



Use of the Eastern Arbuckle-Simpson Aquifer Groundwater-Flow Model to Protect Water-Resources in Chickasaw National Recreation Area

Natural Resource Technical Report NPS/NRSS/WRD/NRTR—2013/775



ON THE COVER

Top left: The falls at Flower Park, as they flow into Travertine Creek, Chickasaw National Recreation Area.

Photograph by: Jack E. Bourcher, courtesy of National Park Service Historic Photograph Collection.

Bottom right: Buffalo Spring, Chickasaw National Recreation Area.

Photograph by: Scott Christenson, U.S. Geological Survey.

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Executive Summary

The U.S. Geological Survey's eastern Arbuckle-Simpson aquifer MODFLOW groundwater-flow model was evaluated to determine if it could be used by the National Park Service to assess the effects of state-recommended groundwater-management options on water resources in Chickasaw National Recreation Area. The regional-scale model was found to be sufficiently refined and calibrated in the vicinity of the park to provide useful information about the potential impacts to major springs and streams from distributed groundwater withdrawals in the Arbuckle-Simpson aquifer. Model simulations described in the U.S. Geological Survey Scientific Investigations Report 2011-5029 were reviewed to better understand how simulated withdrawals affected base flow to Travertine, Rock, and Wilson Creeks, and water levels at Antelope and Buffalo Springs. New model simulations were run to evaluate how the distribution and pumping rate of wells affected simulated groundwater discharge in the park. The results indicate that when proposed withdrawals were distributed as an equal proportional share equivalent to 0.200 acre-ft per acre per year, simulated base flow for Travertine Creek was reduced by over 25%. These results are believed to represent a high-impact scenario based upon the conceptualization of the aquifer system as entirely confined. This information is intended to inform decision-making regarding the Oklahoma Water Resources Board's process for determining the maximum annual yield of the Arbuckle-Simpson Groundwater Basin and discussions with other stakeholders. Further characterization of hydraulic properties and boundary conditions in the vicinity of Chickasaw National Recreation Area would reduce the uncertainty of these predicted impacts.

Introduction

Chickasaw National Recreation Area (NRA) is located in Murray County in south-central Oklahoma. The Arbuckle-Simpson aquifer is the principal source of water to springs, perennial streams, and a flowing well in the park. Concerned that large-scale groundwater withdrawals could adversely affect water supplies, recreational opportunities, and aquatic habitat that depend upon the flow of springs and streams emanating from the Arbuckle-Simpson aquifer, the Oklahoma Water Resources Board (OWRB) initiated a study to determine the volume of water that could be withdrawn without degrading these water resources. The OWRB, in collaboration with the U.S. Geological Survey (USGS), completed a study of the aquifer that included simulating discharge to springs and streams (Figure 1). USGS Scientific Investigations Report (SIR) 2011-5029 (Christenson et al. 2011) describes the study and documents the development of the eastern Arbuckle-Simpson aquifer MODFLOW (Harbaugh et al. 2000) groundwater-flow model, as well as the results of simulations performed to calibrate the model and to evaluate changes in stream and spring flows due to various groundwater-withdrawal scenarios.

On March 13, 2012, the OWRB tentatively determined the maximum annual yield of the Arbuckle-Simpson Groundwater Basin to be 78,404 acre-ft and the equal proportionate share (EPS) of the yield to be allocated to each acre of land overlying the basin to be 0.200 acre-ft per acre per year (OWRB 2012). One of the considerations leading to this determination was a recommendation by the Surface Water Technical Advisory Group that "...if the 5-year base flow calculated for area streams is not reduced by more than 25%, such a decrease should result in an acceptable maintenance of the representative fish species in the Blue River and Pennington Creek" (OWRB 2012).

The OWRB's March 13, 2012 Tentative Order also determined that rules concerning a well spacing distance or "set-back" from springs and streams should be promulgated so that the cumulative impact of pumping from existing wells and proposed pumping from a specific well do not impact the flow of a particular identified spring or stream by more than 25% of the base flow (OWRB 2012). A public hearing on the Tentative Order was held on May 15-16, 2012, in Sulphur, Oklahoma.

The National Park Service (NPS) has a statutory mandate to preserve the groundwater component of discharge for Antelope and Buffalo Springs, Travertine and Rock Creeks, and Vendome Well in Chickasaw NRA for the enjoyment of present and future generations (Figure 2). Because groundwater withdrawals outside the park could adversely impact these resources, the NPS is participating in the state process for determining the maximum annual yield, and seeks to use the eastern Arbuckle-Simpson MODFLOW groundwater-flow model as a tool to evaluate the effects of the proposed yield on park resources. The scope of SIR 2011-5029 and the model, however, are much larger than the area of the park and the model was not optimized to simulate effects on the park's water-related resources. Furthermore, distributed withdrawals allocated as an EPS = 0.200 acre-ft per acre per year were not simulated by Christenson et al. (2011). More information was therefore needed to determine the suitability of using the model to simulate groundwater discharge to principal springs and streams in Chickasaw NRA and the potential cumulative impacts of existing and proposed groundwater withdrawals on park resources and values.

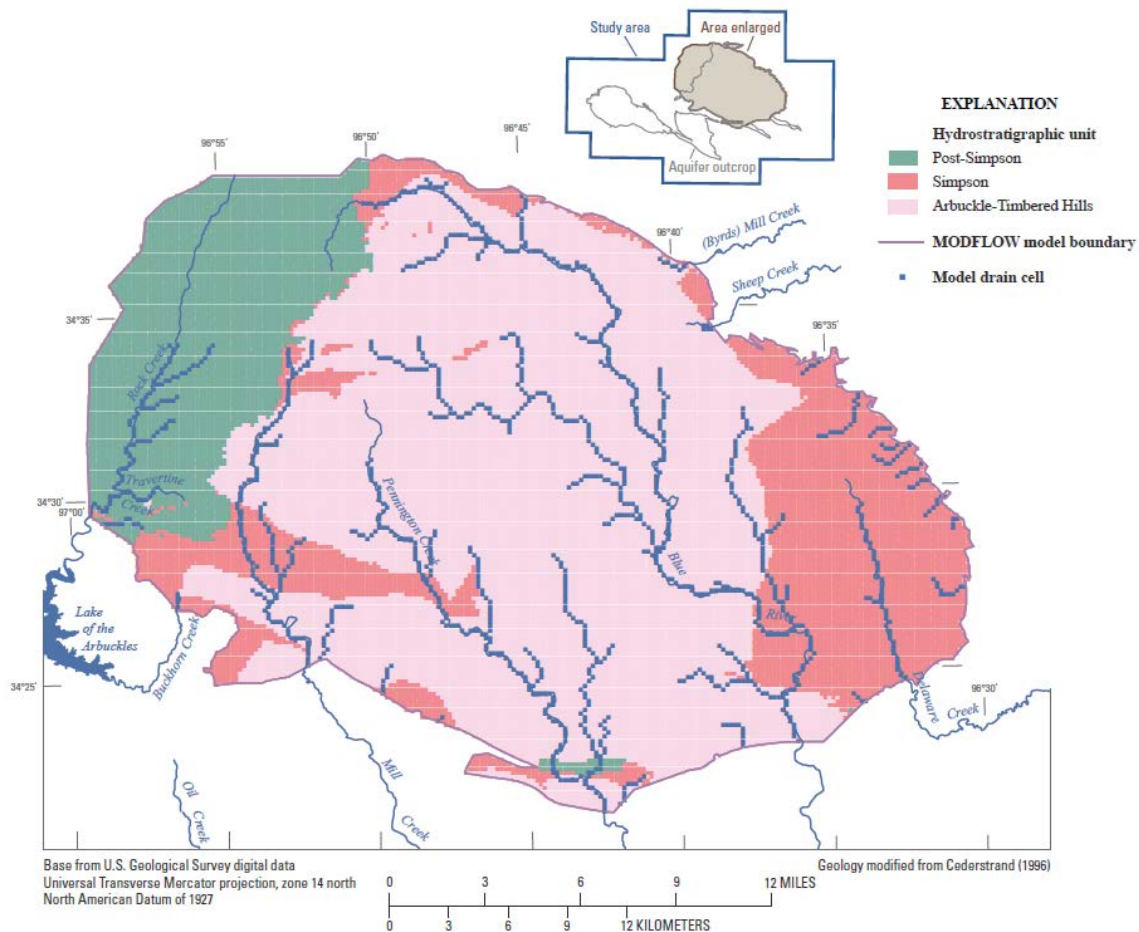


Figure 1. The study area and domain of the eastern Arbuckle-Simpson aquifer MODFLOW groundwater-flow model (from Christenson et al. 2011, Figure 30).

The objectives of the study described here were (1) to understand how major springs and streams in Chickasaw NRA were represented in the groundwater-flow model; (2) to quantify the simulated depletion in average base flow for Travertine Creek when distributed groundwater withdrawals are allocated as an EPS = 0.200 acre-ft per acre per year; and (3) to evaluate how a well set-back from Antelope and Buffalo Springs affects simulated drawdown and depletions in base flow in Chickasaw NRA.

The results of model simulations run by Christenson et al. (2011) with regard to base flow and water-level decline in Chickasaw NRA are described first, followed by the results of new model simulations run by the NPS. This information is intended to inform resource-management decisions.



Explanation

- Chickasaw NRA
- Arbuckle-Simpson aquifer outcrop
- ▲ Streamgage, station number
- ▲ Well, name

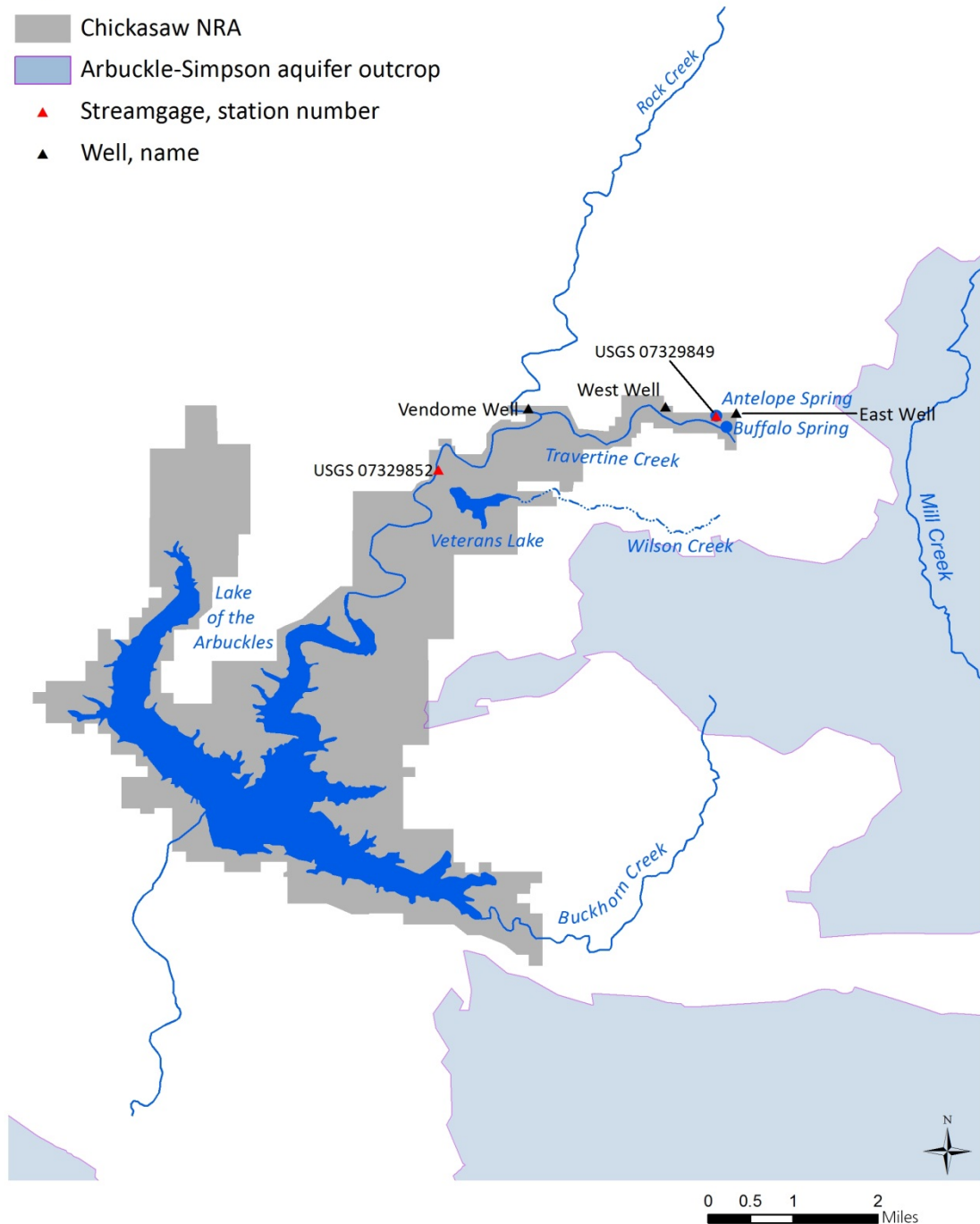


Figure 2. Major water-related resources and the outcrop boundary of the Arbuckle-Simpson aquifer in the vicinity of Chickasaw NRA.

Study Area

In 1902, Sulphur Springs Reservation was established through an agreement between the Chickasaw and Choctaw Nations and the Federal government to protect the unique freshwater and mineral springs along Travertine and Rock Creeks; the reservation was later renamed Platt National Park and became Chickasaw NRA in 1976 after merging with the Arbuckle Recreation Area (http://www.nps.gov/chic/historyculture/remembering_platt-np.htm).

Antelope and Buffalo Springs are located in the eastern end of the Platt Historic District in Chickasaw NRA. Discharge from these freshwater springs forms the headwaters of Travertine Creek. Travertine Creek is the principal tributary to Rock Creek and also receives discharge from the flowing Vendome Well. Wilson Creek forms Veterans Lake near its confluence with Rock Creek. Rock Creek is the largest stream in Chickasaw NRA and is one of the major streams contributing to Lake of the Arbuckles. Lake of the Arbuckles was constructed by the Bureau of Reclamation to provide water supply for municipal and industrial uses. According to Christenson et al. (2011), discharge from Antelope Spring has been gaged since 1985 (USGS streamgage number 07329849) and discharge on Rock Creek at Sulphur since 1989 (USGS streamgage number 07329852) (Figure 2).

In addition to contributing to public water-supply systems, these springs and streams provide aquatic habitat and a variety of recreational opportunities such as fishing, boating, and swimming in Chickasaw NRA. Groundwater discharge from the Arbuckle-Simpson aquifer maintains base flow to and discharge from these important hydrologic features. The reader is referred to Christenson et al. (2011) for a detailed description of the study area of the eastern Arbuckle-Simpson aquifer MODFLOW groundwater-flow model, and to Hanson and Cates (1994) and Christenson et al. (2009) for more information on the hydrogeology of Chickasaw NRA.

Methods

Model Input and Output Files

The model files for the eastern Arbuckle-Simpson aquifer MODFLOW groundwater-flow model and the modified MODFLOW executable file (*mf2kplus.exe*) were made available to the public by the USGS at <http://ok.water.usgs.gov/projects/arbsimp/eastindex.htm>. The MODFLOW model files were downloaded by the NPS and each model scenario was run to obtain the output for the simulations described in SIR 2011-5029.

It was also necessary to download the USGS program ZONEBUDGET (Harbaugh 1990). This program was run after each transient simulation to read the binary cell-by-cell MODFLOW output file (*.cbc) containing the flow data for sources and sinks in subregions of the model domain.

In addition, the NPS calculated the change in water level at Antelope and Buffalo Springs in model layer 3 for each simulation. For the EPS simulations, water-level decline was calculated as the difference between the initial heads listed in the *arbsimmaytr.bas6* input file for the “Reported water use” simulation and the final heads in the *.drawdown MODFLOW output file for each transient simulation.

Model Discretization

The eastern Arbuckle-Simpson aquifer MODFLOW groundwater-flow model covers an area of 387 mi². The rectangular finite-difference grid was discretized into 200-m × 200-m cells. There are about 10 cells per acre.

The center of each MODFLOW model cell is referred to as a node. The model consists of active and inactive nodes. Groundwater-flow equations are solved for hydraulic head (water-level elevation) at each active node. Inactive nodes are used to maintain a rectangular grid structure but are considered outside the model domain. The perimeter and base of the model domain were simulated as no-flow boundaries.

Less than 3 mi² of the northeastern portion of Chickasaw NRA is within the active model domain (Figure 3). Although the Arbuckle-Simpson aquifer extends into the subsurface to the west of the park, the model boundary in this area is believed to be the boundary of the freshwater flow system, beyond which the aquifer contains saline water (Christenson et al. 2011). This fresh/saline water interface was modeled as a no-flow boundary. The close proximity of the no-flow boundary to water resources in Chickasaw NRA likely affects the accuracy of the model results in this area. For example, water-level declines may be exacerbated by the no-flow boundary.

The model domain was discretized vertically into six layers. The MODFLOW layer type was specified as confined for all layers; the unconfined behavior of portions of the aquifer system was therefore not simulated. The top of layer 1 is the elevation of the land surface. The thicknesses of layers 1 through 5 are constant over the model domain while the thickness of layer 6 varies to accommodate the total aquifer thickness at each node (e.g., Figure 29 in Christenson et al. 2011). The land-surface elevation of nodes within the boundary of Chickasaw NRA ranges from 278 m (912 ft) to 350 m (1148 ft) above the North American Vertical Datum of 1988; the bottom elevation of nodes in layer 6 within the park ranges from 799 m (2621 ft) to 1337 m (4386 ft) below the North American Vertical Datum of 1988.

Drains

Groundwater discharge from the Arbuckle-Simpson aquifer to streams was simulated using the MODFLOW drain package. Model-simulated discharge to drains represents the groundwater component of streamflow (base flow). There are 1266 drain cells in the model (Figure 1). Drain cells were assigned to Rock Creek, Travertine Creek, Wilson Creek, and Veterans Lake to simulate known areas of groundwater discharge (Figure 3).

Vendome Well and Antelope and Buffalo Springs are not explicitly modeled in the eastern Arbuckle-Simpson aquifer MODFLOW groundwater-flow model; their discharge was considered to be part of the groundwater discharge to Travertine Creek. Although drains cells were not extended to these springs in the model, there are model nodes at the locations of both Antelope and Buffalo Springs (Figure 3). Simulated water-level declines at these locations under various pumping scenarios can therefore be quantified from the model output.

Steady-State Model

Under steady-state conditions, the volume of water recharging the aquifer is balanced by the volume of water discharging from the aquifer, and heads and the volume of water in storage are



Explanation

- | | |
|----------------------------------|-------------------|
| Chickasaw NRA | Model drain cells |
| Arbuckle-Simpson aquifer outcrop | Rock Creek |
| Inactive model node | Travertine Creek |
| Active model node | Wilson Creek |
| Vert. anisotropy=0.001 | Other |
| Simulated well | |

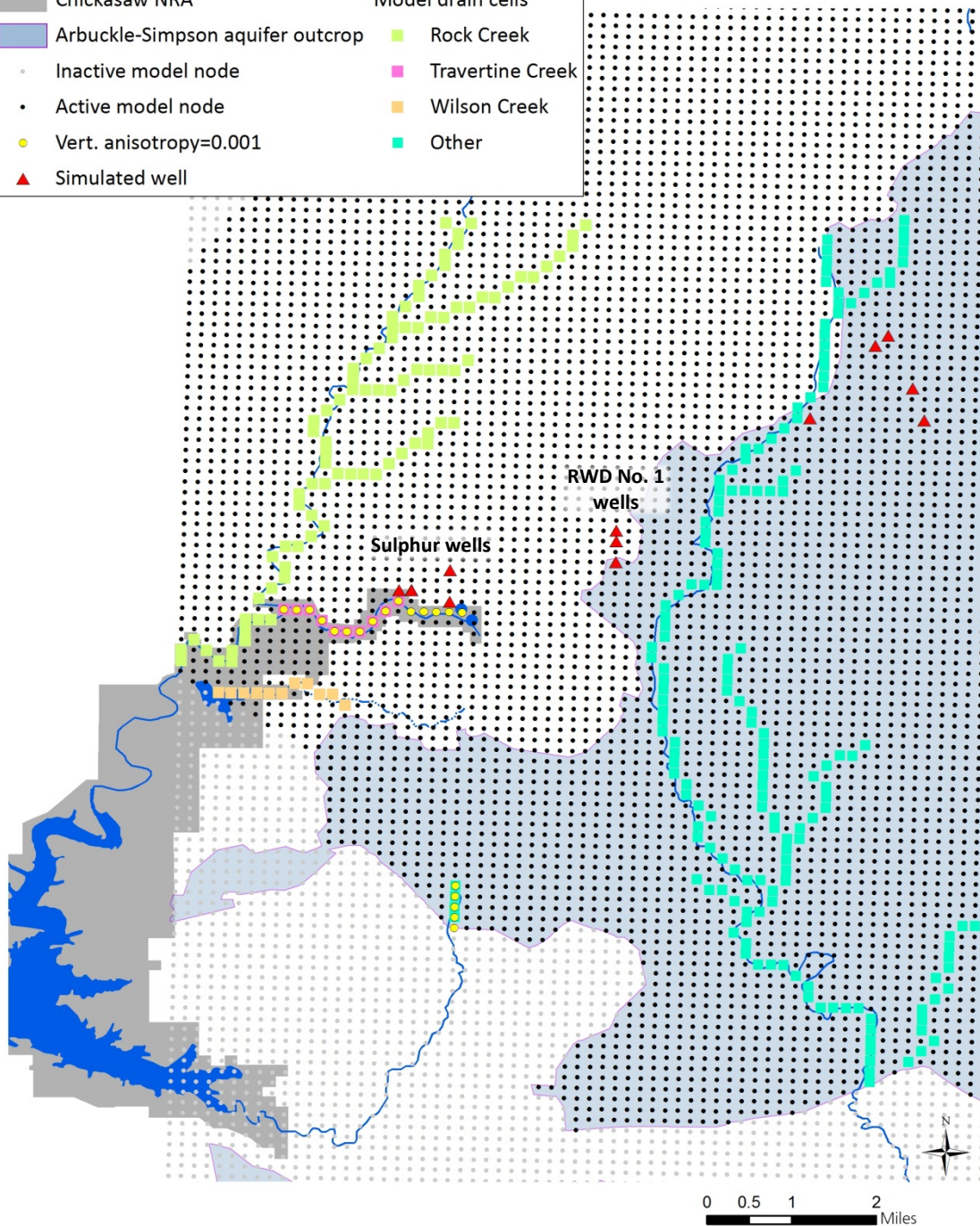


Figure 3. Eastern Arbuckle-Simpson aquifer MODFLOW groundwater-flow model nodes, drain cells, wells, and vertical anisotropy in the vicinity of Chickasaw NRA.

constant. The steady-state model was calibrated to minimize the difference between synoptic water-level and streamflow measurements made during August 1995 and simulated water levels and streamflow. According to Christenson et al. (2011), streamflow measurements for this period represent base flow because there was no surface runoff in the stream channels. The steady-state model did not include groundwater discharged by existing pumping wells, so it cannot be used to evaluate the effects of long-term withdrawals near the park. The model parameters that were adjusted during the steady-state calibration were horizontal hydraulic conductivity (Hx), vertical hydraulic conductivity (Hv) and recharge. In the vicinity of Chickasaw NRA, simulated heads were up to 82 ft lower than observed heads. Although the model was not calibrated to optimize water levels in Chickasaw NRA, simulated changes in head are useful for understanding the potential timing and magnitude of the effects of withdrawals on water levels in Chickasaw NRA.

Horizontal and vertical hydraulic conductivity

Values of Hx and Hv for each hydrostratigraphic unit were determined during the steady-state calibration (Table 1). The MODFLOW Layer Property Flow package was used to specify hydraulic properties at each model node and they are uniform within each hydrostratigraphic unit, with some exceptions. The value of Hx assigned to the Arbuckle-Timbered Hills hydrostratigraphic unit is consistent with a transmissivity of 12,000 ft²/day estimated by Fairchild et al. (1990) and Christensen et al. (2011) based on aquifer tests and an aquifer thickness of 3281 ft (1000 m).

Table 1. Values of hydraulic conductivity determined from the steady-state calibration for the MODFLOW model.

Model hydrostratigraphic unit	Horizontal	Vertical
	Hydraulic conductivity (ft/day)	
Post-Simpson	1.10×10^{-3}	2.20×10^{-6}
Simpson	3.90×10^{-1}	1.95×10^{-4}
Arbuckle-Timbered Hills	3.30×10^0	5.53×10^{-1}
Arbuckle-Timbered Hills (near springs)	3.30×10^0	3.30×10^3

The boundaries of the hydrostratigraphic units (Figure 1) are based upon geologic and geophysical data. The area of Chickasaw NRA occurs beyond the outcrop of the Arbuckle-Simpson aquifer (Figure 2). In the portion of the park that is within the model domain, the aquifer is confined beneath younger sedimentary rocks characterized as the post-Simpson hydrostratigraphic unit. This unit is underlain by the Simpson or Arbuckle-Timbered Hills hydrostratigraphic units in the modeled area of the park. The Simpson and Arbuckle-Timbered Hills units outcrop in several cells near Travertine and Rock Creeks in model layer 1 based upon the geology at a depth of 10 m (Figure 1).

Christenson et al. (2011) found the best fit between observed and simulated streamflow on Travertine Creek was achieved when Hv was increased substantially in nodes beneath Travertine Creek. This was attributed to hypogene speleogenesis in the area of Antelope and Buffalo Springs (Christenson et al. 2011). As a result, the ratio Hx/Hv, or vertical anisotropy, was set to 0.001 at these nodes (Table 1; Figure 3).

Recharge

Recharge from the infiltration of precipitation was applied to the land surface in model layer 1. In general, recharge was uniform within each of the four hydrostratigraphic units. In some cases where the thickness of a hydrostratigraphic unit was thin (< 10 m), recharge was assigned on the basis of the geology at the land surface. The entire modeled area of Chickasaw NRA was assigned the recharge value for the post-Simpson hydrostratigraphic unit = 1.10×10^{-7} m/day (3.60×10^{-7} ft/day) for the steady-state calibration. This rate is several orders of magnitude less than that assigned to Simpson and Arbuckle-Timbered Hills hydrostratigraphic units, consistent with the conceptualization of the post-Simpson unit as a confining layer. For reference, mean annual precipitation at Chickasaw NRA for January 1919 to December 1987 was 38.29 inches (Hanson & Cates 1994) and the average recharge rate for the Arbuckle-Simpson aquifer estimated by Fairchild et al. (1990) is 4.7 in/year. Recharge assigned to the Simpson and Arbuckle-Timbered Hills (north of Sulphur fault) hydrostratigraphic units outside of the park is equivalent to 0.39 in/year and 12 in/year, respectively.

Transient Model

In a transient model, hydraulic heads and discharge to streams are time-dependent due to changes in recharge and withdrawals by wells. The simulation of transient groundwater-flow requires definition of the storage properties of the hydrostratigraphic units. In the eastern Arbuckle-Simpson aquifer MODFLOW groundwater-flow model, specific storage (S_s) was defined for each model layer. A value of $S_s = 8.0 \times 10^{-6} \text{ m}^{-1}$ ($2.4 \times 10^{-6} \text{ ft}^{-1}$) was assigned to all hydrostratigraphic units based upon a storage coefficient (S) of 0.008 and an aquifer thickness of 1000 m. The value of $S = 0.008$ was calculated by Fairchild et al. (1990) and is within the range of storage coefficients calculated by Christenson et al. (2011) for the Arbuckle-Simpson study. The Layer Property Flow package multiplies S_s by the model layer thickness to calculate S for each cell in a confined layer. This parameterization scheme indicates that the Arbuckle-Simpson aquifer was simulated as a confined aquifer system and that flow between cells under unconfined conditions was not simulated in any layer. Other hydraulic properties were unchanged from the calibrated steady-state model.

Harmonic analysis of hourly water-level fluctuations in the East (USGS 343017096561501) and West (USGS 343022096565701) Observation Wells in Chickasaw NRA was performed to further investigate aquifer conditions in the park (Figure 4). The East and West Observation Wells are 238 ft- and 436 ft-deep, respectively, and are completed in the Arbuckle-Simpson aquifer (Figure 2). Rahi & Halihan (2013) analyzed the response of nine wells in the Arbuckle-Simpson aquifer to earth tides and barometric-pressure oscillations; they found that the aquifer penetrated by each well can be characterized as unconfined, semi-confined, or confined based upon the water-level fluctuation spectrum data. The results of the NPS analysis indicated that according to the Rahi & Halihan (2013) criteria, confined to semi-confined conditions exist in area of the park's two observation wells.

Recharge in the calibrated steady-state model was adjusted to estimate initial conditions for a 5-water-year transient calibration. The time period of the transient calibration was October 1, 2003, to September 30, 2008, and was simulated using daily time steps. Recharge was adjusted until the steady-state heads and streamflow at Blue River and Pennington Creek matched conditions on October 1, 2003. The transient model was therefore optimized to simulate groundwater flow

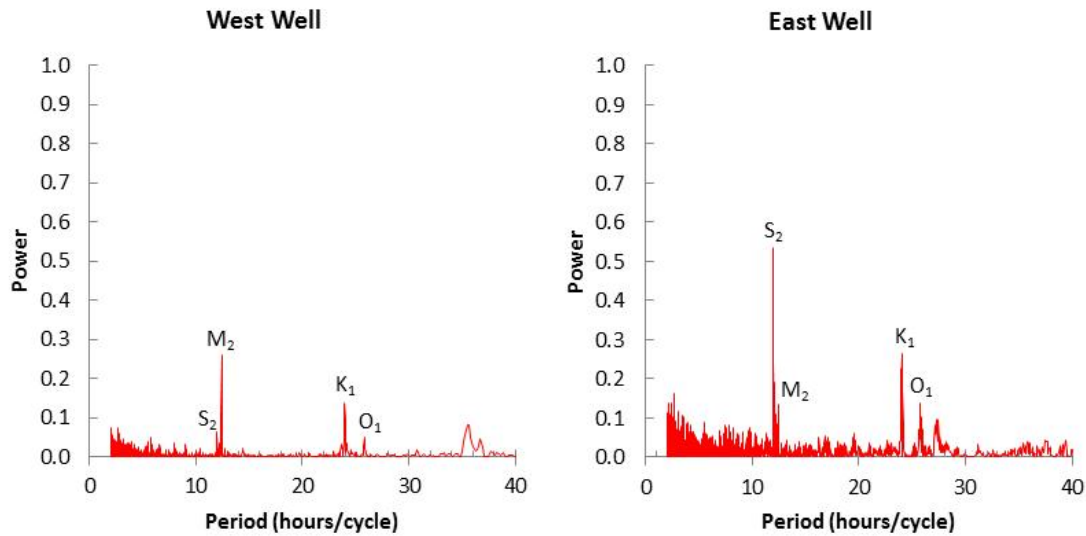


Figure 4. Harmonic analysis of water-level fluctuations in the West Observation Well (USGS 343022096565701) for the time period of 10/1/2010 to 3/31/2011 and in the East Observation Well (USGS 343017096561501) for the time period of 10/1/2011 to 10/31/2011. The power spectrum of the West Well is dominated by the M_2 (main lunar semidiurnal) harmonic component indicating confined aquifer conditions. The presence of both the lunar (M_2 and O_1) and solar (S_2 and K_1) harmonics in the power spectrum of the East Well may indicate semi-confined aquifer conditions.

to Blue River and Pennington Creek, which are the two streams overlying the eastern Arbuckle-Simpson aquifer with the largest flows (Figure 1).

Daily runoff components of streamflow were calculated for Blue River and Pennington Creek using the PART program (Rutledge 1998) and then added to MODFLOW-simulated base flows prior to comparing to total flow measured at the stream gauges. Recharge rates were applied based upon the hydrostratigraphic unit at the land surface. Daily recharge was computed by a separate program and then adjusted by a constant factor until total simulated streamflow matched total measured streamflow at the Blue River and Pennington Creek stream gauges. Area-weighted annual recharge rates averaged 5.58 in/yr for the 2004-8 calibrated transient model.

Because Chickasaw NRA is not within the drainage basins of Blue River and Pennington Creek, the suitability of the transient model for simulating potential impacts to major hydrologic features in the park was further evaluated by the NPS. It was determined that MODFLOW-computed base flow for Travertine Creek compares favorably with base flow inferred from streamflow at the USGS gage 07329852 on Rock Creek (J. Back, NPS, personal communication, 2012), and that the transient MODFLOW model reasonably simulates the character and variability in head in the East and West Observation Wells in Chickasaw NRA (S. Christenson, USGS, written communication, May 6, 2012).

The simulated daily and average base flow for Rock Creek and for Wilson Creek over the 5-year simulation was not included in SIR 2011-5029. Christenson et al. (2011) assigned drains representing Travertine and Rock Creeks to separate zones, but Wilson Creek and Veterans Lake drain cells were lumped into a zone with other minor streams. The NPS modified the USGS

program ZONEBUDGET input files (*budget.zones.key.txt* and *budget.zones*) to include the Wilson Creek and Veterans Lake drain cells as a separate zone. The NPS then ran ZONEBUDGET after each transient simulation to calculate daily and average base flow for streams in Chickasaw NRA.

Results of Model Simulations

“No Withdrawals” Simulation

Christenson et al. (2011) describe an additional “test of concept” transient simulation designed to quantify the effects of current reported water use on groundwater discharge to streams and springs. The transient model with no groundwater withdrawals was run in successive 5-water-year periods until base flow for Blue River and Pennington Creek changed by less than one percent. This simulation was not included in the MODFLOW files that were made available to the public, but was provided to the NPS by S. Christenson (USGS, written communication February 3, 2012).

Recharge varies daily and seasonally over the 5-year transient simulation. The effect of the daily time step is best illustrated by the “No withdrawals” simulation because in this scenario, changes in simulated daily base flow for streams in Chickasaw NRA are driven by daily changes in recharge as opposed to withdrawals (Figure 5). Above-average recharge in water year 2007 resulted in an overall water-level rise (i.e., negative water-level decline) at Antelope and Buffalo Springs at the end of the “No withdrawals” simulation (Table 2). Simulated daily base flow for Rock and Wilson Creeks remained well under 1 cfs during the 5-year “No withdrawals” simulation.

“Reported Water Use” Simulation

Reported water use for the period of October 1, 2003, to September 30, 2008, was included in the transient model as groundwater withdrawals from wells. Reported monthly usage was distributed evenly over each month. Up to 40 wells were simulated with a 5-year average annual withdrawal of 5,564 acre-ft/year (Table 2). The two pumping centers located nearest to Chickasaw NRA are operated by the city of Sulphur and Rural Water District (RWD) No. 1 (Figure 3).

Sulphur’s pumping wells (Permit 19560906) were simulated as 6 wells in model layers 3 through 5; the 5-year average annual withdrawal from these wells was 930 acre-ft/year. RWD No. 1’s pumping wells (Permit 19820935) were simulated as 3 wells in model layers 4 and 5; the 5-year average annual withdrawal from these wells was 614 acre-ft/year.

The effects of the simulated reported water use propagate into the area of Chickasaw NRA within the 5-year simulation period, depleting base flow to Travertine Creek and lowering water levels at Antelope and Buffalo Springs (Table 2). While the “Reported water use” simulation indicates that nearby pumping centers have the potential to reduce heads and base flow in the park, the cumulative impact of decades of historic water use from the aquifer on water resources in the park remains uncertain.

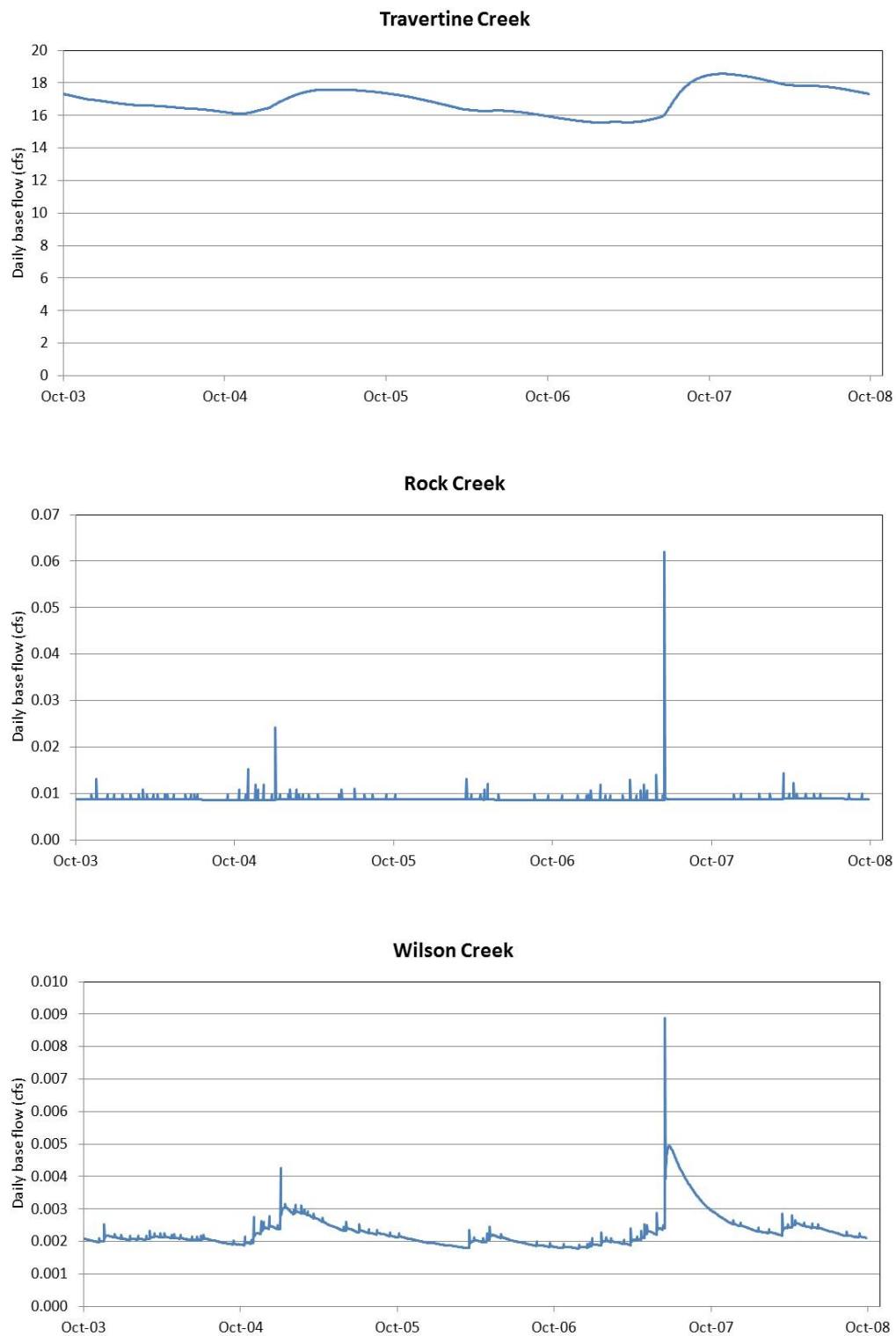


Figure 5. Simulated daily average base flow for water years 2004-8 based on the “No withdrawals” MODFLOW model simulation.

Table 2. Five-year average base flow for water years 2004-8 for major streams in Chickasaw NRA, water-level decline at major springs in the park, water use, and depletion of 5-year average base flow for Travertine Creek, simulated by the MODFLOW model.

	Travertine Creek	Rock Creek	Wilson Creek	Antelope Spring	Buffalo Spring	5-year groundwater withdrawal	Average annual groundwater withdrawal	Depletion of 5- year average base flow for Travertine Creek
Simulation	5-year average base flow (cfs)			Water-level decline (ft)		(acre-ft)	(acre-ft)	(percent)
No withdrawals	16.90	0.0088	0.0023	-3.75	-3.78	0	0	-9.6%
Reported water use	15.41	0.0085	0.0021	2.60	2.58	27,818	5,564	0.0%
EPS = 0.125	13.59	0.0079	0.0019	8.52	9.33	141,974	28,395	11.8%
EPS = 0.200 & 5-mi buffer	14.20	0.0079	0.0021	6.10	6.31	189,624	37,925	7.9%
EPS = 0.200 & 2-mi buffer	11.41	0.0073	0.0017	14.57	15.08	224,207	44,841	26.0%
EPS = 0.200	11.12	0.0073	0.0017	17.83	19.20	227,160	45,432	27.8%
EPS = 0.250	9.28	0.0071	0.0015	25.27	27.02	283,949	56,790	39.8%
EPS = 0.392	2.61	0.0043	0.0008	62.61	65.53	445,232	89,046	83.1%

It should also be emphasized that the eastern Arbuckle-Simpson aquifer MODFLOW groundwater-flow model is a regional-scale model developed to simulate long-term average base flows. It may, therefore, not be the best tool for simulating the short-term effects of withdrawals on discharge to nearby springs and streams. For example, Sulphur's wells were simulated in the model with monthly average pumping rates as total discharge from a model cell, as opposed to simulating the actual pumping cycle at individual wells. This limits the ability of the model to match the short-term effects of these withdrawals on discharge to Travertine Creek (S. Christenson, USGS, written communication, May 6, 2012). The simulations are, however, useful for understanding how the location and concentration of simulated withdrawals affects discharge to springs and streams in Chickasaw NRA.

Equal Proportionate Share Simulations

The purpose and methods for the EPS simulations are well-documented in SIR 2011-5029. These simulations involved placing a hypothetical well in every active model cell in layer 3 where the Arbuckle-Timbered Hills or Simpson hydrostratigraphic units were present. Three simulations of distributed withdrawals were completed for total allocations of 0.125, 0.250 and 0.392 acre-ft per acre per year. As noted by Christensen et al. (2011), a rate of 0.392 acre-ft per acre per year is equivalent to the recharge rate of 4.7 in/year estimated for the Arbuckle-Simpson aquifer by Fairchild et al. (1990). The EPS simulations did not include existing reported groundwater use. Total groundwater withdrawals for the EPS simulations were 5 to 16 times greater than water use reported from October 1, 2003 to September 30, 2008. Hydraulic properties and the 2004-8 recharge distribution were unchanged from the transient model.

Because one objective of the EPS simulations was to determine the potential long-term effects of groundwater withdrawals on springs and streamflow, Christenson et al. (2011) ran the transient model in successive 5-water-year periods until the simulated average base flow for Blue River and Pennington Creek changed by less than one percent. This method minimizes the transitional period where most of the pumped water comes from aquifer storage. The final simulations for each EPS scenario can be considered a new equilibrium state. As expected, simulated base flow for Travertine, Rock, and Wilson Creeks declined as distributed withdrawals increased (Figure 6).

The EPS simulations resulted in depletions of up to 85% of the average base flow for Travertine Creek and over 60 ft of water-level decline at Antelope and Buffalo Springs in Chickasaw NRA (Table 2). From these simulations, it was assumed that an EPS = 0.200 acre-ft per acre per day could deplete simulated average base flow for Travertine Creek between 12% to 40% relative to the "Reported water use" simulation. Because depletions in base flow greater than 25% were considered unacceptable to the OWRB, the NPS ran the model with a rate of 0.200 acre-ft per acre per year to better inform decision-making regarding the proposed tentative order. This new simulation is described below.

NPS Simulations

This section describes the additional simulations run by the NPS to better understand the potential effects of proposed withdrawals on water resources in Chickasaw NRA. The following documents the changes that were made to the model input files and the results of the simulations. Simulated depletion of average base flow for Travertine, Rock, and Wilson Creeks, and simulated water-level decline at Antelope and Buffalo Springs are quantified for each simulation.

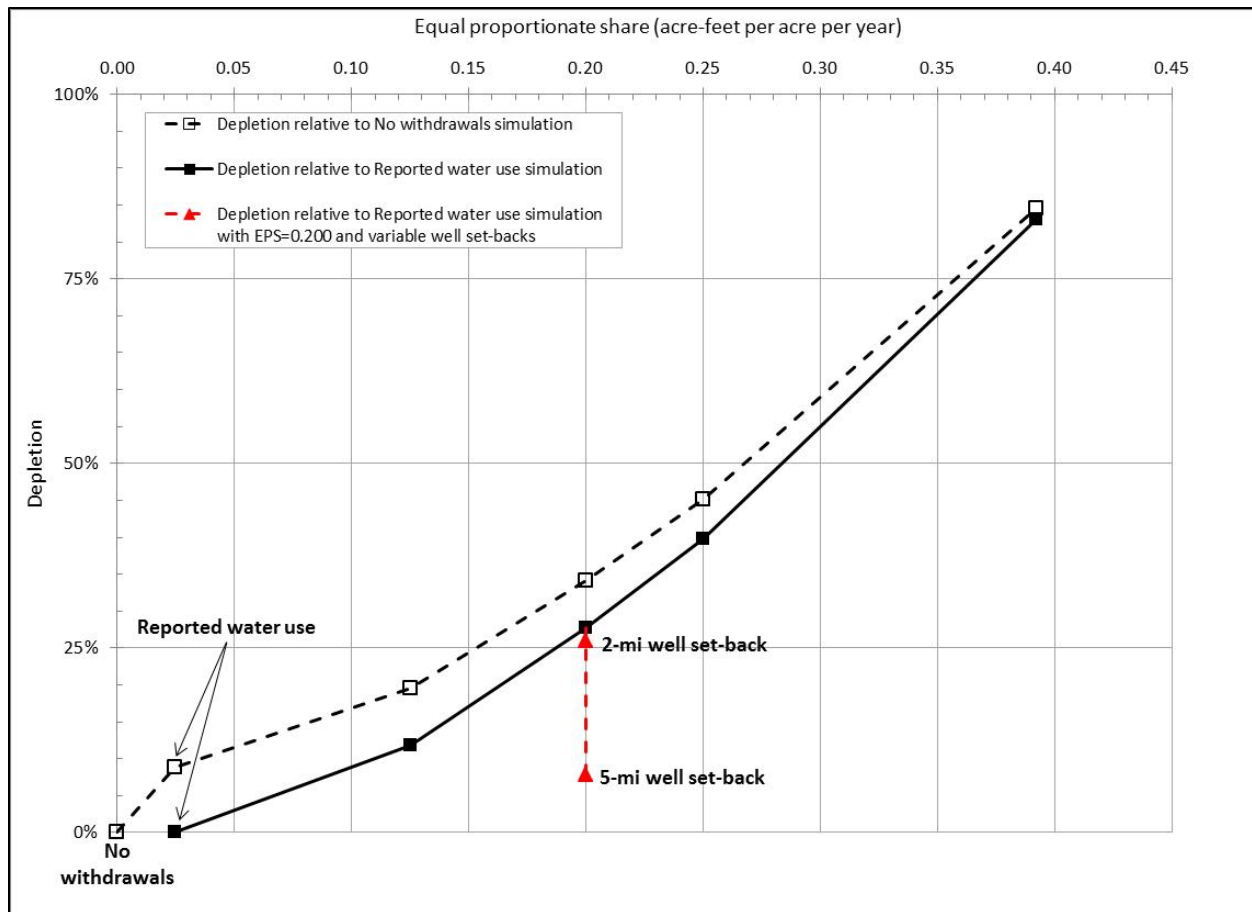


Figure 6. Depletion of 5-year average base flow for Travertine Creek based on MODFLOW-simulated groundwater withdrawals.

EPS = 0.200 acre-ft per acre per year

To simulate distributed withdrawals as an $EPS = 0.200$ acre-ft per acre per year, the *arbsimmay.eps0.250.wel* MODFLOW input file was modified to reduce Q at each time step by a factor of 0.800. The model was run in successive 5-water-year periods until simulated average base flow for Travertine Creek changed by less than 0.10%. An $EPS = 0.200$ acre-ft per acre per year resulted in a 28% simulated depletion of average base flow for Travertine Creek relative to the “Reported water use” simulation (Figure 6). Water-level declines at Antelope and Buffalo Springs were up to 19 ft (Table 2).

Water-level declines over the model domain for the “ $EPS=0.200$ acre-ft per acre per year” simulation were contoured using the ArcMap 10.0 ordinary kriging routine, linear semivariogram model; the locations of the contours are therefore approximate (Figure 7). This information may help stakeholders better understand the effects of this simulation in other areas of concern.

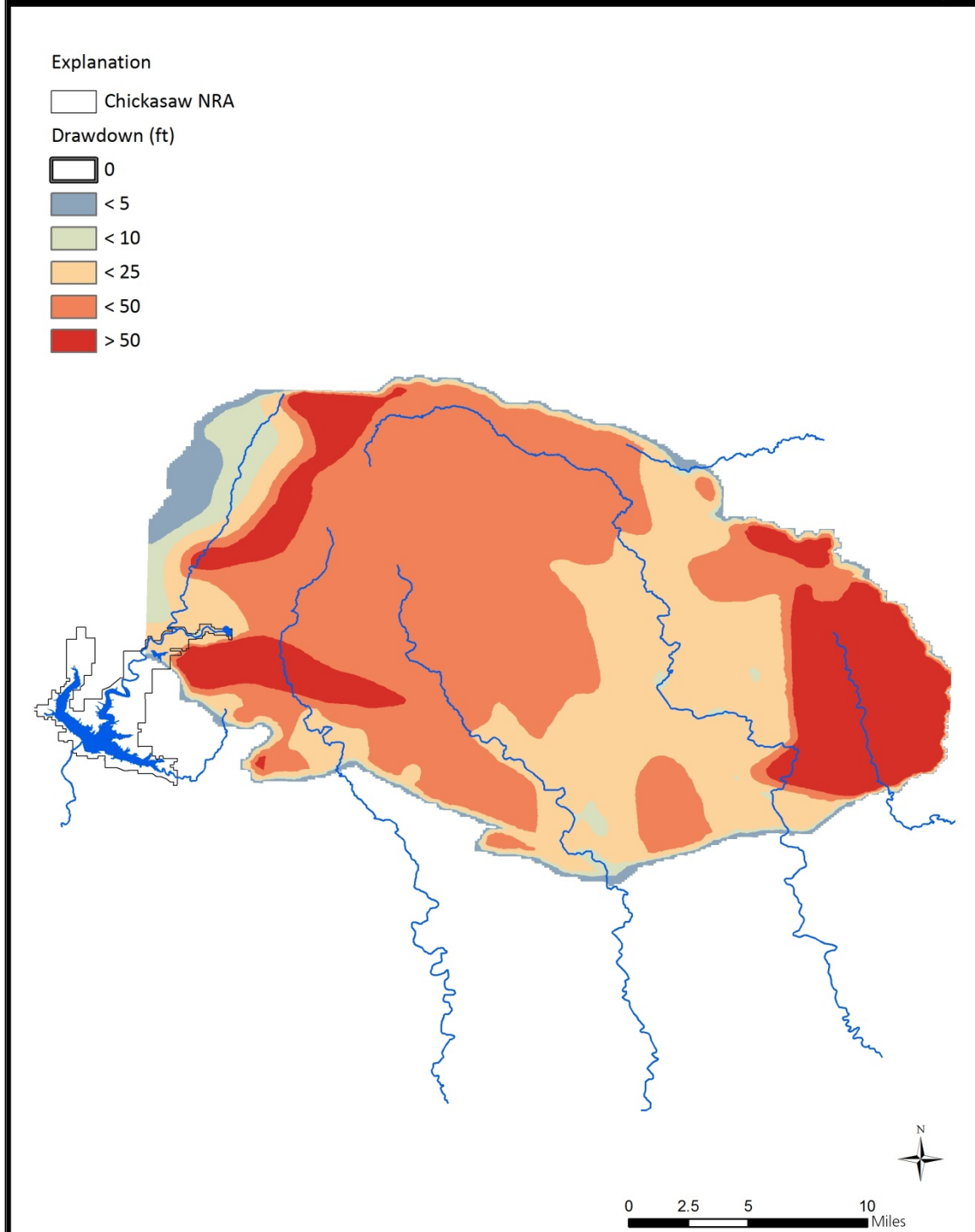


Figure 7. Water-level declines based on MODFLOW-simulated groundwater withdrawals distributed as an equal proportionate share of 0.200 acre-ft per acre per year.

Well Set-Back with EPS = 0.200 acre-ft per acre per year

As noted above, the OWRB's March 13, 2012 Tentative Order also determined that rules concerning a well set-back from springs and streams should be promulgated to protect these resources from the cumulative effects of existing and proposed wells (OWRB 2012). No information was provided in SIR 2011-5029 about the effectiveness of a well set-back on protecting discharge from springs and streams. The NPS, therefore, used the MODFLOW model to test a 2-mi and 5-mi well set-back around Antelope Spring. ESRI ArcMap 10.0 was used to identify the model nodes within a given radius around Antelope Spring. The *arbsimmay.eps0.200.wel* MODFLOW input file created for the "EPS = 0.200 acre-ft per acre per year" simulation was modified so that $Q = 0 \text{ m}^3/\text{day}$ at the nodes within the well set-back area. The model was run in successive 5-water-year periods until simulated average base flow for Travertine Creek changed by 0.10% to ensure a new equilibrium state was reached.

A 2-mi well set-back reduced average annual groundwater withdrawals by only 591 acre-ft and did not significantly restore base flow or water levels in Chickasaw NRA (Table 2; Figure 6). A 5-mi well set-back reduced average annual groundwater withdrawals by 6,916 acre-ft, but limited the depletion of average base flow to Travertine Creek to less than 10% relative to the "Reported water use" simulation (Table 2; Figure 6).

Comparison of Figures 7 & 8 indicates that the 5-mi well set-back around Antelope Spring buffers springs and streams in Chickasaw NRA to a certain extent from the effects of distributed groundwater withdrawals. It is worth noting that implementing a 5-mi well set-back around Antelope Spring with an EPS = 0.200 acre-ft per acre per year limited depletions of average base flow for Travertine Creek to less than 10%, while allowing more groundwater to be withdrawn from the aquifer than an EPS = 0.125 acre-ft per acre per year with no well set-back (Table 2).

Conclusions

The OWRB's March 13, 2012 Tentative Order for Maximum Annual Yield Determination indicates that a reduction in base flow for Blue River and Pennington Creek of not more than 25% would be an acceptable impact (OWRB 2012). Although the NPS does not apply the same criteria to determine if a proposed action will cause adverse impacts to park resources, using the eastern Arbuckle-Simpson aquifer MODFLOW groundwater-flow model to evaluate if the OWRB's criteria would be met with respect to water resources in Chickasaw NRA allows the NPS to engage constructively in the state's process for allocating groundwater, and assists the NPS in determining if additional measures will be needed to protect water-related resources should the proposed action be implemented.

The model is sufficiently refined in the area of Chickasaw NRA to provide useful information about the potential adverse impacts of regionally distributed groundwater withdrawals on discharge to major springs and streams in the park. The model was optimized to simulate the effects on Blue River and Pennington Creek, so only the magnitude of the depletion in base flow to these streams can be considered calibrated. However, the model is suitable for simulating long-term average base flow for Travertine Creek. Likewise, the magnitude of simulated water-level declines in the Arbuckle-Simpson aquifer due to groundwater withdrawals are not considered calibrated, but the simulated changes in head are useful for understanding the potential range of water-level declines due to various groundwater-withdrawal scenarios.

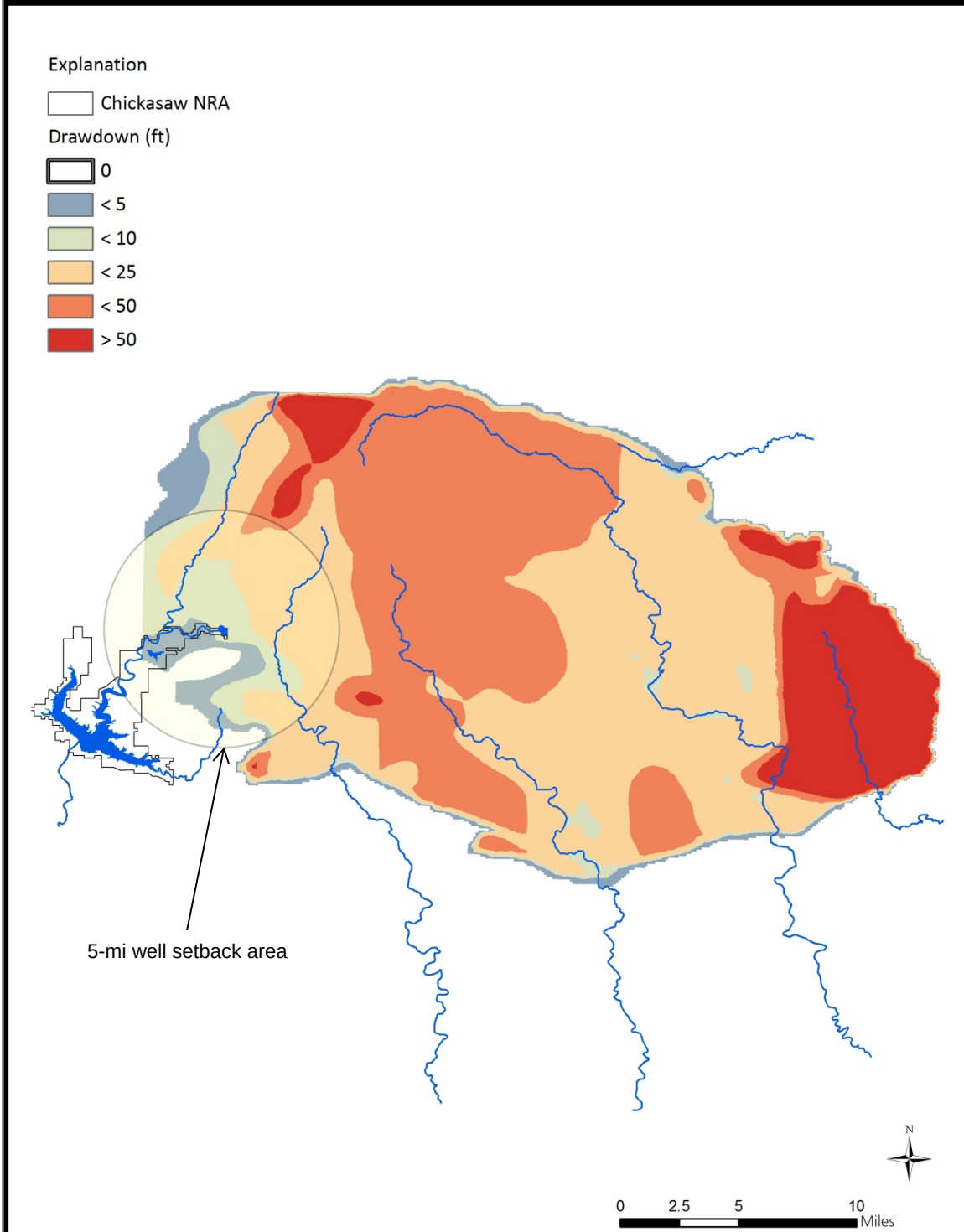


Figure 8. Water-level declines based on MODFLOW-simulated groundwater withdrawals distributed as an equal proportionate share of 0.200 acre-ft per acre per year, with a 5-mi well set-back around Antelope Spring in Chickasaw NRA.

Because the aquifer system is represented as entirely confined, groundwater discharge is sensitive to changes in recharge and discharge, and the simulated streamflow depletions due to groundwater withdrawals may be considered a high-impact scenario.

Daily average base flow for Travertine, Rock and Wilson Creeks was calculated from the model output for all simulations described in this report. According to the results of these simulations, existing nearby withdrawals, as well as proposed distributed withdrawals from the eastern Arbuckle-Simpson aquifer, have the potential to deplete spring flows and base flow to streams in Chickasaw NRA. The “Reported water use” simulation indicates that the base flow for Travertine Creek could be depleted by about 10% within five years at the current rate of withdrawal from the Arbuckle-Simpson aquifer.

If distributed withdrawals are allocated as an EPS = 0.200 acre-ft per acre per year, base flow for Travertine Creek could be depleted by an additional 28%. A 5-mi well set-back has a greater effect on protecting base flow for Travertine Creek than the lower EPS = 0.125 acre-ft per acre per year with no well set-back.

At the time of this report, it is not known whether the maximum annual yield based on an EPS = 0.200 acre-ft per acre per year will be implemented for the Arbuckle-Simpson Groundwater Basin. Regardless, the model simulations indicate that actions to reduce groundwater withdrawals within five miles of Chickasaw NRA will aid in protecting base flow for Travertine Creek and discharge to Antelope and Buffalo Springs. Confidence in the ability of the model to accurately simulate the potential effects of withdrawals on water resources in the park could be improved by analyzing the sensitivity of the model results to the no-flow boundary. The uncertainty of the short-term effects of nearby and/or concentrated groundwater withdrawals on water resources in Chickasaw NRA can be reduced by improved characterization of hydraulic properties in the vicinity of the park. This can be accomplished by performing aquifer tests and further evaluating environmental fluctuations in water-levels in wells in this area.

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