1994, Applied hydrogeology (3d ed.), Upper Saddle River, New Jersey, Prentice-Hall, 691 p.

Harbaugh, A.W., 1990, A computer program for calculating subregional water budgets using results from the U.S. Geological Survey modular three-dimensional ground-water flow model: U.S. Geological Survey Open-File Report 90-392, 46 p. [Also available at http://water.usgs.gov/nrp/gwsoftware/zonebud3/ofr90392.pdf.]

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 2000-92, 121 p.

Havens, J.S., 1989, Geohydrology of the alluvial and terrace deposits of the North Canadian River from Oklahoma City to Eufaula Lake, central Oklahoma: U.S. Geological Survey Water-Resources Investigations Report 88-4234, 32 p., 12 plates.

Heran, W.D., Green, G.N., and Stoeser, D.B., 2003, A digital geologic map database for the state of Oklahoma: U.S. Geological Survey Open-File Report 03-247, 10 p.

Konikow, L.F., Hornberger, G.Z., Halford, K.J., and Hanson, R.T., 2009, Revised multi-node well (MNW2) package for MODFLOW ground-water flow model: U.S. Geological Survey Techniques and Methods 6–A30, 67 p.

Mashburn, S.L., Ryter, D.W., Neel, C.R., Smith, S.J., and Magers, J.S., 2013, Hydrogeology and simulation of groundwater flow in the Central Oklahoma (Garber-Wellington) Aquifer, Oklahoma, 1987 to 2009, and simulation of available water in storage, 2010–2059: U.S. Geological Survey Scientific Investigations Report 2013–5219, 92 p. [Also available at http://dx.doi.org/10.3133/sir20135219.]

Merritt, M.L., and Konikow, L.F., 2000, Documentation of a computer program to simulate lake-aquifer interaction using the MODFLOW Ground-Water Flow Model and the MOC3D Solute-Transport Model: U.S. Geological Survey Water-Resources Investigations Report 00-4167, 146 p.

National Climatic Data Center, 2013, Locate weather observation station record: Asheville, N.C., National Climatic Data Center, data accessed June 15, 2013, at http://www.ncdc.noaa.gov/oa/climate/stationlocator.html.

Niswonger, R.G. and Prudic, D.E., 2005, Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams--A modification to SFR1: U.S. Geological Survey Techniques and Methods, Book 6, Chap. A13, 47 p.

Niswonger, R.G., Panday, S., and Ibaraki, M., 2011, MODFLOW-NWT, A Newton formulation for MODFLOW-2005: U.S. Geological Survey Techniques and Methods 6–A37, 44 p.

Oklahoma Water Resources Board, 2012, 2012 Oklahoma Comprehensive Water Plan Executive Report: Oklahoma Water Resources Board, 159 p.

Oklahoma Water Resources Board, 2013, Water Well Record Search, accessed January 1, 2013, at http://www.owrb.ok.gov/wd/search/search.php?type=wl.

Shivers, M.J., and Andrews, W.J., 2013, Hydrologic drought of water year 2011 compared to four major drought periods of the 20th century in Oklahoma: U.S. Geological Survey Scientific Investigations Report 2013–5018, 52 p. [Also available at http://pubs.usgs.gov/sir/2013/5018/.]

Thornthwaite, C.W., and Mather, J.R., 1957, Instructions and tables for computing potential evapotranspiration and the water balance: Centerton, N.J., Laboratory of Climatology, Publications in Climatology, v. 10, no. 3, p. 185–311.

U.S. Army Corps of Engineers, 2013, Reservoir release, storage, evaporation, and precipitation data for lakes, accessed January, 2013 at: http://www.swt-wc.usace.army.mil/stations.htm.

U.S. Geological Survey, 2013a, National Elevation Dataset: accessed January, 2013 at http://ned.usgs.gov/index.html.

U.S. Geological Survey, 2013b, National Hydrography Dataset: accessed January, 2013 at http://nhd.usgs.gov/data.html.

U.S. Geological Survey, 2012, National Water Information System data available on the World Wide Web (USGS Water Data for the Nation), accessed December 2, 2013, at http://waterdata.usgs.gov/nwis/.

Wahl, T.L., and Wahl, K.L., 2007, BFI—A computer program for determining an index to base flow, version 4.15: Bureau of Reclamation software release, accessed July 23, 2008, [Also available at http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/.]

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury,K.R., 2010, SWB—A modified Thornthwaite-Mather Soil-Water-Balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods 6-A31, 60 p.

Publishing support provided by
Lafayette Publishing Service Center

Ryter and others—**Numerical Simulation of Groundwater Flow, Resource Optimization, and Potential Effects of Prolonged Drought for the CPN**—SIR 2014–5167

ISSN 2328-031X (print)
ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20145167

ISBN 978-1-4113-3932-3

Printed on recycled paper