Ozark Plateau Aquifer Hydrologic Report, MODFLOW Model Results, and Safe Yield Determination

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I. EXECUTIVE SUMMARY

Throughout the Tri-State region of southeast Kansas, southwest Missouri, and northeastern Oklahoma, the Ozark Plateau aquifer system is an important source of water. Concerns on the quantity and quality of water available within the aquifer system prompted Chief Engineer David Pope to place a moratorium on new, permanent appropriations from the aquifer system within southeast Kansas in 2004 until further studies could be completed per K.A.R. 5-3-29 (Kansas 2010).

The U.S. Geological Survey (USGS), with funding by the state of Kansas and the participation of state agencies in a technical advisory committee, completed a groundwater flow model of the Ozark Plateau aquifer system in 2009. Using MODFLOW software, the model is able to better assess the effects that increased water use is having on the long-term availability of groundwater within the Tri-State area. From this model, the Kansas Department of Agriculture, Division of Water Resources (KDA-DWR) determined that additional groundwater beyond the current pumping level is available for appropriation in southeast Kansas.

Therefore, KDA-DWR performed supplemental model runs utilizing the USGS model to determine the additional amount available within the safe yield of the Ozark aquifer. The chief engineer determined that the safe yield for this area would be defined as pumping that could be sustained without reducing storage in the Ozark aquifer by more than 25 percent over the next 100 years. To determine the safe yield, a series of model runs were developed with increased pumping in multiples of the current authorized quantity, while Missouri and Oklahoma were held at two times existing pumping. Based on these scenarios, the Ozark Plateau aquifer safe yield has been determined to be at least 36,000 acre-feet per year, or approximately three times the currently authorized amount. In addition, when determining if future applications should be approved, a localized 2-mile safe yield test will also be performed, so the overall limitation will vary locally. In this way, additional growth may occur within a reasonable boundary.

Continued monitoring of the hydrologic conditions summarized in this report is essential to the management of this area for the long-term as the safe yield could be re-evaluated at a future time based on the improved data. This is due to the short duration of the groundwater monitoring network and the water quality measurements currently available. The hydrologic data in conjunction with the groundwater model allows for continued management to meet safe yield into the future.

DWR staff believes the safe yield determination contained herein is conservatively estimated and should allow for development from the aquifer system in the area for some time to come. Staff recommends that as the total appropriations of the aquifer system approach the estimated safe yield, that an update to the safe yield determination be made based on the actual development and updated data and methods available at that time.

II. INTRODUCTION

This document provides a historical summary and background information on the Ozark Plateau aquifer system. The report includes data analysis by the Basin Management Team (BMT) and other technical staff of the Division of Water Resources (DWR) for both ground and surface water within the Ozark moratorium area in Kansas. A summary of the USGS Ozark Plateau aquifer groundwater model and the supplemental model work from DWR is also included. The moratorium area includes portions of the Neosho and Spring Rivers, as well as two aquifer systems, the upper Springfield Plateau aquifer and the lower Ozark aquifer, which are separated by a discontinuous confining layer.

BMT was created in 1993 by KDA-DWR to analyze aquifers and stream systems in targeted areas and collaborate with stakeholders to develop and assess water resource management tools and strategies to protect water rights and improve hydrologic sustainability. The targeted areas are hydrologic subbasins designated by the State Water Plan as having water resource challenges. BMT works with federal, state, local agencies and private entities to establish and implement management strategies.

The Ozark Plateau, also referred to as the Ozark Mountains, covers approximately 47,000 square miles through the four state region, which includes Oklahoma, Arkansas, Missouri and Kansas. The Ozark Plateau makes up the widest mountainous expanse found between the Rocky and Appalachian mountains and is divided into four basin/mountainous regions. These four regions include the Springfield Plateau, Salem Plateau, Saint Francois Mountains and Boston Mountains (Figure 1). Of these four regions, only a small portion of the Springfield Plateau extends into the furthest southeastern corner of Kansas in all of Cherokee and Crawford counties, and parts of Linn, Bourbon, Allen, Neosho, and Labette counties.

There are several issues concerning the quality and availability of groundwater in southeast Kansas. The Ozark aquifer is the main source of groundwater to area municipalities and rural water districts within southeast Kansas due to the contamination of the overlying Springfield aquifer from prior extensive mining. However, the quantity of water within the Ozark aquifer was not well understood and the quality is at risk in southeast Kansas, not only from the overlying Springfield aquifer, but also from an underlying brine layer (salt water) that is moving laterally across a transition zone and could potentially adversely affect groundwater quality in areas of significant pumping (Figure 2). Furthermore, the projected increase in population will place further demands on the aquifer system and surface water sources.

A study was initiated in Missouri by Missouri American Water Company after concerns were raised about groundwater pumping from the aquifer and the future availability of groundwater supply to meet projected demands. The study by Wittman and Associates, released in 2003, concluded that the groundwater system may be unable to meet the demands 10 years into the future under drought conditions (Wittman, 2003). Based on this study and concerns of groundwater declines during drought conditions that occurred in Missouri, the Neosho River Basin Advisory Committee requested that the Kansas chief engineer of DWR study the groundwater system for both quantity and quality concerns.

This prompted further study including the USGS groundwater model, the re-establishment of a monitoring well network, and the placement of a moratorium on groundwater appropriations within southeast Kansas in 2004. With the release of the USGS groundwater model and the model work by DWR, a greater understanding of the aquifer has been acquired and appropriate management decisions have been made.

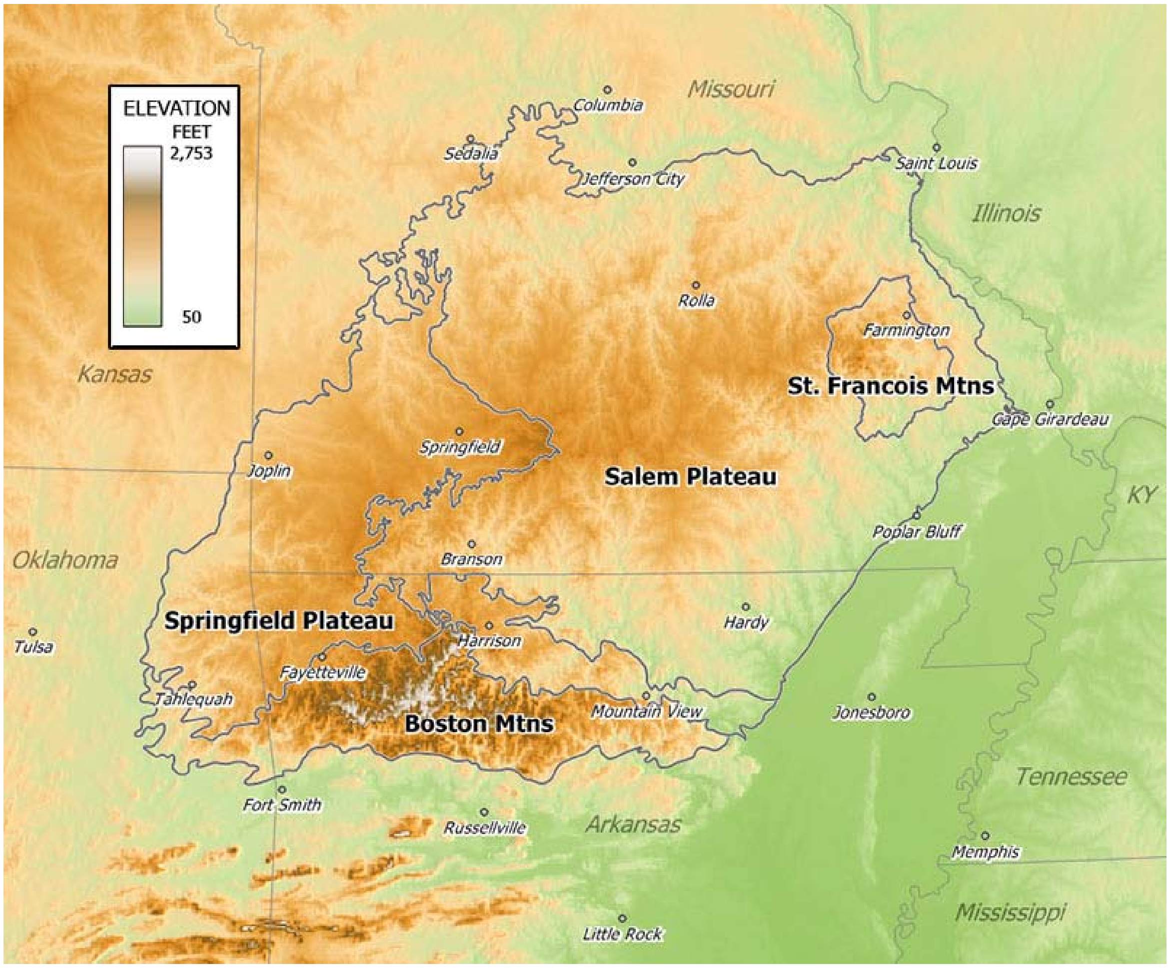

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Figure 1: Ozark Plateau Extent

A. History of the Moratorium Area

In 1945, the State of Kansas adopted the prior appropriation doctrine system of water law common to the Western United States. This dramatically changed water law in Kansas, which had been previously managed under the riparian system. A significant portion of ground and surface water flowing into southeast Kansas originates from Missouri, which is under the riparian system. In Missouri, the riparian system allows land owners reasonable use of the water that is underlying or contiguous to their property. Reasonable use requires that other users and landowners not be overly adversely impacted (Missouri DNR 2006).

However, the prior appropriation doctrine recognizes that in times of drought, not all water rights will be satisfied, so the beneficial use of water is based on a priority system. In Kansas, water belongs to the public and is allocated by the state under the Kansas Water Appropriation Act (KWAA). The state requires non-domestic users to apply for and receive a permit for water use as specified in the KWAA.

Water rights established under the riparian system prior to the KWAA of June 28, 1945 were reviewed and established as vested rights; all vested rights have the same priority unless adjudicated. Any water right obtained and developed after that date has a priority based on the time the application was received and are referred to as appropriated water rights. The prior appropriation act's basic principle is "first in time, first in right" (Kansas 2010, K.S.A 82a-707c). In areas with uncertainty, or limited water, or under drought conditions when supply cannot meet demand, owners of junior, or most recent, water rights are restricted to ensure water for senior (older) rights when administration is required.

Due to the uncertainty about the availability of the water supply within the Ozark aquifer, as well as water quality concerns, a moratorium on new appropriations was put into effect in 2004 by KDA-DWR. The moratorium closed the Ozark aquifer and the Springfield Plateau aquifer to new groundwater appropriations except for specified exceptions such as domestic use, requests less than 5 acre-feet (Kansas 2010, K.A.R. 5-3-16a) and temporary and term permits.

Moratorium term permits were allowed to be filed as long as the availability of a primary supply was demonstrated. K.A.R. 5-3-29 established the moratorium and set a December 31, 2010 deadline for completion of a study and the evaluation of moratorium term permit status. With the aid of a groundwater model, as discussed in section V, the study determined that moratorium term permits did not cause safe yield to be exceeded or impair senior rights and can become regular appropriations. The groundwater model serves as a support tool for KDA-DWR to make management decisions.

The Ozark moratorium area, or regulation boundary, extends through ranges 20 east through 25 east and townships 26 south through 35 south (Kansas 2010, K.A.R. 5-3-29). Counties within the area include all of Cherokee and Crawford Counties, and parts of Allen, Bourbon, Labette and Neosho Counties (Figure 2). River basins involved in the area are all of the Spring River basin, the southern half of the Marmaton River basin, and a small section of the eastern lower Neosho River basin. The two major river systems flowing through the area are the Neosho River and the Spring River.

The lower Neosho River flows through Neosho and Labette counties, and briefly flows through the southwest corner of Cherokee County before flowing out of Kansas into Oklahoma. The Spring River enters Kansas from Missouri on the eastern side of Cherokee County, flows through Cherokee County, and exits the state at the southern part of the county into Oklahoma (Figure 2).

In order to ensure streamflow and protect habitat, the Kansas legislature amended the KWAA to establish Minimum Desirable Streamflow (MDS) on certain watercourses in Kansas in 1984, which includes the Neosho and Spring Rivers at specific locations (Kansas 2010, K.S.A. 82a-

703c). MDS was established on the Neosho River at Iola, Kansas and also at Parsons, Kansas. The KDA-DWR utilizes the USGS gage located near Parsons, Kansas, to administer MDS on the lower Neosho River for the stream reach from Iola to Parsons. The Spring River USGS gage located near Quapaw, Oklahoma has been used to administer MDS at Baxter Springs, KS.

If streamflow drops below the specified value at a minimum desirable streamflow gage station for seven consecutive days the chief engineer has the authority to take action to meet MDS with consideration to hydrologic conditions, streamflow contribution, drought, magnitude of effect, and reservoir operations (Kansas 2010, K.A.R. 5-15-1(d)). Individuals with water rights or approvals of applications prior to April 12, 1984 may continue to divert water as necessary. Rights junior to that date must cease pumping until MDS administration is ceased. This occurs when flow at the gage exceeds the MDS criteria for a period of 14 consecutive days or when hydrologic conditions indicate that MDS criteria will be met for the foreseeable future.

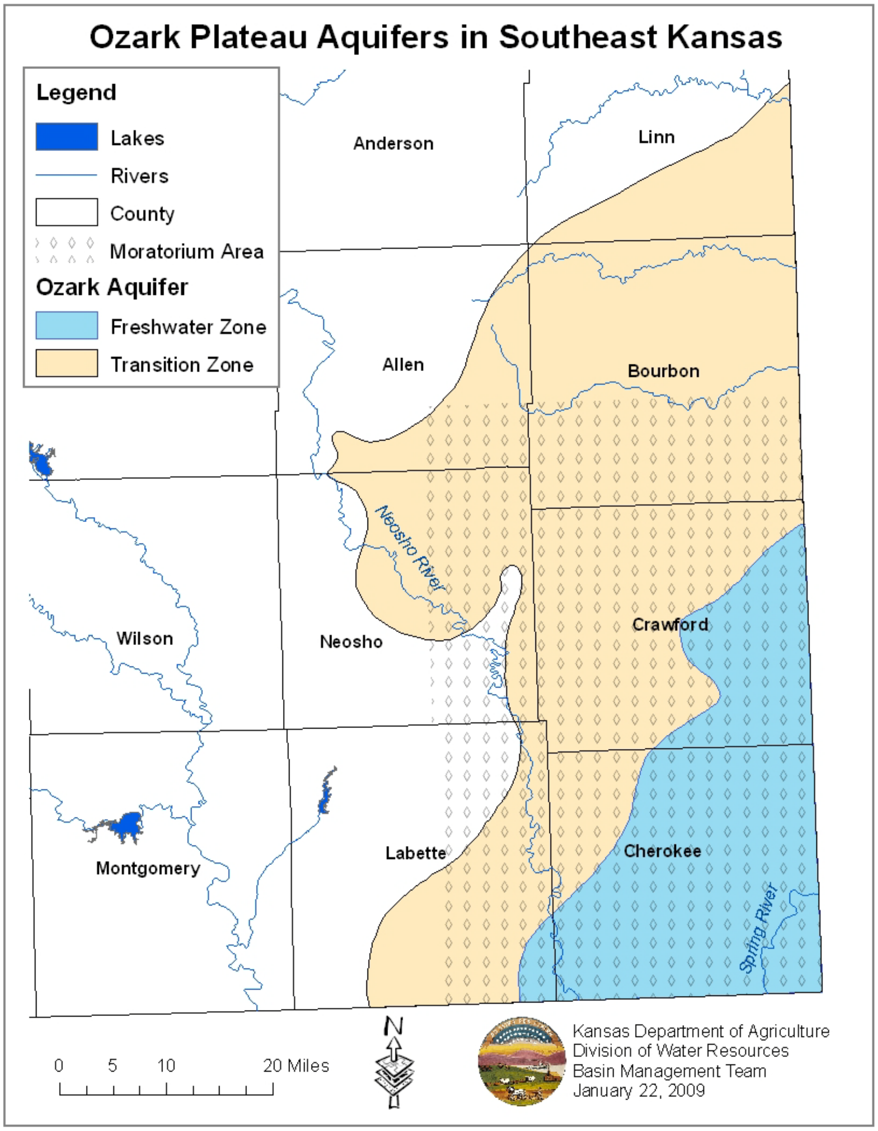

Figure 2: Ozark Plateau Aquifer showing the Moratorium Area, Freshwater and Transition Zones

Mining History

Historically, the groundwater in southeast Kansas was used primarily for lead and zinc mining and milling activities. Many of the rock layers that were mined were aquifers, or water-bearing formations. During the 100 year span from about 1870 to 1970, mining activities played an important economic role for southeast Kansas, as well as parts of Missouri and Oklahoma. Mining operations focused on the extraction of coal, lead and zinc (Sawin et al. 2006). Figure 3 shows the impact that surface mining had on the landscape in southeast Kansas.

Mining left the environment contaminated with heavy metals such as lead, zinc, and cadmium. After the cessation of mining activities in the early 1970s, many mining shafts and surface mining pits were abandoned. Some of these abandoned mines created potential property and health hazards resulting from sinkholes and the contamination of surface water, groundwater, soil and air. In southeast Kansas, parts of Cherokee County including the towns of Galena and Baxter Springs were significantly impacted. Since most mining companies had disbanded years before, cleanup/reclamation responsibility was placed under federal, state, and local entities (Sawin et al. 2006).

With the decline of the mining industry in the mid 20th century, the main use of groundwater within the moratorium area in Kansas is from the deeper Ozark aquifer. In Galena, KS two new wells were constructed within the Ozark aquifer to ensure safe drinking water and a rural water district was established to provide supply. This was required due to the contamination of surface water and the overlying Springfield Plateau aquifer that occurred from mining practices. Currently, primary uses of the Ozark aquifer are drinking water, municipal and industrial use (Sawin et al. 2006).

Figure 3: Surface (strip mining) near West Mineral, KS

Photo by Thad Allendar taken from Lawrence Journal World. *Mining's Legacy A Scar on Kansas.* 30 Oct 2008 <http://www2.ljworld.com/news/mining/>

B. Water Appropriation and Use

A variety of water uses exist within the Ozark moratorium area including industrial, municipal, recreational, and irrigation. There are 237 active groundwater and surface water rights within the Ozark moratorium area. Groundwater rights include vested, appropriated, and term permits. Table 1 shows the approximate currently authorized quantities of water for each source of use as well as the average use from 1990-2008. In addition, the percent in the table shows on average how much of the currently authorized quantity has been used. For instance, groundwater use is at about 63 percent of authorized quantities. As a note, included in the "other" use under the Spring River surface water is Jayhawk Fine Chemicals Corporation's water right for fire protection. Although this water right authorizes the beneficial use of a substantial quantity of water, at 46,217 acre-feet, insignificant actual use related to testing of fire suppression equipment occurs annually.

Table 1: Authorized Quantity, Average Quantity Used, and Percent of Authorized Use from 1990-2008 (all quantities in acre-feet)

Source	Authorized AF	Average AF Used	% of AF Used
Ozark and Springfield Groundwater	11,758	7,435	63%
Spring River Surface Water[1]	226,599	108,377	48%
Neosho River Surface Water	19,407	5,724	29%
Total	**257,764**	**121,536**	**47%**

Of the current total appropriated amount of 257,764 acre-feet, the average use for the years 1990-2008 was 121,536 acre-feet, or about 47 percent of the total amount authorized (Table 1). Figure 4 shows a breakdown of the authorized amounts by category and allows us to visualize the main water uses within the moratorium area per surface and groundwater rights.

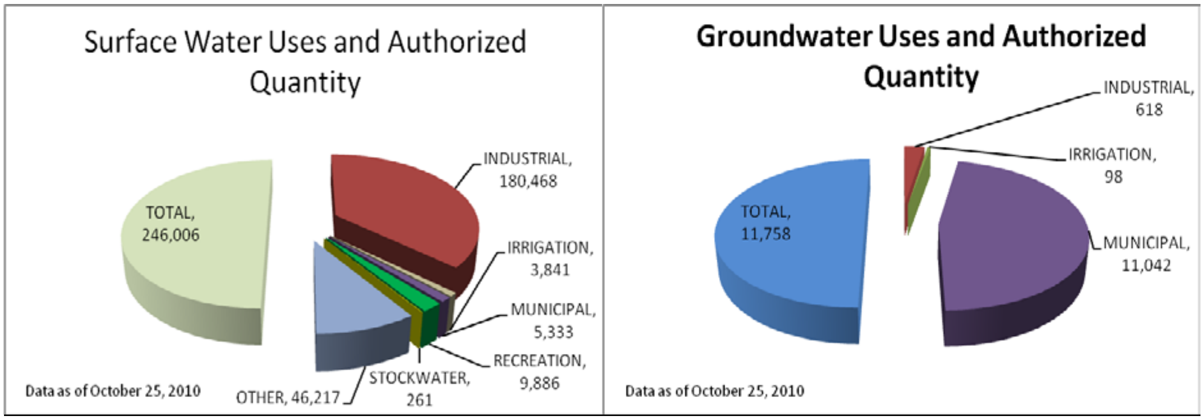

Figure 4: Moratorium Area Surface and Groundwater Use per Category and Authorized Quantities (given in acre-feet)

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[1] The authorized acre-feet and average acre-feet of use for the Spring River include the amount of water that is diverted for industrial use by the Empire District Electric Company. The operations at the plant are largely flow-through cooling and a large portion of this water is discharged back into the Spring River.

III. PHYSIOGRAPHY

A. Climate

Kansas is centrally located on the North American continent; therefore, it experiences extreme weather conditions. The continental climate of the region is characterized by large monthly, seasonal and annual variations in weather including precipitation and temperatures.

In Kansas, the main source of precipitation originates in the Gulf of Mexico and the subtropical Atlantic Ocean. Some moisture also comes from the Pacific Ocean, but the moisture must travel over several mountain ranges before reaching Kansas, thereby losing moisture to the rain shadow effect. The sources of rainfall also control the amount and season of precipitation. Greater precipitation is seen in Kansas during the summer months. During the summer, southerly winds carry moisture from the Gulf of Mexico and only face a minor hindrance of the Ouachita Mountains in Oklahoma and Arkansas. The precipitation tends to shift eastward due to the Westerlies in the midlatitudes. This brings less precipitation to the northern and western parts of the states; however, it brings more rainfall to southeastern Kansas and the Ozark Plateau region of the state. The Gulf of Mexico moisture influence brings about 75 percent of the area's precipitation between April and September. On average, the wettest month is June and the driest month is January.

Precipitation tends to form when a cold air mass moving south and a warm, moist air mass moving north meet. These rainstorms are either thunderstorms that cover relatively small areas and produce intense rains of short duration or storms that last for several days and cover a large area.

Temperatures also range widely from winter to summer. During the summer, the area experiences intense solar radiation and during the winter strong arctic masses descend into Kansas. Each year of record in Kansas has seen temperatures above 100 degrees Fahrenheit and below 32 degrees Fahrenheit.

Due to the location of the Ozark region in southeast Kansas, weather varies greatly, and drought can be a concern. Therefore, it is important to have a stable source of groundwater and surface water in this region of Kansas. In not only southeast Kansas but also parts of southwest Missouri, northeast Oklahoma, and far northwest Arkansas, the Ozark Plateau aquifer system serves as an important source of freshwater to municipal water supplies, industry, and agriculture.

B. Mining Area

The Ozark Plateau contains a Precambrian granite core that is covered by Ordovician and Devonian deposits and younger sediments of Mississippian age (Macfarlane 2005). Within the younger Mississippian sedimentary rock units are contained the minerals that led to a lot of the mining in the Tri-State area. About 345 million years ago these Mississippian aged rocks were deposited as sediment in a shallow sea (Sawin et al. 2006).

The rocks, composed mainly of limestones and chert, were exposed to erosion over time. The softer limestone was leached from the beds leaving the more resistant chert, which produced a landscape of caverns and sinkholes called karst topography. Following the period of erosion, the seas returned during the Pennsylvanian Period, which occurred 323 to 290 million years ago, and capped the Mississippian rocks with shale. Mineral-laden solutions deposited zinc, lead, and other minerals into some of the karst features within the Mississippian rocks. The shale served as an impermeable layer that forced metal-bearing solution to expand laterally (Sawin et al. 2006). These deposits created the lead and zinc ore that were mined for about a century.

C. Aquifers

The Ozark Plateau aquifer system is subdivided into the Springfield Plateau aquifer, the upper aquifer, and the Ozark aquifer, the lower aquifer. In Kansas, the two aquifers are separated by the Ozark confining unit (Figure 5). The Springfield Plateau aquifer is composed of Mississippian-age rocks that have been historically mined for lead and zinc. The Ozark aquifer, which is located below the confining unit, occupies Ordovician-age rock.

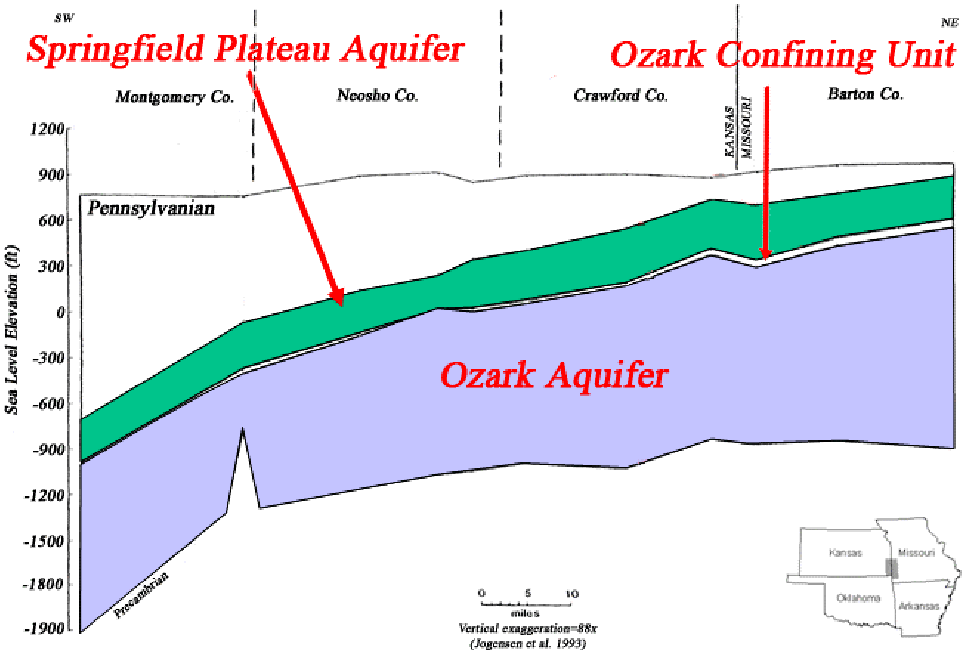


Figure 5: Springfield and Ozark Aquifers separated by the Ozark Confining unit
Figure taken from Kansas Geological Survey Open File Report 2007-20 *The Southeast Kansas Ozark Aquifer Water Supply Program*.

Springfield Plateau Aquifer

The Springfield Plateau aquifer is composed of Mississippian limestones and cherts with a thickness range of 200 to 400 feet thick in the Tri-State region of southeast Kansas, southwest Missouri, and northeast Oklahoma. In Missouri, extreme southeast Kansas, and parts of Oklahoma these rocks are exposed at the surface and are capped by Pennsylvanian shales farther to the west (Sawin et al. 2006). The strata that form the Springfield Plateau aquifer are at the surface in southeast Cherokee County, and the top of the Ozark aquifer is within 300 feet of the surface. At Pittsburg, KS the top of the Springfield Plateau aquifer is within 200 feet of the surface, while the depth to the top of the Ozark aquifer is about 450 feet (Macfarlane 2005).

Most of the recharge occurs to the Springfield Plateau aquifer in the form of precipitation where the rocks crop out at the surface (Imes 1994). The water then enters the aquifer and moves underground to the west where it discharges into the Spring and Neosho Rivers. In addition, the aquifer is also recharged by surface water entering lead and zinc mining-related shafts and pits. These mining shafts have allowed contaminated water to move from the surface into the aquifer. In the late 19th century, the Springfield Plateau aquifer was pumped to dewater the mines. As a result of this dewatering, the sulfide minerals oxidized, and when the mines refilled, this allowed the sulfide minerals to dissolve into the water. Consequently, there are higher concentrations of contaminants in local areas of the Springfield Plateau aquifer (Sawin et al. 2006).

Ozark Aquifer

The Ozark aquifer is composed of a thick sequence of water-bearing dolomites, limestones, and sandstones of the Cambrian and Ordovician age. Locally it is referred to as the Roubidoux aquifer named after the Roubidoux Formation, which is a significant water producing zone within the Ozark aquifer (Sawin et al. 2006). Throughout the Tri-State region the thickness of the Ozark aquifer varies from 800 to 1,500 feet, generally increasing from northwest to southeast (Imes 1994). In southwest Missouri the strata that forms the Ozark aquifer is at the surface or at shallow depths with increasing depth in the direction of southeast Kansas. The topographically higher region of southern Missouri where the aquifer's rocks crop out near Springfield, Missouri, serves as the recharge area for the Ozark aquifer (Sawin et al. 2006).

The outcrop area serves as a route for rainwater to enter the aquifer where it moves by gravity in a westerly direction into the deeper part of the aquifer in southeast Kansas and northeast Oklahoma. There it encounters saltwater moving east from deeper rocks in western Kansas and Oklahoma (Imes 1994). These deeper rocks are referred to as the Arbuckle group, which is an important source of hydrocarbons further west. Stretching northeast to southwest across the region where these two water masses meet, lays a 20-30-mile-wide fresh-to-saline transition zone (Sawin et al. 2006). As mentioned before, there is concern that significant groundwater pumping could potentially cause upwelling of brines within the aquifer that decrease the water quality. Rocks of the Precambrian age confine the Ozark aquifer from below (Macfarlane 2005).

Ozark Confining Unit

Above the Ozark aquifer is the Ozark confining unit that largely separates the aquifer from the overlying Springfield Plateau aquifer. It is composed of shale, dense limestones and dolomites that are Devonian and Mississippian in age (Imes 1994). In most regions the confining unit forms an effective permeability barrier; however, there are a small number of regions where these confining rocks are absent. Here the potential lies for mining-related contamination from the Springfield Plateau aquifer to enter the Ozark aquifer (Sawin et al. 2006).

IV. ANALYSIS

A. Precipitation

Precipitation in the Ozark Plateau area in Kansas averages 41 inches per year based on six precipitation stations. Figure 6 shows the annual variation in precipitation; the red line represents the average rainfall. This chart was derived from National Climatic Data Center (NCDC) stations located in Columbus (Cherokee County), Erie (Neosho County), Fort Scott (Bourbon County), Moran (Allen County), Parsons (Labette County) and Pittsburg (Crawford County). The data is downloaded then averaged to create the following chart.

In 1985, the highest precipitation total occurred with 59 inches. In contrast, the lowest precipitation occurred in 1963 with 22 inches. It is not uncommon to have sufficient rainfall followed by periods of lesser rainfall. For instance, in 1951 the rainfall amount was above average at 54 inches, but it was followed by a subsequent drought with rainfall only totaling 25 inches in 1952. In 2007 and 2008, the precipitation total was 53 inches and 54 inches respectively, which is above average. Annual precipitation data for these NCDC stations is currently available through 2008.

Precipitation does have a direct effect on streamflow and recharge to the Springfield aquifer, as these areas are open to receive precipitation in southeast Kansas. However, as mentioned before, the Ozark aquifer is largely recharged near Springfield, Missouri where the rocks crop out at the surface. Therefore, precipitation falling in southeast Kansas provides minimal recharge to the Ozark aquifer, as it is largely separated from the Springfield aquifer by the confining layer. With the release of the groundwater model, surface water and groundwater interactions, as well as recharge, is better understood.

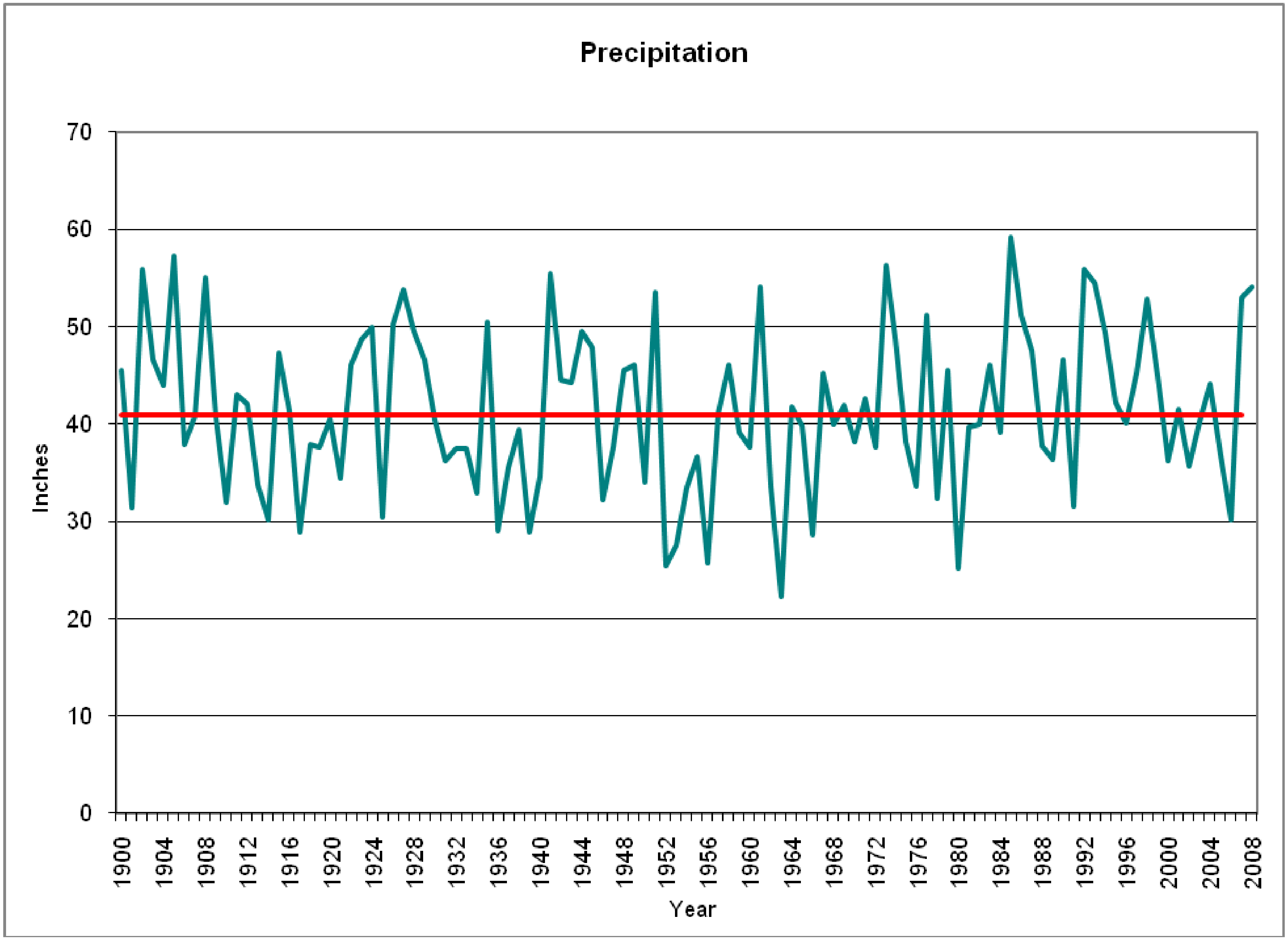


Figure 6: Average Ozark Precipitation 1900-2008

B. Groundwater

Water Rights

The area queried for water rights was Ozark and Ozark Plateau wells located in the Ozark moratorium area. This area has a total of 109 active water rights with a groundwater source. The approximate total authorized amount to these water rights is 11,758 acre-feet (Table 2).

Table 2: Groundwater Rights and Acre-Feet Appropriated

Type	Number of Rights	% Rights	Authorized AF	% AF
Vested	14	13%	2,111	18%
Appropriated	83	76%	8,340	71%
Moratorium Terms	12	11%	1,307	11%
Total	**109**		**11,758**	

All rights with proven beneficial use prior to June 28, 1945 were established as vested water rights. There are 14 vested water rights, which account for about 13 percent of total groundwater rights within the Ozark moratorium area. The authorized quantity for vested groundwater rights is only 2,111 acre-feet, or 18 percent of the total authorized quantity. The appropriated groundwater rights total to 83, or 76 percent of the water rights. In addition, the authorized quantity is 8,340 acre-feet, or 71 percent of total authorized quantity. At the time of this report there are 12 groundwater term permits with an authorized quantity of 1,307 acre-feet. The City of Pittsburg has four term permits with 918 acre-feet authorized. Not all of the quantity authorized under the moratorium term permits is an outright quantity, as some allow for the flexibility in the pumping of wells. The authorized quantity and average use per groundwater right holder is shown in Figure 8.

Reported Water Use

Figure 7 shows the approximate total reported groundwater use within the moratorium area by year from 1990 to 2008 for active groundwater rights. The approximate average reported water use during this time frame is 7,435 acre-feet. The average use divided by the currently authorized amount, shows us that about 63 percent of authorized groundwater quantities are being used.

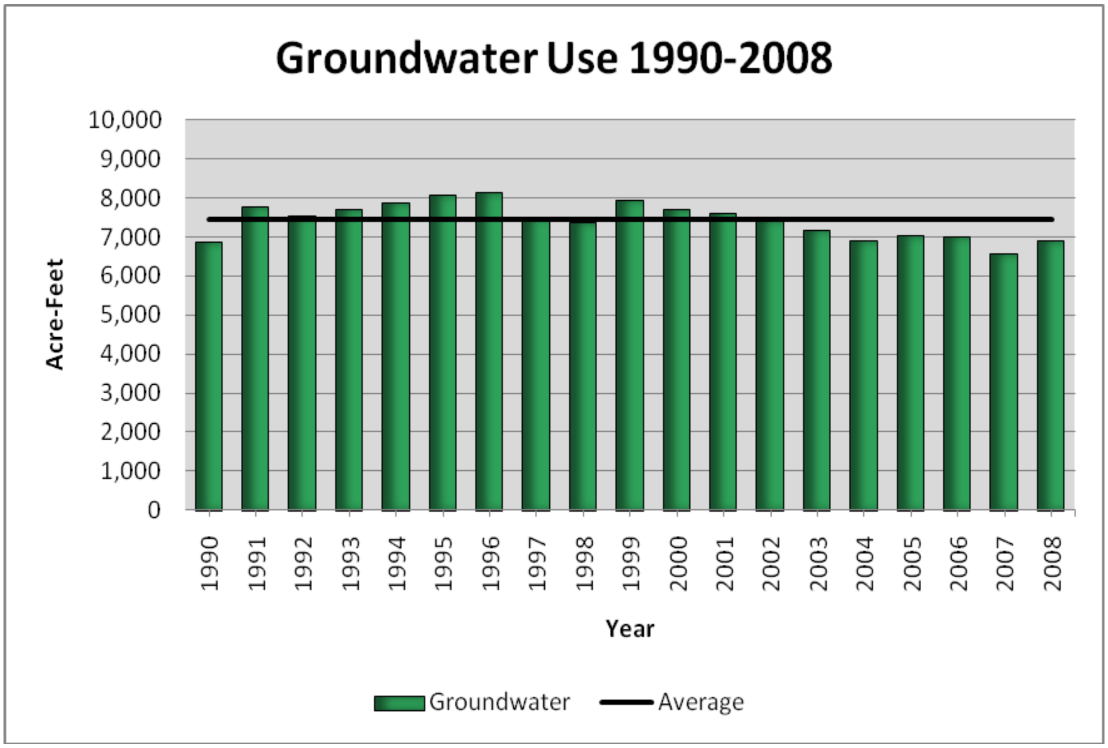
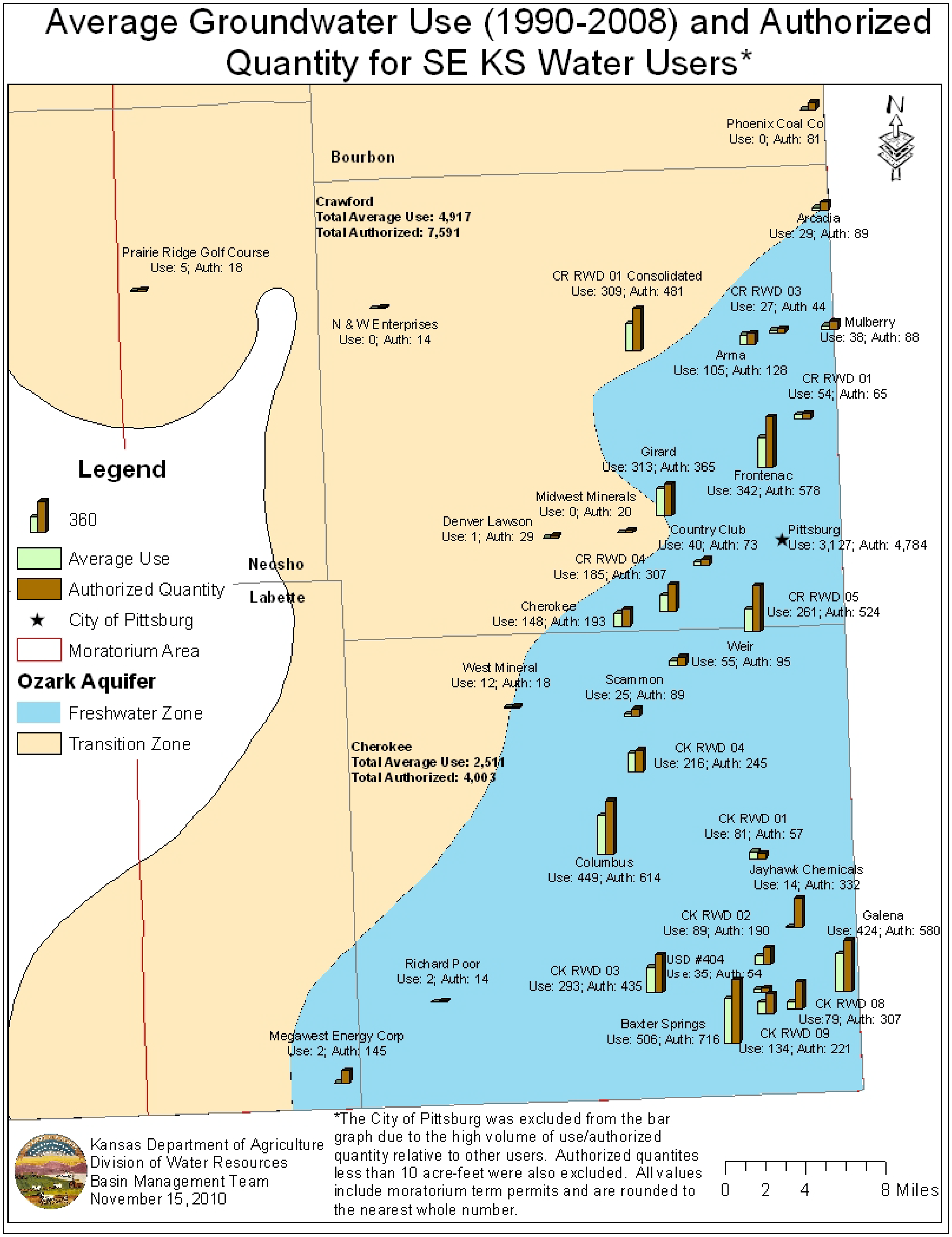


Figure 7: Reported Groundwater Use for Ozark Moratorium Area 1990-2008


Average Groundwater Use (1990-2008) and Authorized Quantity for SE KS Water Users*

Kansas Department of Agriculture
Division of Water Resources
Basin Management Team
November 15, 2010

*The City of Pittsburg was excluded from the bar graph due to the high volume of use/authorized quantity relative to other users. Authorized quantites less than 10 acre-feet were also excluded. All values include moratorium term permits and are rounded to the nearest whole number.

Figure 8: Moratorium Area Groundwater Users, Authorized Quantity, and Average Use

Monitoring Wells

In 2004, a groundwater well monitoring network was re-established for the Ozark aquifer moratorium area (Figure 9). The network consists of 24 wells that are screened within the Springfield Plateau aquifer, the Ozark aquifer, or both aquifers (referred to as the Ozark Plateau aquifer). The wells are measured on a quarterly basis. There are no known monitoring wells solely screened in the Springfield Plateau aquifer besides the dedicated observation well at Pittsburg, Kansas.

Also, in order to detect the potential eastward movement of salt water, a network consisting of 12 wells has been established within the network from which water quality samples are taken quarterly. Lastly, three continuous monitoring wells have been drilled. Two of the monitoring wells are located in the Ozark aquifer at McCune and Pittsburg and one is located in the Springfield Plateau aquifer, also located at Pittsburg. All three wells have transducers installed and are equipped with satellite telemetry capabilities. The re-established network of 24 wells plus the three continuous monitoring wells total 27 wells measured by KDA-DWR.

When looking at historical data for the wells, there is little water level data to compare current water levels to. In the future, five-year rolling averages will be prepared. In reviewing the data, fall measurements (September, October, and November) seemed to be the most consistent time in which groundwater levels were taken; therefore, they were used for this analysis. Figures 10 through 12 chart the groundwater levels in the Ozark and the Ozark Plateau aquifer. Well depths and water level trends vary between individual wells, which are partly due to majority of the well network consisting of active municipal wells. Legal descriptions for monitoring wells are available in Appendix A.

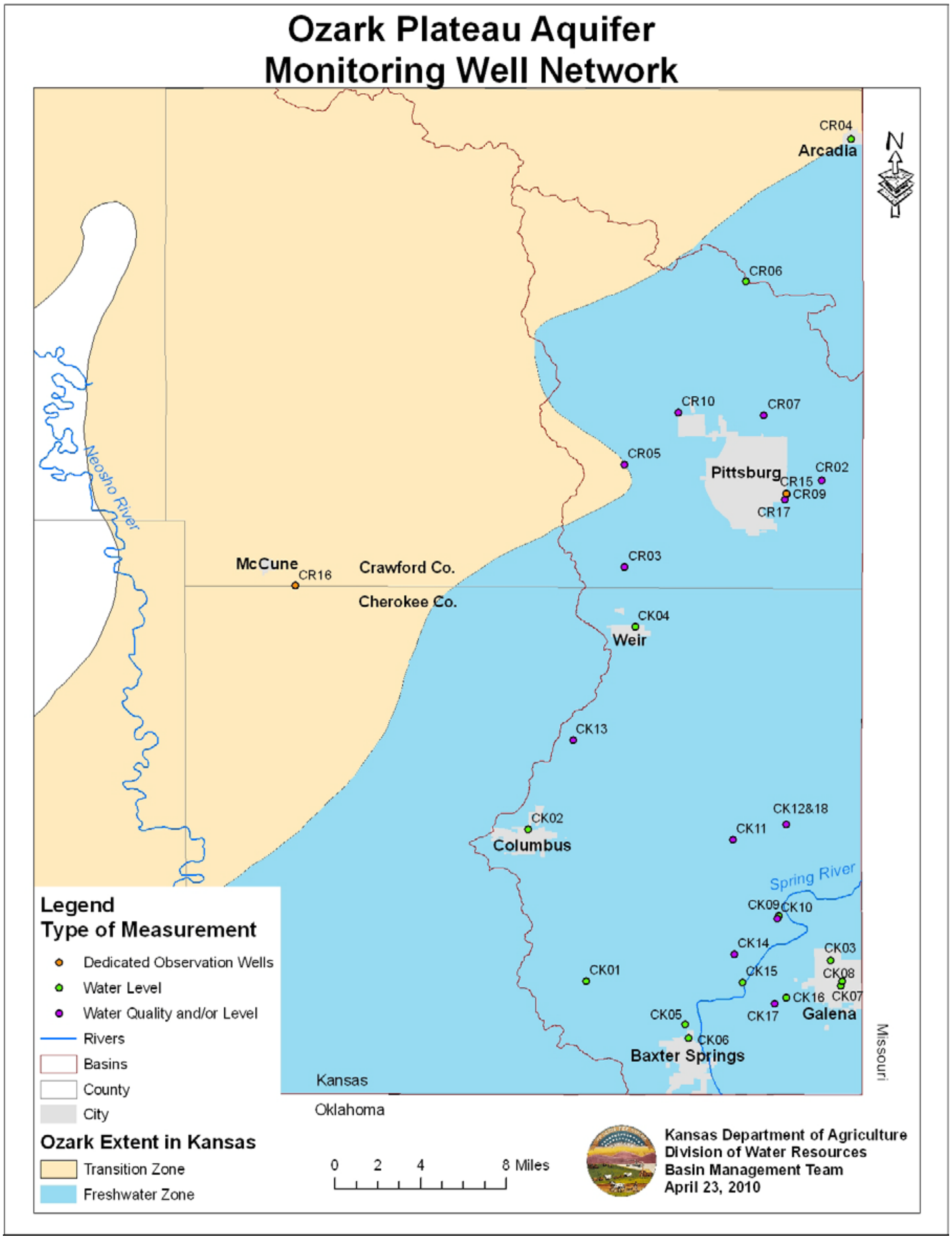


Figure 9: Ozark Monitoring Wells

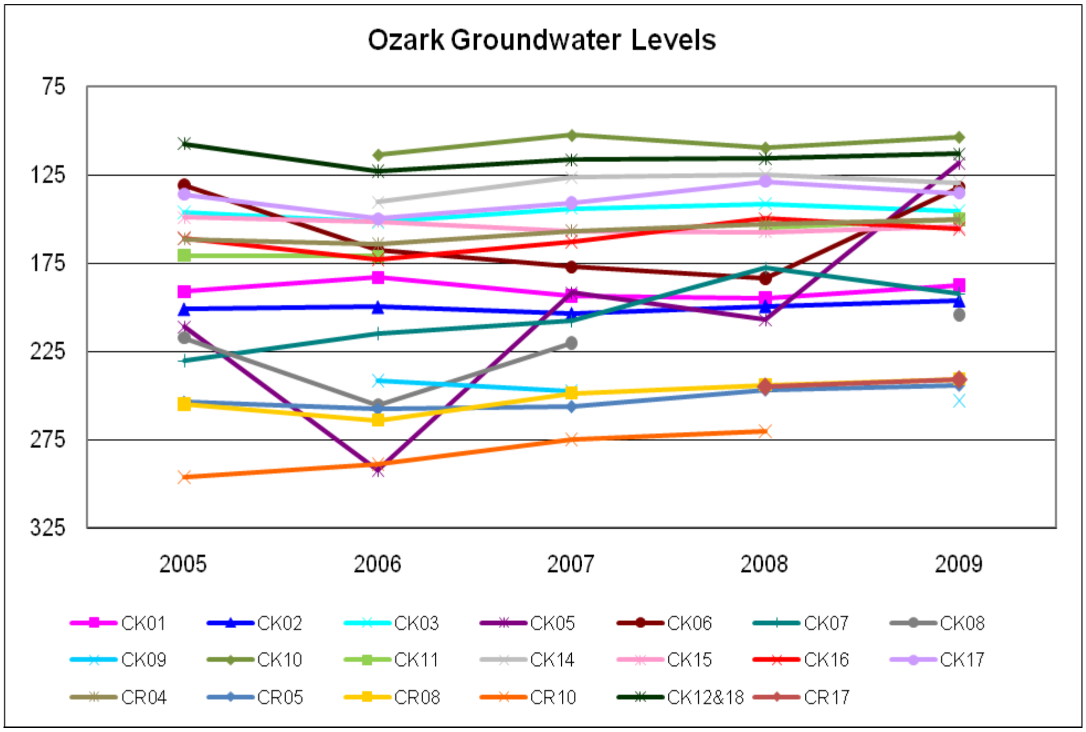


Figure 10: Groundwater Levels from the Ozark Aquifer

Figure 10 shows the monitoring wells located in the Ozark aquifer. Overall, the majority of well levels have increased by about 9 feet from 2005 to 2009. Since CK05 and CK06 have wide yearly fluctuations likely attributed to variations in resting time since pumping, they were not included in the overall analysis above.

CK05 has declined approximately 3 feet from 1988 to 2009 with yearly fluctuations sometimes as great as 100 feet. CK06 has an overall decline of about 1 foot from 2005 to 2009 with yearly fluctuations of up to 50 feet. CK12/CK18 has declined about 36 feet from 1975-2009. As a note, well CR17 has replaced CR08 in the network. Since these are pumping wells, some data is representative of pumping levels instead of static water levels.

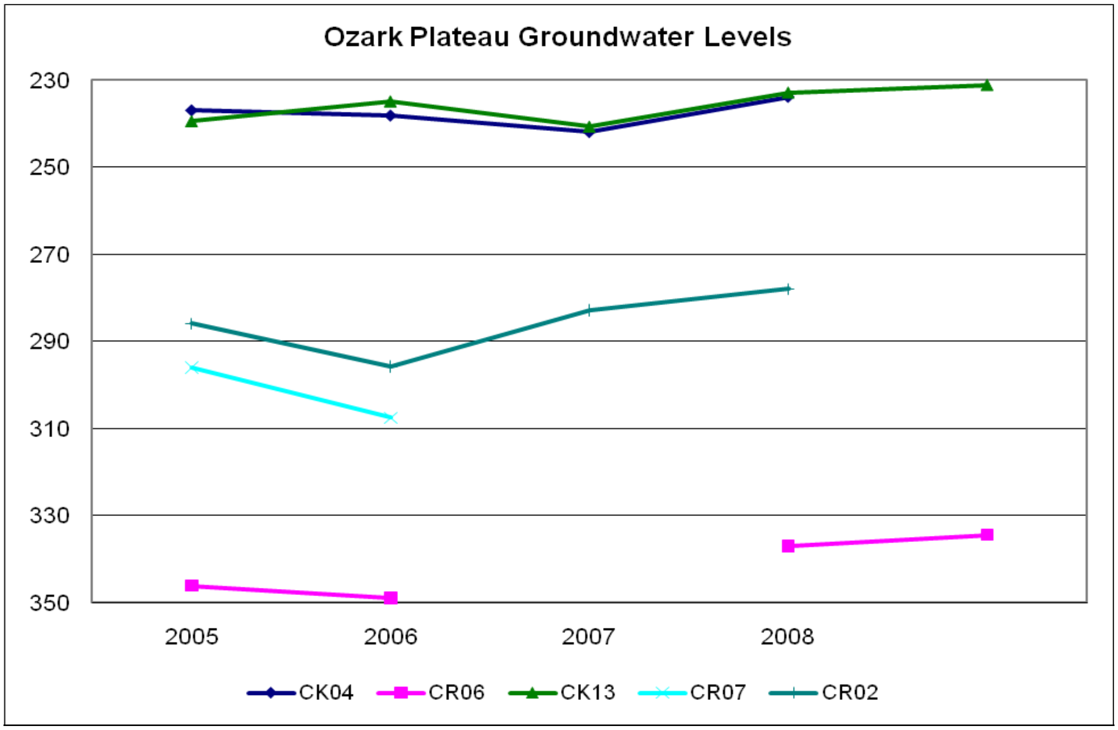


Figure 11: Groundwater Levels from the Ozark Plateau Aquifer

In the Ozark Plateau aquifer there are five monitoring wells (Figure 11). Overall, water levels have also increased by about 9 feet from 2005 to 2009. CR07 has not been measured for the past three years due to sludge.

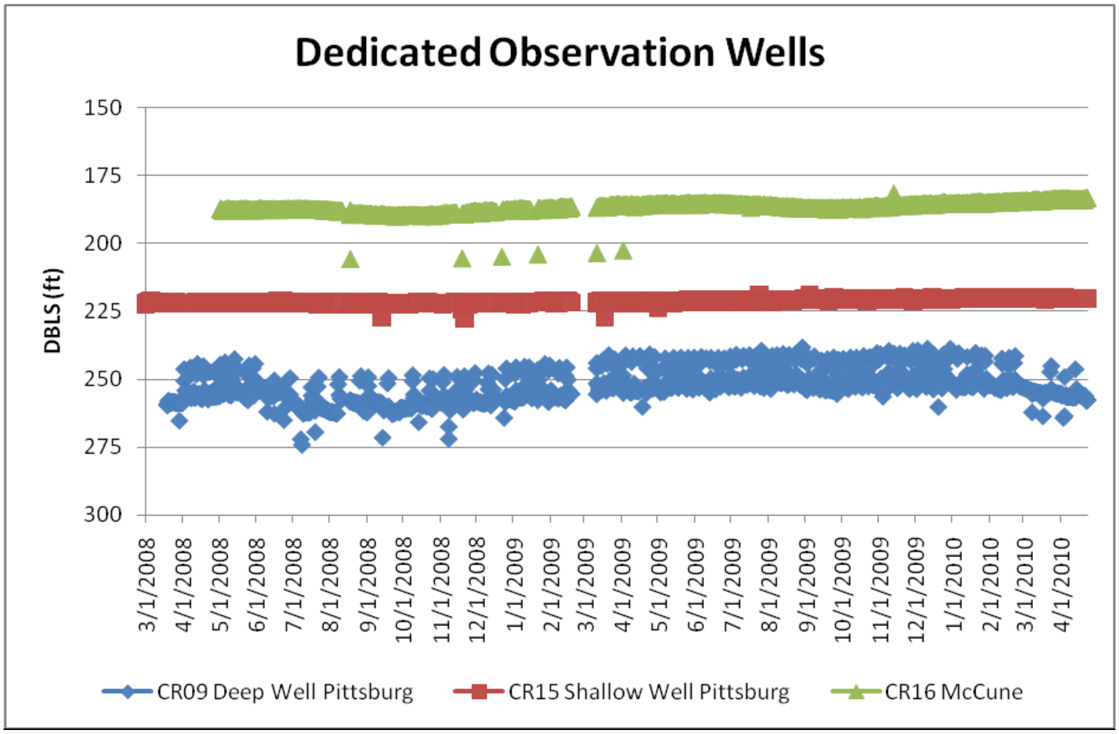


Figure 12: Groundwater Levels from Dedicated Observation Wells

Figure 12 shows the three dedicated observation wells. CR09 and CR16 are measured in the Ozark aquifer, while CR15 is measured in the Springfield Plateau aquifer. Each well has a measurement recorded every 24 hours. The graph shows daily measurements starting from March 2008. CR09 shows the most significant daily fluctuations, with an overall increasing trend. CR15 and CR16 have remained relatively stable but also show a slight increasing trend since June 2008.

C. Surface Water

Water Rights

The Ozark moratorium area has 127 active surface water rights, which is greater in number than the 109 groundwater rights. These rights are broken down in the following table by the Spring River basin and Neosho River basin with a total approximate quantity of 246,006 acre-feet authorized by these surface water rights (Table 3).

Table 3: Surface Water Rights and Acre-Feet Appropriated

Basin	Number of Rights	% Rights	Authorized AF	% AF
Spring[2]- Vested	3	2%	152,087	62%
Appropriated	16	13%	74,512	30%
Neosho-Vested	9	7%	4,873	2%
Appropriated	99	78%	14,534	6%
Total	**127**		**246,006**	

There are 19 surface water rights within the Spring River basin, which is 15 percent of the total rights. However, the total quantity authorized for use in the Spring River basin is 226,599 acre-feet, or 92 percent of the total acre-feet appropriated. This is primarily related to 177,794 acre-feet being authorized for surface water diversion for three water rights pertaining to cooling operations of the Empire District Electric Company. In addition, 46,217 acre-feet are also authorized in the Spring River basin for one fire protection vested water right. The Neosho basin has 108 water rights, which is 85 percent of the total rights. There are less total authorized acre-feet at 19,407, or 8 percent of total authorized acre-feet. The points of diversion associated with active surface water rights are shown in Figure 13.

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[2] Spring River basin authorized quantities are higher due to the diversion of water used for cooling by Empire Electric District Company. Most of the flows are discharged back into the Spring River. The Empire District Electric Company has three water rights within the Spring River basin; one of these rights is vested and the other two are appropriated. The total combined maximum authorized acre-feet for this company's rights totals to 177,794 acre-feet.

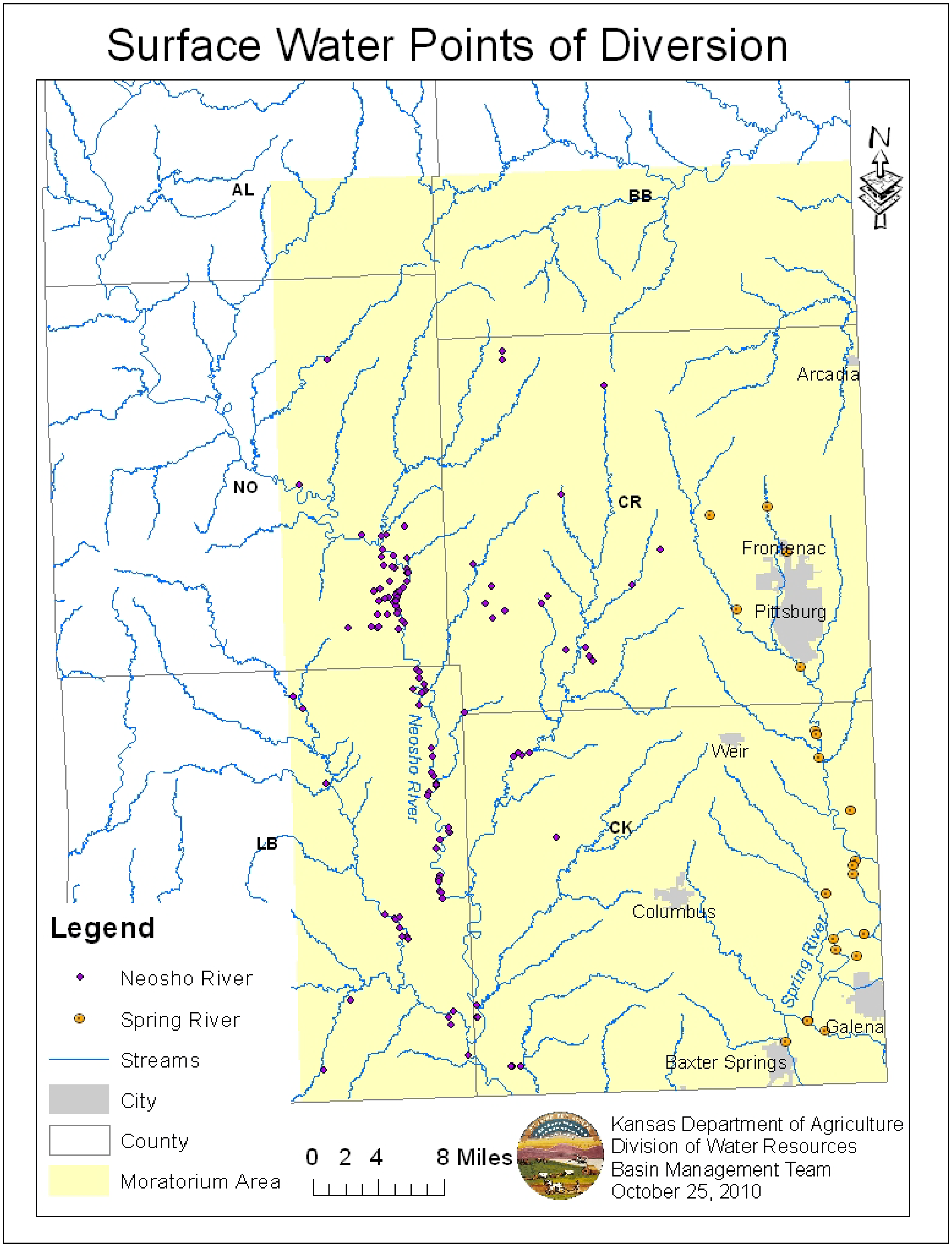

Figure 13: Surface Water Points of Diversion within the Ozark Moratorium Area

Reported Water Use

Figure 14 and Figure 15 show the total reported surface water use from active rights by year from 1990-2008 for the Spring River basin and Neosho River basin within the Ozark moratorium area. Average reported surface water use for the Spring River is 108,499 acre-feet; this is largely due to the diversions used for cooling the Empire District Electric Company. The average reported surface water use for the Neosho River basin is 5,724 acre-feet.

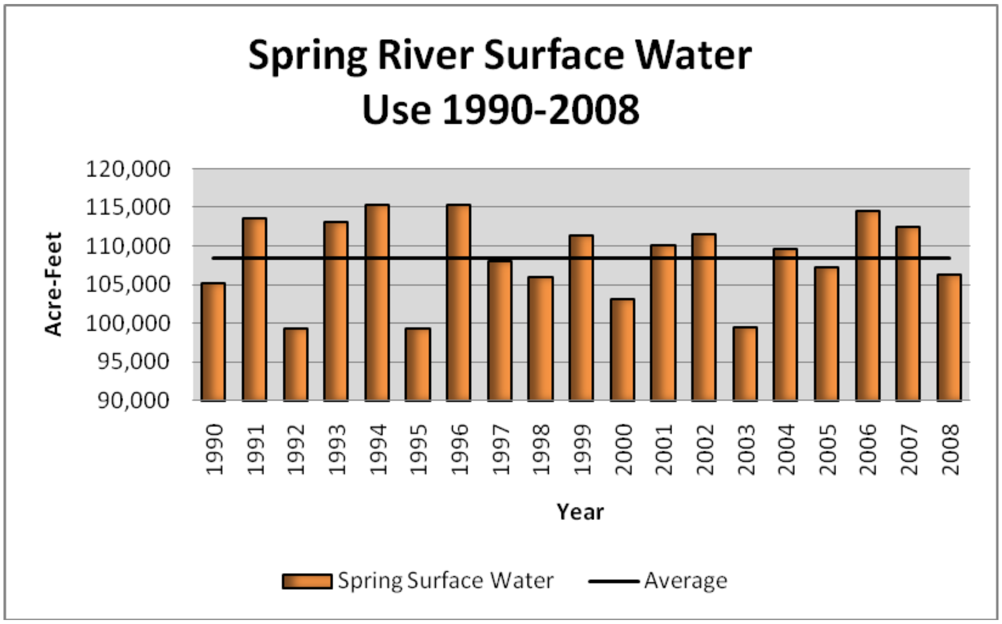

Figure 14: Reported Spring River Surface Water Use within Ozark Moratorium Area 1990-2008

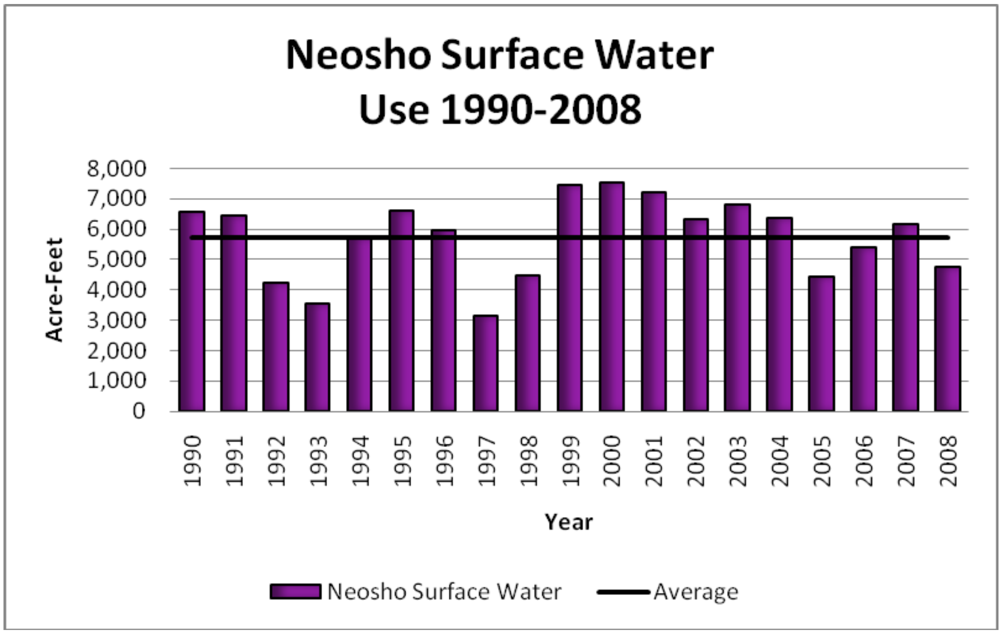

Figure 15: Reported Neosho Surface Water Use within Ozark Moratorium Area 1990-2008

Stream Flow

The Neosho River and the Spring River are the two major river systems that flow through the moratorium regulation area boundary of the Ozark Plateau aquifer (Figure 16). Both river systems are monitored by the USGS and have streamflow gages positioned near Parsons, Kansas on the lower Neosho River and near Baxter Springs, Kansas and Quapaw, Oklahoma on the Spring River (Figure 16). In addition, the USGS Spring River gage near Waco, Missouri is shown, as well as the USGS Shoal Creek gage near Joplin, MO (Figure 16). These gages measure flow entering Kansas since the water systems flow east over the state line from Missouri. Shoal Creek is the tributary to the Spring River, meeting it at the Empire District Lake.

Figure 17 was derived from the Parsons, Kansas, Quapaw, Oklahoma, Joplin, Missouri, and Waco, Missouri USGS gages and demonstrates how flow can vary each year. The Baxter Springs gage was installed in 2009, and is not included in this report. Following the 1951 flood the Neosho River reached periods of little to no flow during the subsequent drought. These events corresponded with the high and low precipitation events as noted earlier**.** It is important to note the difference between the Neosho and Spring River. Since the 1960s, the Neosho has been a largely controlled system due to federal reservoir operations, lake level management plans, and water assurance district operations. Table 4 gives a summary of the annual average streamflow at each gage for various time frames.

Table 4: Annual Average streamflow for USGS Gages near Ozark Moratorium Area

Gage, River, and Period of Record	**Period of Record Streamflow**	**1990-1999 Streamflow**	**2000-2008 Streamflow**
Parsons – Neosho River (1922 to present)	2,761 cfs	3,649 cfs	2,537 cfs
Waco – Spring River (1925 to present)	954 cfs	1,348 cfs	1,002 cfs
Joplin – Shoal Creek (1942 to present)	422 cfs	551 cfs	399 cfs
Quapaw – Spring River (1940 to present)	2,212 cfs	2,948 cfs	2,177 cfs

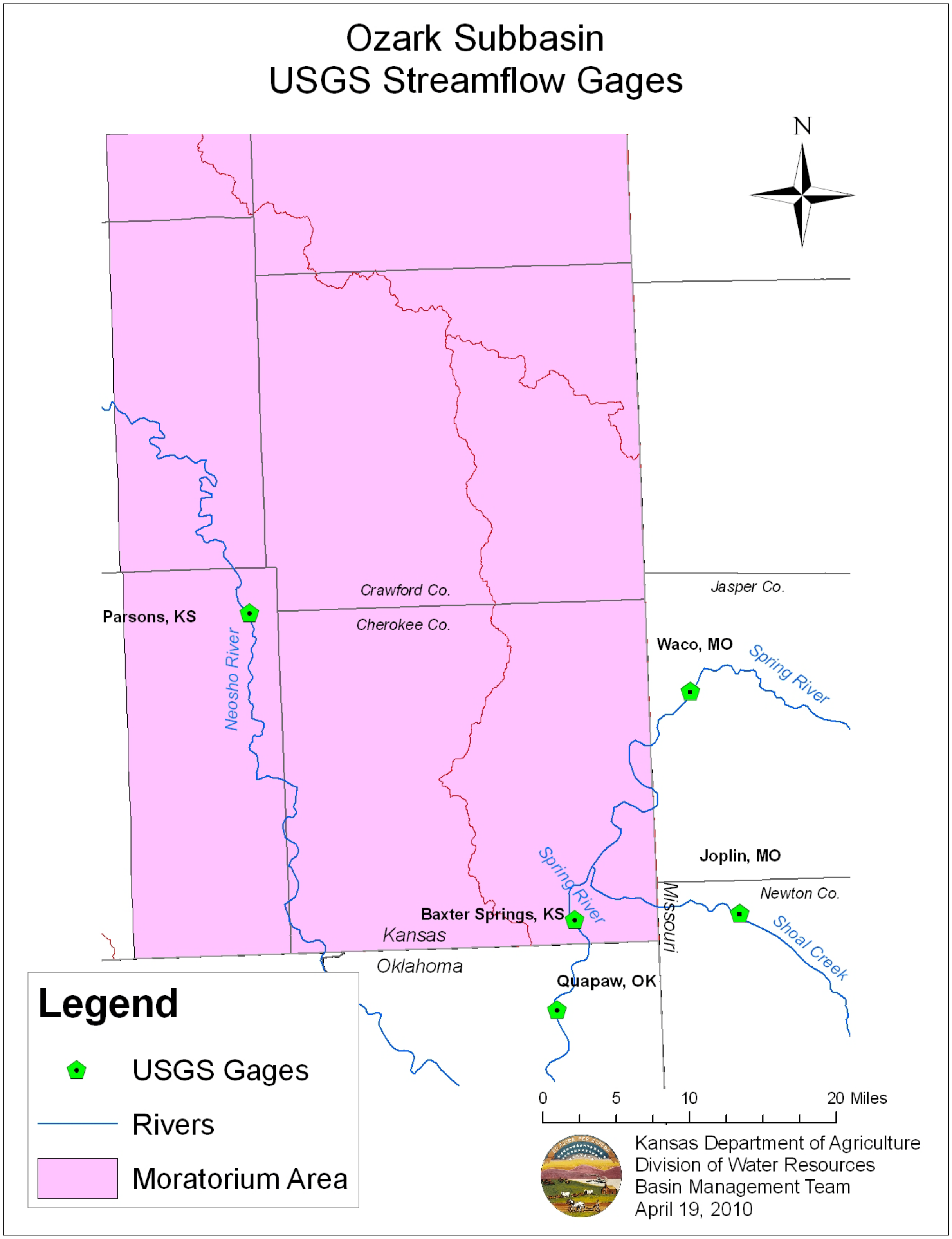

Figure 16: Neosho River, Spring River, and Shoal Creek USGS streamflow gages

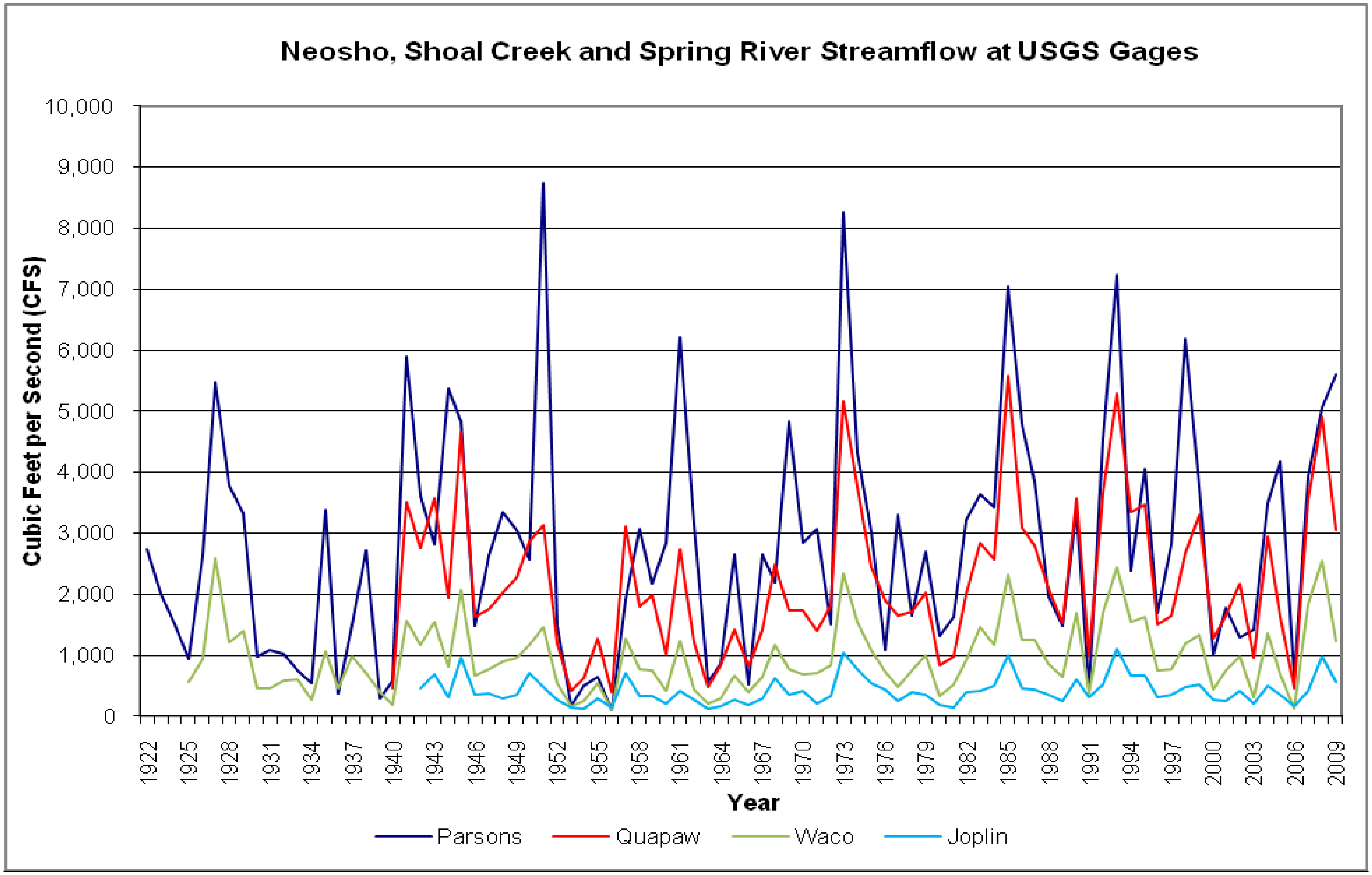

Figure 17: Streamflow at USGS Gages 1921-2009

Minimum Desirable Streamflow

Table 5 represents the MDS criteria for Parsons, Kansas and Baxter Springs, Kansas, respectively. The Quapaw gage in Oklahoma is used in the administration of MDS for the Spring River in Baxter Springs, as specified in K.S.A. 82a-703c (Kansas 2010). The MDS values for the Neosho River near Parsons in parenthesis in Table 5 represent the spawning flows that are managed if the reservoir (John Redmond) is in flood pool.

Table 5: Minimum Desirable Streamflow (MDS)

Watercourse	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Neosho- Parsons	50	50	50	50 (100)	50 (300)	50 (300)	50	50	50	50	50	50
Spring- Baxter Springs	175	200	250	300	450	350	200	160	120	120	150	175

The frequency of streamflow below the MDS criteria has been greater at the Parsons gage for the Neosho River than for the Spring River since the establishment of MDS in 1984 (Figure 18). This is partly due to the fact that streamflows on the lower Neosho River are affected by operations of three federal reservoirs located within the basin (Marion, Council Grove, and John Redmond Reservoirs). Administration of MDS on the Neosho River occurred in 2002, 2003, 2006, and 2007.

Although Spring River streamflow tends to be above MDS criteria, MDS administration did occur for the first time in 2006. Additional demands on the Spring River may increase the potential for minimum desirable streamflow administration on permits junior to the provision in order to protect flows.

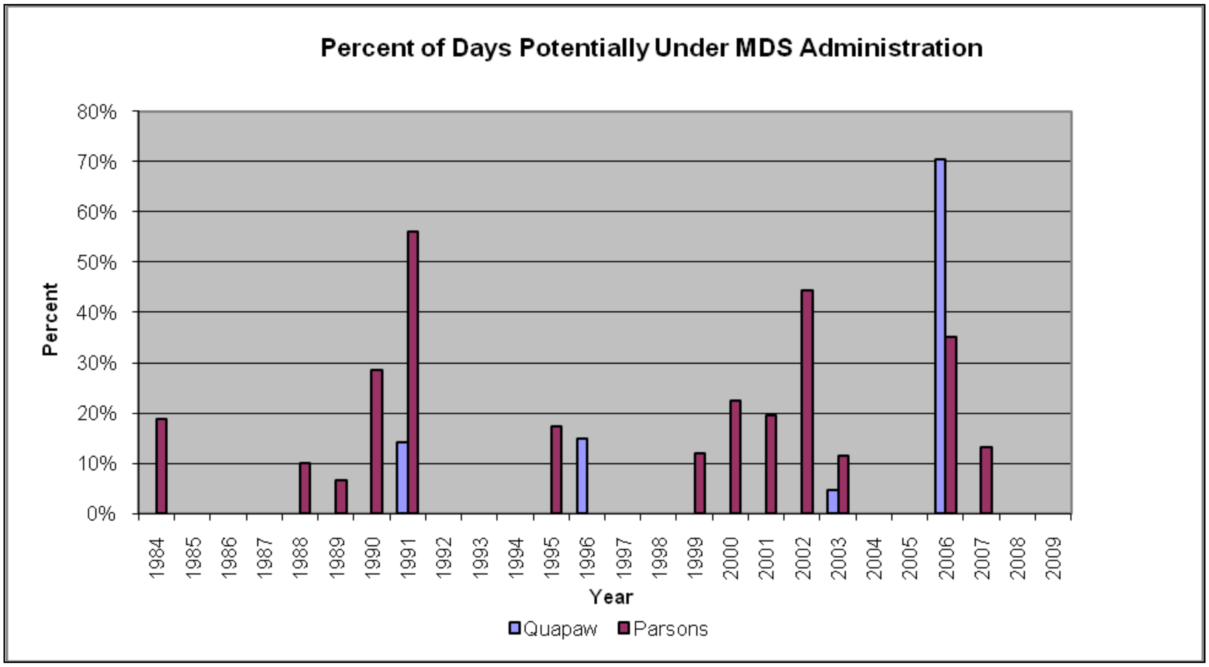

Figure 18: Percent of Days Potential MDS is not met at USGS gages

D. Water Quality

Figure 19 to 22 chart salinity and conductivity values in the Ozark aquifer and Ozark Plateau aquifer from March 2007 to September 2009. Figure 19 and 20 show salinity levels have remained fairly consistent throughout the network. Figure 19 charts a range in salinity from 200 to 600 parts per million (ppm) in the Ozark aquifer, while the Ozark Plateau aquifer (Figure 20) has a range from 300 to 600 ppm. The U.S. Environmental Protection Agency's (EPA) secondary drinking water standard for chloride is 250 ppm. Since the salinity measurement includes all salts, it is not directly comparable to the safe drinking water chloride standard.

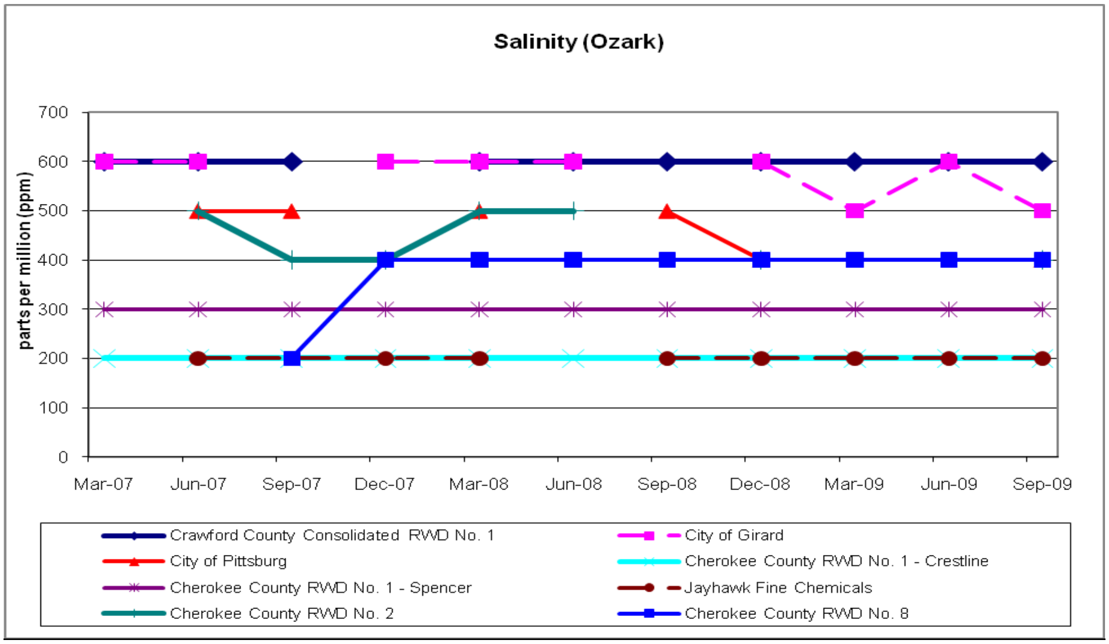

Figure 19: Ozark Aquifer Salinity

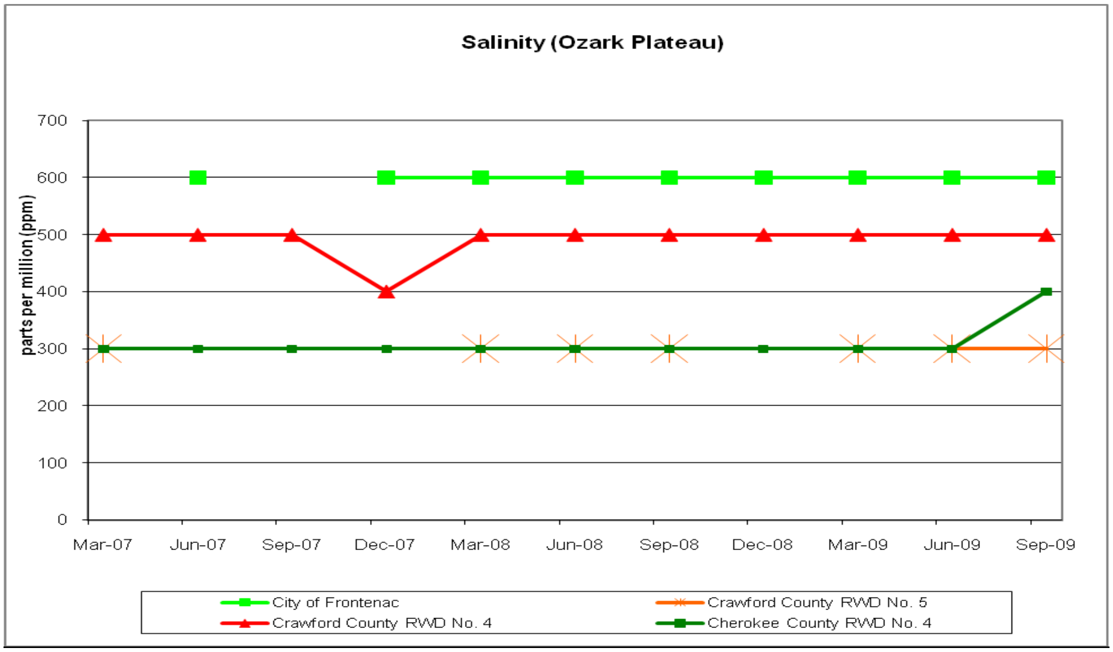

Figure 20: Ozark Plateau Aquifer Salinity

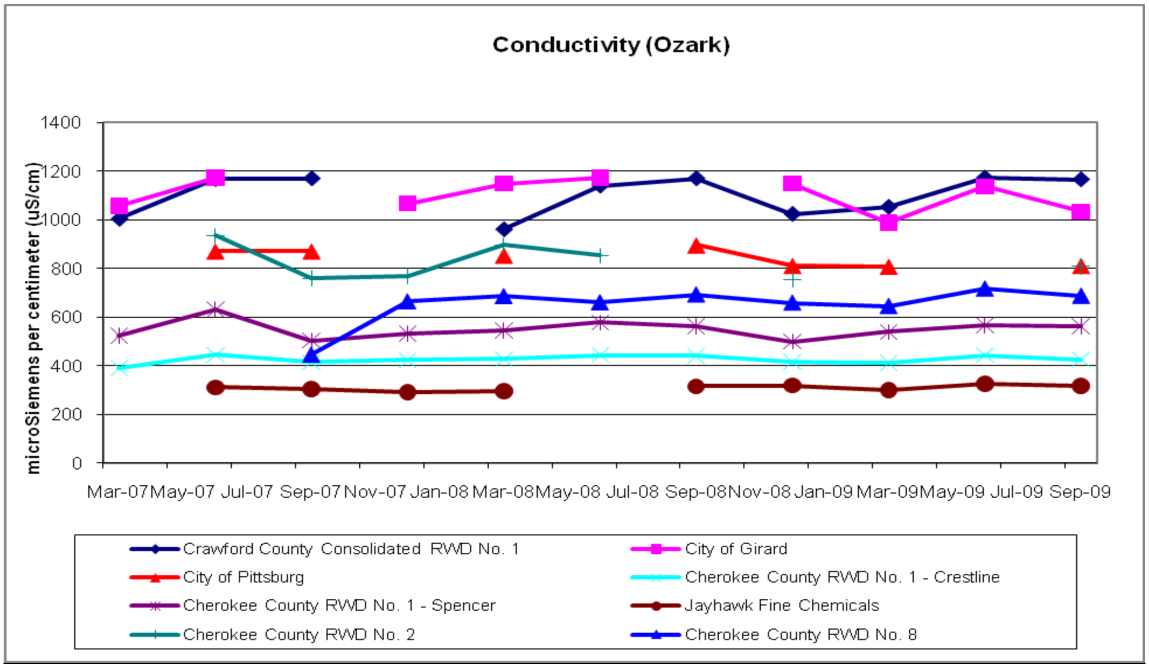

Figure 21: Ozark Aquifer Conductivity

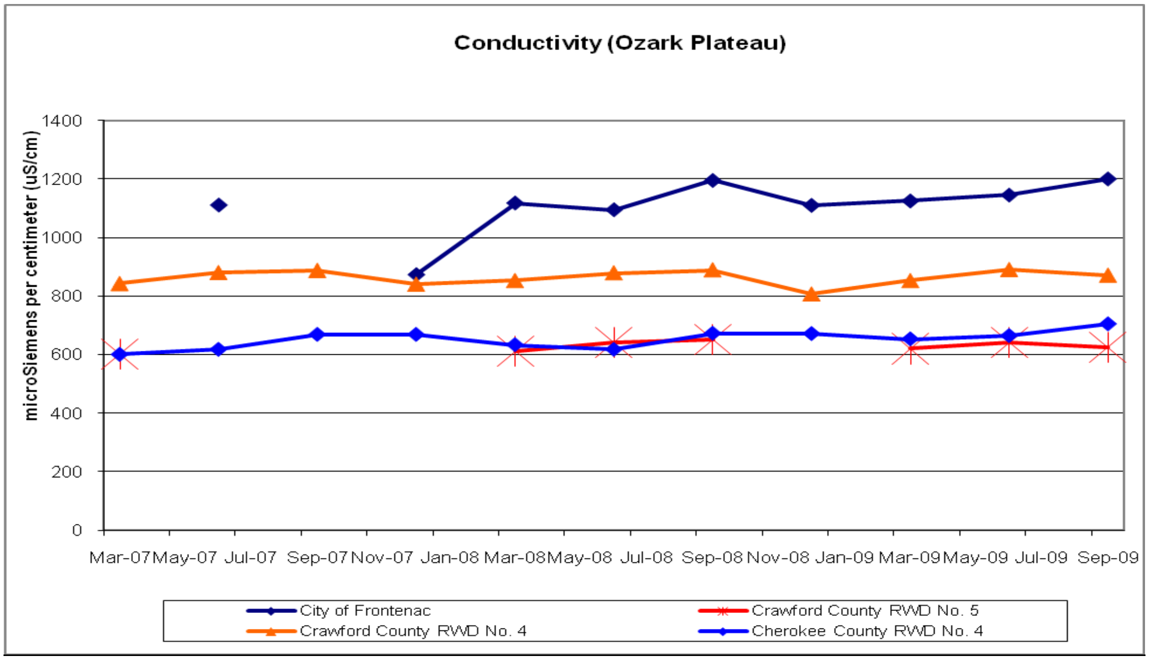

Figure 22: Ozark Plateau Aquifer Conductivity

Figure 21 and 22 chart conductivity values for the Ozark aquifer and the Ozark Plateau aquifer. As with the salinity values, conductivity values remain fairly consistent with a range in the Ozark aquifer of 200 micosiemens/centimeter (µS/cm) to 1200 µS/cm (Figure 21) and a range in Ozark Plateau aquifer from 600 µS/cm to 1200 µS/cm (Figure 22). The electrical conductivity of water is directly related to the concentration of dissolved solids in the water. However, in order to determine the relationship laboratory tests are needed to correlate conductivity with total dissolved solids. The EPA secondary drinking water standard for total dissolved solids is 500 ppm; without knowing the correlation factor for these groundwater sources it is unknown at this time whether the range of conductivity measured in these aquifers is above or below the secondary drinking water standard. It is important to note that these samples were taken prior to any water treatment.

V. OZARK PLATEAU AQUIFER MODEL

Water demands are projected to increase along with population within the Tri-State region, raising concerns about future water availability (Black and Veatch 2006). In addition there are also concerns about the water quality from prior mining and the underlying brine layer. In 2004, these concerns prompted the chief engineer to institute a moratorium area in the Ozark Plateau aquifer system of southeast Kansas and have created the need to further understand this resource for long-term management. More information on the moratorium area is available in the Introduction under Section *A. History of the Moratorium Area*.

In order to address these water supply and quality issues, the USGS initiated a study in August 2005. This study was done with the cooperation of the state water agencies in the Tri-State area, and includes a USGS groundwater flow model using MODFLOW computer software. This model simulates groundwater flow within the Ozark and Springfield aquifers and includes ground and surface water interaction. The model study area is shown in Figure 23. Through the model, resource managers are able to simulate the effect of additional groundwater withdrawals and provide water availability information (USGS 2008).

Representatives from the three states, the USGS, U.S. Environmental Protection Agency (USEPA), and local representatives, comprised the Ozark Aquifer Technical Advisory Committee (TAC). From KDA-DWR, Sam Perkins served as the Kansas representative in the TAC. Phone conferences were held quarterly in order to discuss the progress of the study. In the fall of each year annual meetings have been held to provide area residents with information about the status of the study (USGS 2008). The model was completed in 2009 and a final public meeting was held to provide results of the study, including the model and water quality work. Funding for the study was provided by the U.S. Geological Survey and the State of Kansas.

USGS Model Results

The groundwater flow model was developed by the U.S. Geological Survey for an area of the Ozark Plateaus aquifer system. The model area covers 7,340 square miles and encompasses parts of Arkansas, Kansas, Missouri, and Oklahoma (Figure 23). From top to bottom, the model has four layers. These are: the Western Interior Plains confining unit; the Springfield Plateau aquifer; the Ozark confining unit; and the Ozark aquifer. The model was developed to assess the effect that increased water use will have on the long-term availability of water to the region and to characterize groundwater flow.

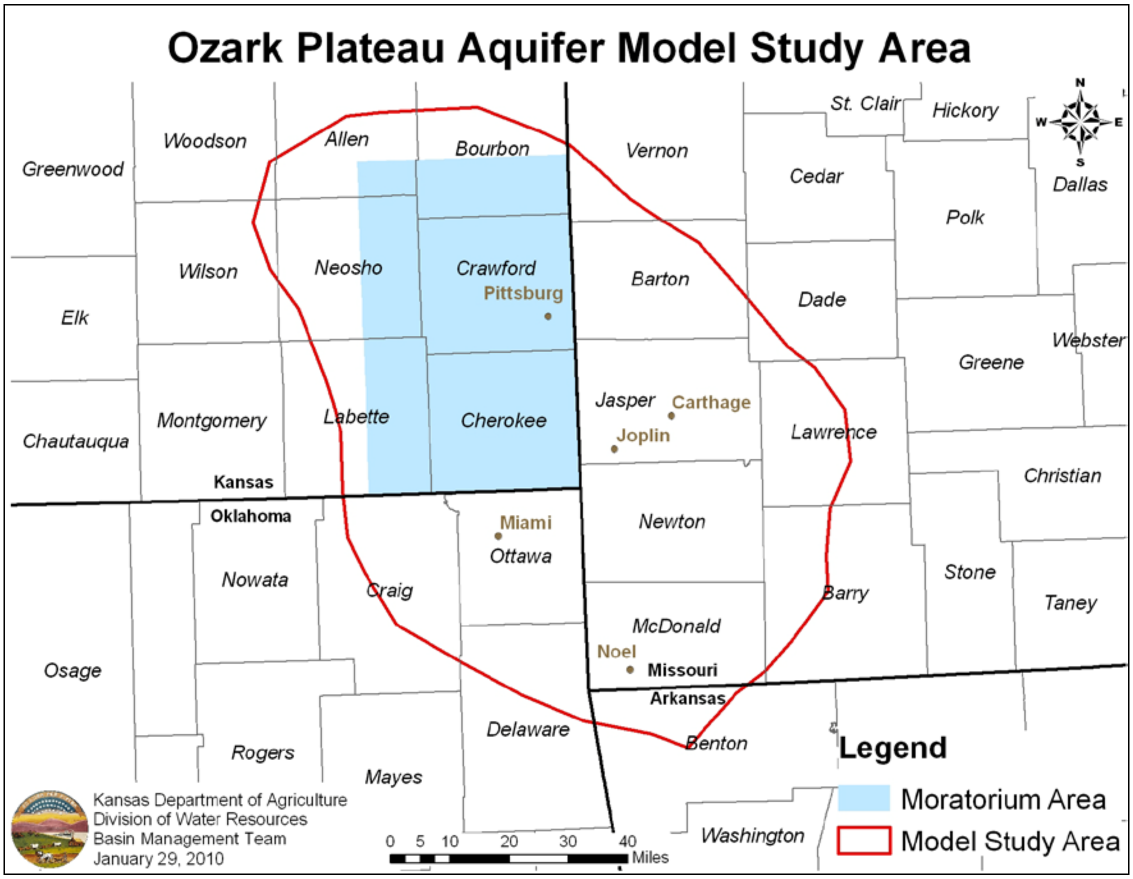

Figure 23: Moratorium Area and Ozark Plateau Aquifer Model Study Area

Within the model area municipal and industrial wells and some residential wells are open to the Ozark aquifer, which is 250 feet to more than 1,000 feet beneath the land surface. Overlying the Ozark aquifer is a confining unit that varies in thickness from 0 to 100 feet. This confining unit generally impedes groundwater flow between the Springfield and Ozark aquifer in most places; however, there are places where flow does occur. Mined zones were present in the model area within the Springfield Plateau aquifer, and were represented as extensive voids with larger hydraulic conductivity.

Water-use data were compiled for the period of 1950 to 2006. In 2006, total water use from the Ozark aquifer in Missouri was 71,537 acre-feet (87 percent of the total water use for the model area), with Kansas using 6,100 acre-feet (7 percent of total), and Oklahoma using 4,624 acre-feet (6 percent of total). Within the model, groundwater flow generally occurs from the highlands of the Springfield Plateau in southwest Missouri toward the west. Localized flow occurs towards rivers and the five pumping centers near Joplin, Carthage, and Noel, Missouri; Pittsburg, Kansas; and Miami, Oklahoma (Czarnecki et al. 2009).

The groundwater model analyzed five hypothetical scenarios to assess changes in water levels in the Ozark aquifer associated with increased rates of pumping (Table 6). The Ozark aquifer is the predominant source of water within the Ozark Plateau aquifer system. Each scenario looked at the effects of increased pumping from 0 (baseline) to a 4 percent increase of the 2006 pumping rate. The scenario was run 50 years into the future, from 2007 to 2057 (Czarnecki et al. 2009).

Table 6: Hypothetical Pumping Scenarios in the Ozark Aquifer

Hypothetical Scenario Number	Pumping Increase per year in Oklahoma and Missouri after 2006	Pumping Increase per year in Kansas after 2006
1	0 %	0 %
2	1 %	1 %
3	1 %	0 %
4	2 %	2 %
5	4 %	4 %

Sustained pumping at 2006 rates under scenario 1 was feasible at all five pumping centers until 2057. However, at varying points in time, model cells go dry in four of the pumping centers (Carthage, Joplin, and Noel, Missouri, and Miami, Oklahoma) with increased pumping under the hypothetical scenarios by 2057 (Table 7). Carthage, Missouri goes dry as early as 2029 with a 4 percent increase. Model cells at Carthage, and Noel, Missouri go dry by years 2037 and 2057, respectively under a 1 percent increase in pumping per year (Czarnecki et al. 2009). Pumping is not sustainable at rates in which dry cells are reached. This suggests that 2006 pumping rates are the maximum rates that can be pumped without model cells going dry in the pumping centers by 2057. It is important to note that the pumping center of Pittsburg, Kansas does not go dry under any scenarios by 2057. This led to additional analysis by DWR staff to determine how much water is available within Kansas to be appropriated.

Table 7: Decline in Water-Level Altitude (in feet) at the five Pumping Centers to the end of 2057 from Hypothetical Pumping Scenarios

Scenario number	Pittsburg, Kansas	Miami, Oklahoma	Joplin, Missouri	Carthage, Missouri	Noel, Missouri
1	169	330	493	650	583
2	245	508	596	Dry	Dry
3	210	505	593	Dry	Dry
4	302	644	756	Dry	Dry
5	505	Dry	Dry	Dry	Dry

Substantial reductions in water storage are caused by groundwater pumping. Flow through the Ozark confining unit is induced for all of the hypothetical scenarios; however, the flow is not uniformly distributed and varies spatially. Downward flow from the overlying Ozark confining unit is the largest component of flow into Kansas, varying from 21 to 41 percent of the total flow for the scenarios. When pumping increases, the amount of water released from storage increases, which causes water level declines. Figure 24 shows simulated water level declines as seen under scenario 4, which is a 2 percent increase per year in pumping to year 2057. Pumping in Kansas is the largest component of flow out of Kansas with variations of 39 to 61 percent for all scenarios. Flow from Kansas to Missouri, induced by pumping in Missouri, is the second largest component of flow out of Kansas. It ranges from 30 to 43 percent of the total flow out of Kansas (Czarnecki et al. 2009).

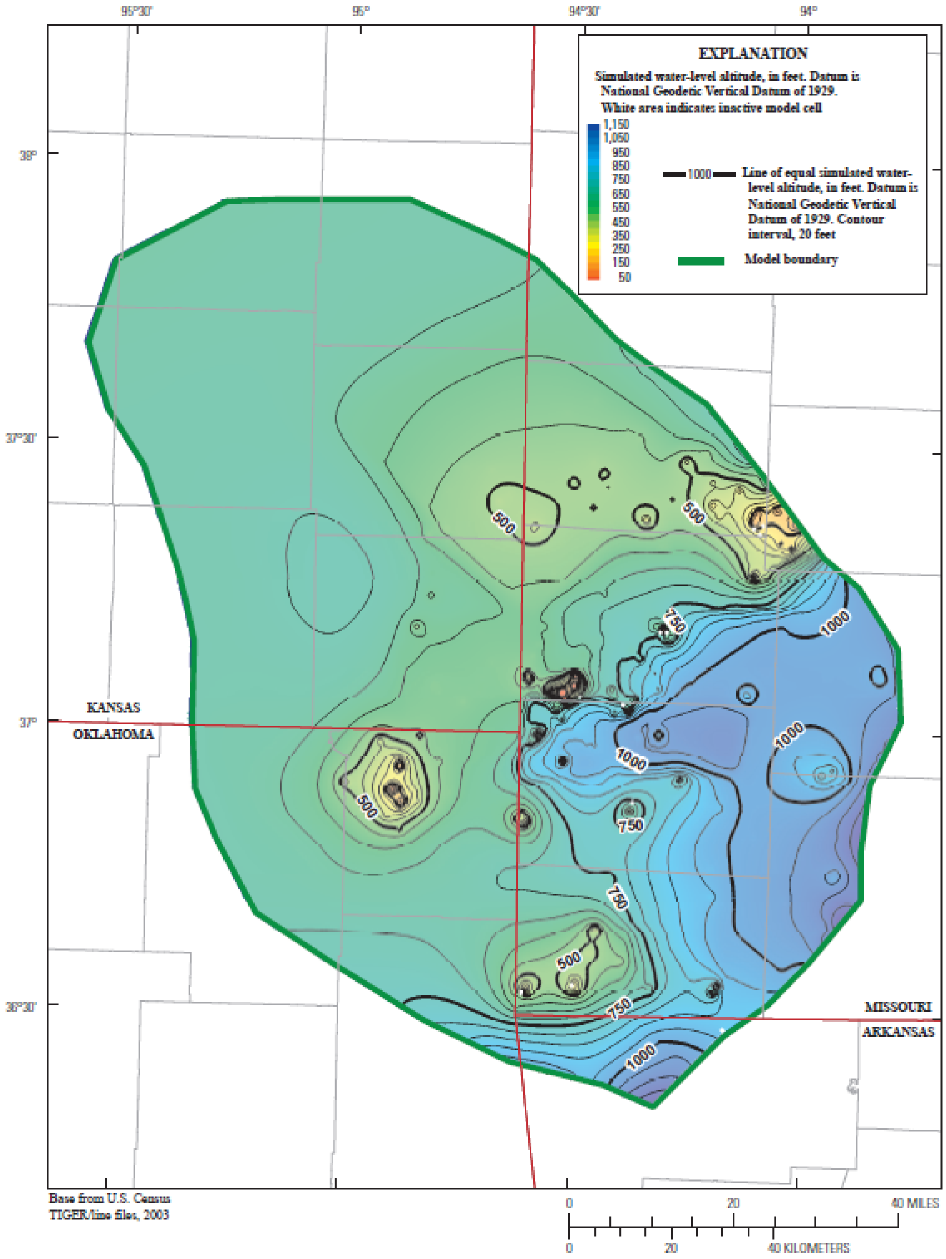

Figure 24: Simulated Water Level Altitude under USGS Scenario 4

Understanding how percent increases in water use affect the availability of water in Kansas is important when making water management decisions. The deadline provided in DWR regulations for the chief engineer to make a decision regarding the aquifer system safe yield and moratorium area is December 31, 2010. The release of the groundwater model and additional model runs performed by DWR staff has guided decision making.

DWR Model Work

The USGS model runs demonstrated that there is additional water available in Kansas, as there were no dry cells in Pittsburg even under scenario 5 with a four percent increase per year.

Therefore, staff within DWR performed supplemental model runs to determine how much additional water is available to appropriate in Kansas.

The approval of any new application to appropriate groundwater or surface water for beneficial use, except for domestic use, temporary use and term permits for five years or less, shall not cause the safe yield of the source of water supply to be exceeded, (Kansas 2010, K.A.R. 5-3-10). For this area, the chief engineer determined that the safe yield would be pumping that could be sustained without reducing the storage in the Ozark aquifer by more than 25 percent in 100 years. This will allow for limited new development of water resources which can be maintained over the long term to meet safe yield requirements.

DWR utilized the USGS Model and ran increased pumping future scenarios in multiples of the current total authorized quantity within the Ozark moratorium area in Kansas. The model was extended to run 100 years into the future and the Ozark and Springfield aquifer pumping distribution was based on transmissivity. In order to maintain the 75 percent remaining in storage at the end of 100 years, it was determined an increase of approximately three times the current authorized quantity would meet safe yield at the end of 100 years (Figure 25). Missouri and Oklahoma pumping were held at two times the current use, and pumping was assumed to be at the full authorized quantity throughout the simulation.

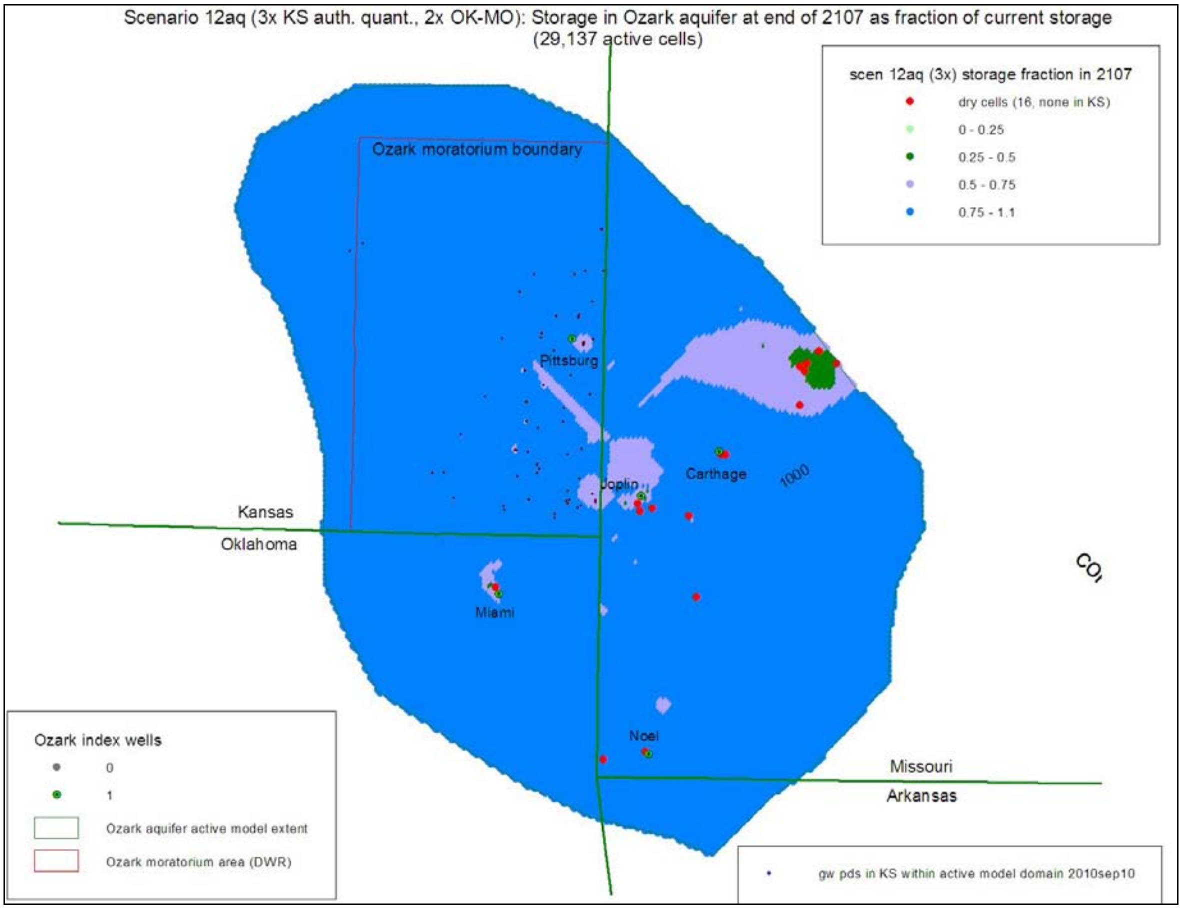

Figure 25: Fraction of Remaining Ozark Aquifer Storage in 100 Years at Three Times the Current Authorized Quantity in Kansas

As shown in Figure 25, approximately three times the currently authorized amount in Kansas leaves the majority of the remaining storage fraction at 75 percent, which meets safe yield in 100 years. In contrast, once four times the authorized quantity in Kansas is reached, larger areas begin to exceed safe yield after 100 years (Figure 26).

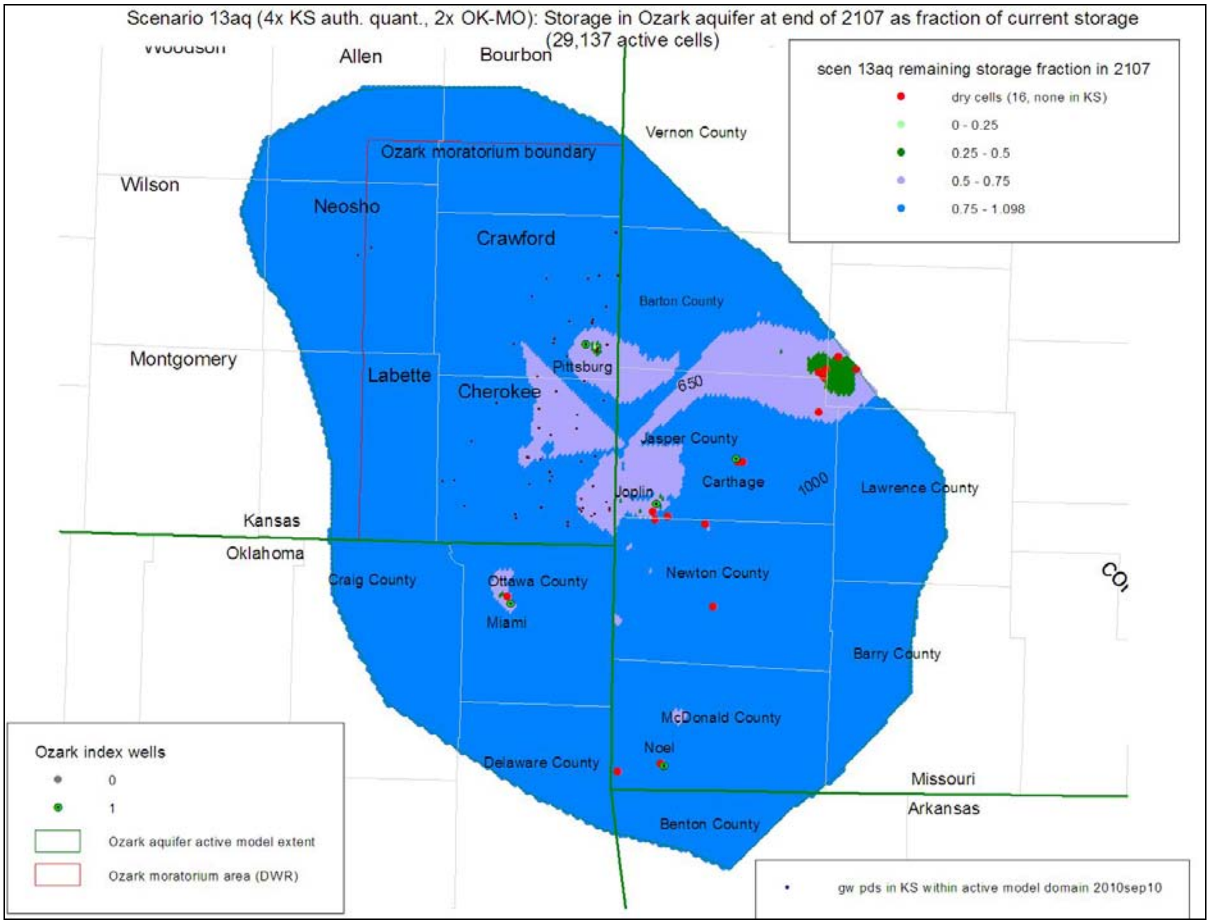

Figure 26: Fraction of Remaining Ozark Aquifer Storage in 100 Years at Four Times the Current Authorized Quantity in Kansas

Three times the current authorized quantity would mean that there are approximately 36,000 acre-feet available for total appropriations within the Ozark Plateau aquifer. With 10,451 acre-feet currently appropriated, and 1,307 acre-feet in term permits that can become regular appropriations, this leaves approximately 24,000 acre-feet available for future appropriation. Depending on local hydrologic conditions and where development occurs, the total amount may vary.

In order to determine the safe yield on a local level, it has been determined that a 2-mile circle radius will be used to analyze what level of appropriation will meet the 75 percent remaining storage in 100 years. A series of 44 points across the Ozark aquifer will be used for this analysis. The 2-mile circle form of analysis is consistent with safe yield determinations across the state of Kansas (Kansas 2010, K.A.R. 5-3-11). On October 25, 2010 DWR and the Kansas Water Office hosted a teleconference with the Ozark stakeholder group on the safe yield and allowable appropriations from the Ozark Plateau aquifer. Detailed information on DWR model runs and assumptions as well as the corresponding analysis to make safe yield determination are available in Appendix B.

Water Quality Study

The Kansas Geological Survey performed a study under grant by the Kansas Water Research Institute. This two-year project was undertaken to determine the influence of pumping on the quality of water produced from wells within the transition zone in southeast Kansas. There are a total of eight supply wells from which water quality samples were taken; five wells were located in the Ozark aquifer and three within the Springfield Plateau aquifer. The samples were analyzed for calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, bromide, boron, fluoride, and strontium. Temperature, specific conductance, and pH were measured in the laboratory and field. Previous studies were conducted more than 25 years ago, and this study assessed long-term changes in the geochemistry of the water since then, in addition to characterizing the month-to-month fluctuations and obtaining a better understanding of the short term and long term changes in the geochemistry of water produced by these wells.

The report suggests that with current pumping rates, the water quality at Pittsburg wells 8 and 10 would exceed the recommended drinking water limit of 250 mg/L for chloride by the years 2045 and 2060, respectively. Comparison of the data to the previous studies from 1979-1980 indicates that water quality has deteriorated in some of the sampled water supplies (Macfarlane 2010). Although the data suggests that chloride may be increasing in the City of Pittsburg wells, several technologies are available to treat for high chloride including reverse osmosis and side-spray ozone.

In the past there have been some instances of water quality concerns documented for the moratorium area in Kansas. For instance, in January, 1980, the Southeast Kansas Water Supply Study Plans of Regional Water Supply Systems cooperative study between the USDA Soil Conservation Service and the Kansas Water Resources Board identified that the town of West Mineral, Kansas has problems with sodium and chlorides in its well (USDA 1980). Since approximately 2000, the well has only been pumped to maintain the equipment and the city has moved to an alternate supplier.

In that report, the Kansas Department of Health and Environment were cited as reporting that the cities of Capaldo, Arcadia, Girard, and McCune, as well as Rural Water District Nos. 2 and 7, Crawford County, have excessive quantities of sodium chloride in their supplies (USDA 1980). Rural Water District No. 2, Crawford County, Capaldo, and McCune no longer obtain their source of water supply from their original wells and have moved to other suppliers. The City of Baxter Springs has had radionuclide in their wells result in condemnation by KDHE. DWR has been advised by one poultry farm operator in the area who obtained his water supply from the Springfield Plateau portion of the aquifer that he has had to move to alternate supply due to “poor quality.” In December of 2009, DWR hosted a meeting to address water quality concerns in the area; however, no water quality concerns were raised at that time.

VI. CONCLUSIONS

Despite concerns about groundwater level declines in southeast Kansas that led to the moratorium and model study, the data collected and groundwater modeling as summarized in this document does not suggest a significant overall groundwater decline during the period of monitoring for the moratorium area of southeast Kansas. In addition, the salinity levels documented have remained fairly constant from March 2007 to September 2009. The short duration of data collection likely may factor in these results as little historical data exists for comparison purposes.

KDA-DWR has reviewed and made additional runs with the USGS groundwater model, and has determined the safe yield of the aquifer system to be at least three times the current authorizations. Based on this work, the moratorium term permits can become regular appropriations and DWR will be developing specific regulations governing future appropriations from the system. Furthermore, continued monitoring of the contamination risks associated with increased pumping and water transport will occur and appropriate management solutions will be determined if and when this becomes an issue that adversely affects water quality.

Water does not adhere to state boundaries, which can make water management for the region complex due to differing water law systems. Despite the seemingly adequate rainfall to the region, drought has been and still remains a concern to this region due to the variability in precipitation affecting surface water and concerns about the aquifers both in quantity and quality. In addition, with the projected population increase to the Tri-State area, a stable water supply source for the region is needed.

The Ozark Plateau aquifer and the Spring River are the sources of water for all public water suppliers in southeast Kansas. Many of these suppliers have been operating at the upper threshold of their authorized water right quantities. These suppliers, and other users, have been working within the constraints of the moratorium put into effect in 2004. It has been determined at this time that with certain limitations, the groundwater users may continue to safely rely on groundwater within the Ozark Plateau aquifer for their supply.

DWR staff believes the safe yield determination contained herein is conservatively estimated and should allow for development from the aquifer system in the area for some time to come. Staff recommends that as the total appropriations of the aquifer system approach the estimated safe yield, that an update to the safe yield determination be made based on the actual development and updated data and methods available at that time.

VII. GLOSSARY

Acre-feet (AF) – The volume of water necessary to cover one acre to a depth of one foot. Conversion to gallons- 1 acre-foot = 325,851 gallons.

Appropriation right – A right, acquired under the provisions of article 7 of chapter 82a of the Kansas Statutes Annotated and amendments thereto, to divert from a definite water supply a specific quantity of water at a specific rate of diversion, provided such water is available in excess of the requirements of all vested rights that relate to such supply and all appropriation rights of earlier date that relate to such supply, and to apply such water to a specific beneficial use or uses in preference to all appropriations right of later date.

Aquifer – A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Brine – Water saturated with or containing large amounts of a salt, especially of sodium chloride. According to *U.S. Geologic Survey (USGS)* classification, water classified as brine contains more than 35,000 ppm (parts per million) total dissolved solids (TDS) of salt

Climate – Generalized weather at a given place on earth over a fairly long period (usually decades); a long term average of weather

Confining Unit — A hydrogeologic unit of relatively impermeable material, bounding one or more aquifers. This is a general term that has replaced *Aquitard*, *Aquifuge*, and *Aquiclude* and is synonymous with *Confining Bed*.

Groundwater – Means water below the surface of the earth.

Groundwater Model – Computer model of groundwater flow systems, used by hydrogeologists. Groundwater models are used to simulate and predict aquifer conditions.

Hydrologic – Of or pertaining to hydrology, that is the science of dealing with water, its properties, phenomena, and distribution over the earth's surface.

Karst topography – The structure of land surface resulting from limestone, dolomite, gypsum beds, and other rocks formed by dissolution and characterized by closed depressions, sinkholes, caves, and underground drainage.

Minimum Desirable Streamflow – The specific amount of water required at a minimum desirable streamflow gaging station. All vested rights, water appropriation rights and applications for permits to appropriate water having a priority date on or before April 12, 1984, shall not be subject to any minimum desirable streamflow requirements established pursuant to law.

Moratorium – A temporary ban or suspension of an activity. In this instance, groundwater appropriations.

Physiography – Description of nature or natural phenomenon in general; physical geography.

Safe yield – Means the long-term sustainable yield of the source of supply, including hydraulically connected surface water or groundwater.

Salinity- The concentration of dissolved salts in water or soil water. Although the measurement takes into account all of the dissolved salts, sodium chloride (NaCl) normally constitutes the primary salt being measured.

Weather – Day to day variation in atmospheric conditions

Vested right- The right of a person under common law or statutory claim to continue the use of water having actually been applied to any beneficial use, including domestic use, on or before June 28, 1945, to the extent of the maximum quantity and rate of diversion for the beneficial use made thereof, and shall include the right to take and use water for beneficial purposes where a person is engaged in the construction of works for the actual application of water to a beneficial use on June 28, 1945, provided such works shall be completed and water is actually applied to such use within a reasonable time thereafter by such person, his heirs, successors or assigns. Such a right does not include, however, those common law claims under which a person has not applied water to any beneficial use within the periods of time set out in this subsection.

Water right- Any vested or appropriated right under which a person may lawfully divert and use water. It is a real property right appurtenant to and severable from the land on or in connection with which the water is used and such water right passes as an appurtenance with a conveyance of the land by deeds, lease, mortgage, will, or other voluntary disposal, or by inheritance.

The following sources were used in the compilation of the Glossary:

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IX. APPENDIX A: WELL DATA

Name	Well ID	Aquifer	Legal	Level	Quality	Latitude	Longitude
Cherokee Co. RWD 2	CK14	Ozark	34S25E08SWNWSW	Yes	Yes	37.0930	-94.7040
Cherokee Co. RWD 9	CK15	Ozark	34S25E20NWNENW	Yes	No	37.0741	-94.6983
Cherokee Co. RWD 8	CK16	Ozark	34S25E21NWNESE	Yes	No	37.0640	-94.6690
Cherokee Co. RWD 8	CK17	Ozark	34S25E28NWNWNW	Yes	Yes	37.0600	-94.6770
Galena	CK07	Ozark	34S25E23SENENE	Yes	No	37.0720	-94.6320
Galena	CK08	Ozark	34S25E13SWSWSW	Yes	No	37.0750	-94.6310
Galena	CK03	Ozark	34S25E14NWNWNE	Yes	No	37.0890	-94.6390
Baxter Springs	CK05	Ozark	34S24E36NENWNW	Yes	No	37.0460	-94.7370
Baxter Springs	CK06	Ozark	34S24E36NWNWSW	Yes	No	37.0370	-94.7350
Cherokee RWD 3	CK01	Ozark	34S24E17SWSWSE	Yes	No	37.0750	-94.8040
Jayhawk Fine Chemicals	CK09	Ozark	34S24E04NENWNE	Yes	No	37.1190	-94.6740
Jayhawk Fine Chemicals	CK10	Ozark	34S25E04NENWNE	Yes	Yes	37.1170	-94.6750
Cherokee RWD 1	CK11	Ozark	33S25E18NENESE	Yes	Yes	37.1700	-94.7050
Cherokee RWD 1	CK12&18	Ozark	33S25E09SENESE	Yes	Yes	37.1800	-94.6690
Columbus	CK02	Ozark	32S23E13NENENW	Yes	No	37.1770	-94.8430
Cherokee Co. RWD 4	CK13	Ozark Plateaus	32S24E29NWNWNW	Yes	Yes	37.2370	-94.8130
Weir	CK04	Ozark Plateaus	31S24E27NWSESW	Yes	No	37.3130	-94.7710
Arma	CR06	Ozark Plateaus	29S25E05SESESW	Yes	No	37.5446	-94.6962
Frontenac	CR07	Ozark Plateaus	20S25E04NESWSW	Yes	Yes	37.4550	-94.6840
Girard	CR05	Ozark	30S24E21NESENE	Yes	Yes	37.4218	-94.7784
Arcadia	CR04	Ozark	28S25E01NESWNE	Yes	No	37.6404	-94.6250
Crawford Co. RWD 1C	CR10	Ozark	30S24E02SESESE	Yes	Yes	37.4568	-94.7419
Pittsburg	CR17	Ozark	30S25E28NESESE	Yes	Yes	37.3980	-94.6700
Crawford Co. RWD 4	CR03	Ozark Plateaus	31S24E16NENENE	No	Yes	37.3530	-94.7780
Crawford Co. RWD 5	CR02	Ozark Plateaus	30S25E23SESWSW	Yes	Yes	37.4111	-94.6449
Pittsburg DWR	CR09	Ozark	30S25E28NENESE	Yes	No	37.4021	-94.6685
McCune	CR16	Ozark	31S22E16SESESW	Yes	No	37.3404	-95.0004
Pittsburg	CR15	Springfield	30S25E28SENESE	Yes	No	37.4021	-94.66876

Appendix B. Operation of Ozark groundwater model and its use to evaluate water availability for appropriation

December 27, 2010

Sam Perkins
With contributions from Andy Lyon on model runs
Kansas Department of Agriculture, Division of Water Resources

Contents

Introduction

Since obtaining the Ozark groundwater model from the USGS in 2009, we have used it to help evaluate available water for appropriation from the Ozark and Springfield aquifer system on the basis of how much water remains in storage in the Ozark aquifer 100 years into the future. This Appendix documents model testing, methods for evaluating availability for appropriation from the Ozark and Springfield Plateau aquifers, and results of the analysis.

Based on recent discussions at DWR, the Chief Engineer determined that water may be appropriated from the Ozark Plateau Aquifer, including both the Springfield Plateau aquifer (source formation code 710) and the Ozark aquifer (source code 890) on the basis of projected storage depletion in the Ozark aquifer, represented by model layer 4.

Remaining storage volume in the Ozark aquifer is based on parameters that have been specified or calibrated for the model and reported in Czarnecki et al. (2009). The best available estimates of remaining storage at present and of remaining storage 100 years into the future are those based on the model. For this purpose, the model period of simulation was extended fifty years to the year 2107, so that the storage depletion due to pumping for 100 years can be directly evaluated for the model run.

The threshold for appropriating water from the Ozark Plateau Aquifer was defined as the quantity of pumping that would deplete storage in the Ozark aquifer by 25 percent in 100 years, as represented by the Ozark groundwater model. Water stored in the layers above the Ozark was not considered in the analysis. The model was used to evaluate both a total maximum authorized quantity of water available for appropriation and a local quantity available within two miles of any point on a map of the model extent within Kansas. The total maximum authorized quantity was found to be 36,000 acre-feet per year within the active model domain of the Ozark Plateau Aquifer in Kansas, which includes currently authorized quantity of roughly 12,000 acre-feet per year. A map of maximum allowed authorized quantity within two miles of any point was produced as shown in Fig. B1.

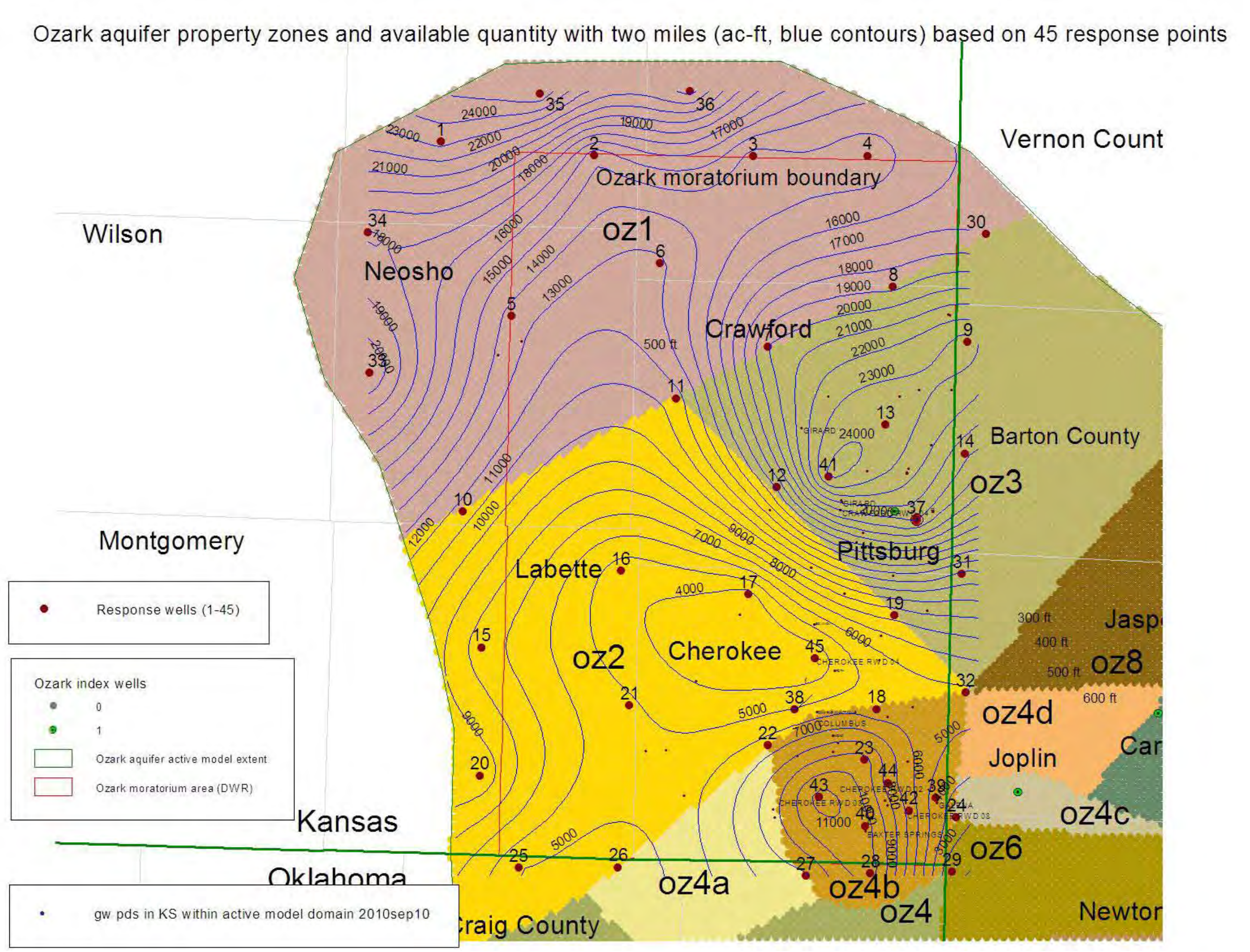

Fig. B1. Map of available quantity for pumping within two miles (ac-ft/yr) without depleting Ozark aquifer by more than twenty-five percent.

Assumptions and conditions of model runs used to evaluate availability

Simulations used to evaluate storage depletion are based on the following conditions (differences from the USGS model are noted):

- Future Kansas pumping is specified in terms of authorized quantity, which is applied at active points of diversion (pd's). For water rights with multiple pd's, authorized quantity is distributed uniformly over associated pd's. DWR representation of Kansas pumping was substituted for USGS representation; pumping in other states is the same as in USGS model. Authorized quantity of water rights is based on September, 2010 query of the KDA-DWR Water Rights Information System (WRIS) database. Option is retained to specify reported use averaged over years 1990-2006 for scenarios. [USGS model represents average reported use in Kansas.]
- For wells screened in both Springfield and Ozark aquifer units, pumping distribution is proportional to transmissivity in the two units. [USGS model splits pumping 50/50.]
- Temporal pumping distribution: Increased future pumping is specified as a step increase that is applied in the first future stress period and held constant through 2107. [USGS model scenarios specify annual percentage increase in pumping, applied as step increase in each future stress period.]

- Spatial pumping distribution: Future pumping is specified at the current set of active points of diversion as a multiple of authorized quantity. [USGS model similarly applies assumed increase as annual percent to average use; locations are not coincident with points of diversion stored in WRIS, but they are close.]
- Storage depletion projections: Model simulations are considered valid only if specified pumping does not drop out as a result of cells going dry.

In addition to the differences noted above, the DWR model version used to evaluate availability differs from the model obtained from USGS as follows:

- Model scenarios were run by DWR with a standard version of MODFLOW 2005 (MF2005) in the public domain. On the other hand, the model developed by the USGS was run under the Groundwater Modeling System (GMS). This difference is discussed further below.
- The number of time steps per stress period was increased, partly to allow extracting intermediate solutions at annual intervals, and partly to improve convergence, especially for the last future stress period with large pumping growth rates. The simulations were also extended by five ten-year stress periods [Discretization (DIS) package]
- Maximum number of allowed solution iterations was increased to help obtain convergence in some cases [preconditioned conjugate gradient (PCG2) package]
- Output control was modified to write computed heads as formatted output for layers 2 and 4 only. [Output Control package]

Preprocessing: Future pumping scenarios are represented by input files for the WEL package, which are specified in an Excel spreadsheet template and exported as space-delimited files.

Postprocessing: The following programs were used to process model results:

- Extracting zone budgets using Zonbud.
- Extracting hydrographs of computed heads at selected locations [Hydmod (HYD) package and Hydfmt postprocessor]
- Extracting computed heads in format for input to Surfer (ReadHeads).

USGS Ozark groundwater model (Czarnecki et al., 2009)

The Ozark groundwater model was developed in the Little Rock, AR office of the USGS; see Czarnecki et al. (2009). The model was developed to run under MODFLOW-2000 (MF2K; Harbaugh et al., 2000) within the proprietary Groundwater Modeling System, or GMS (Aquaveo, 2010), He provided the model to DWR via ftp in December, 2009 as a set of computer files organized into folders corresponding to scenarios 1-5 as defined in his report. We requested that John also produce a version of the model that would run under a public domain version of MODFLOW, which he did for scenario 1, and ran using MODFLOW-2005 (MF2005; Harbaugh, 2005). Scenario 1 assumes no future increase in water use represented in the model for Kansas, Oklahoma and Missouri. He also provided, via email, a comparison of computed heads for scenario 1 between the models he ran under the GMS version using MF2K and the public domain version of MF2005 (Czarnecki, 2008).

Groundwater model calibration by the USGS focused on hydraulic parameters for the Ozark aquifer (layer 4) and precipitation recharge to the top model layer. These model parameters were calibrated automatically using PEST (Doherty, 1994) within the GMS environment; GMS imposed a maximum allowed limit of 99 parameters. Other model parameters were adjusted manually.

Initial DWR model testing

Initial work by DWR with the Ozark groundwater model is summarized here and documented in greater detail in a separate memo (Perkins, 2010), which is reproduced at the end of this Appendix. This memo should serve as an introduction to using the model.

Having obtained the Ozark groundwater model from USGS, we ran scenario 1 with MF2005 and compared results with those reported in Czarnecki et al. (2009). We then set up and ran Scenario 4 (two percent annual pumping increase in KS, OK and MO) to compare with published results, and addition scenarios of interest. Variations on Scenario 1 consisted of changes to the pumping file for input to the well package. Pumping files were constructed in Microsoft Excel file stress_periods.xls, with a spreadsheet serving as a template in which scenario conditions were specified. Based on initial testing, changes were made to discretization and solution files to increase the number of time steps per stress period and the maximum allowed solution iterations. In the original model, one time step was specified for each stress period, which vary in length from 120 to 9,497 days. We increased the number of time steps to specify one year per time step for the historical period (1958 through 2007) and for the future period (through 2057) represented by five ten-year stress periods, with one exception: 60 time steps (six per year) were specified for the last stress period (2048-2057) to counter difficulty in obtaining convergence.

Model runs for Scenarios 1 and 4 were compared against reported results in Czarnecki et al. (2009) on the basis of volumetric budgets, spatial distribution of computed heads at the end of model runs, and time series of computed heads at selected locations. Volumetric budgets are compared in Perkins (2010): T. 7a (USGS) vs. T. 7b (DWR). [These tables show budget inflow, outflow and net inflow, whereas the corresponding Table 10 in the USGS report shows only inflow and outflow, but not net inflow.] To compare computed head contours in the Ozark aquifer at end of Scenario 1 simulation, see Fig. 25 (USGS) and Fig 6 in DWR memo. [The contours shown in Fig. 6 were produced in Surfer and exported as shapefiles for ArcGIS or ArcView.] Compare simulated water-level altitude time series for Scenario 1 in Fig. 26 (USGS) and Fig. 5 (DWR memo). [Model grid cell coordinates for which time series were plotted in the USGS report were obtained from John by private communication.] A noticeable difference between DWR and USGS model version results for Scenario 4 is apparent in computed head time series for future stress periods when pumping causes cells to go dry; compare time series for Noel, MO in Fig. 32 (USGS) and Fig. 10 (DWR memo). For the DWR runs, the time when this occurs is bracketed more precisely with multiple time steps per stress period. Compare also the Carthage, MO time series in the same figures: in Fig. 32 (USGS), this cell goes dry in the same stress period as the Noel, MO cell; but Fig. 10 (DWR memo) shows that it does not go dry, but instead rebounds when a nearby cell with pumping apparently goes dry and shuts off the pumping.

Methods used in the analysis

Groundwater storage depletion: calculation of remaining storage volume

Remaining storage volume is calculated for a given model cell or extent of cells (i.e., zone) within a specified layer. We are interested primarily in remaining storage in the Ozark aquifer unit, layer 4, within Kansas, and will discuss storage in terms of that layer. We calculate two components of storage corresponding to confined and unconfined conditions as follows.

Available storage in a given layer, i (=4) under confined conditions requires that $h_i > z_{i-1}$; i.e., that the piezometric head measured or computed in that layer, h_i, is greater than the elevation of the top of the layer, which is defined by the bottom of layer i – 1 (=3), or z_{i-1}. Stored water under confined conditions is based on the compressibility of water; decreasing the head releases water by expansion of water. Available storage volume over a given area, A, under confined conditions corresponds to the water released when the piezometric head declines to z_{i-1}. This is given by $V_c = A(h_i - z_{i-1})S$, where $S = S_c(z_{i-1} - z_i)$, S = storativity, S_c = specific storage [L^{-1}], $(z_{i-1} - z_i) =$ saturated thickness of layer i,

Available storage in layer i under unconfined conditions is associated with gravity drainage of the layer as the head falls below the top of the layer. If the head is below the top of the layer, remaining storage is given by $V_u = A(h_i - z_i)S_y$, where S_y = specific yield, or the drainable porosity of the aquifer. Table 6 in Czarnecki et al. (2009) lists values for specific storage and specific yield (as well as horizontal and vertical components of hydraulic conductivity, ft/day) for all zones in each aquifer layer.

In summary, remaining storage volume is represented as the sum of storage under both confined and unconfined conditions, i.e. $V_r = V_c + V_u$, which is evaluated as follows, depending on the head, for each model grid cell within a given extent in layer i:

$$\begin{aligned} V_c &= A(h_i - z_{i-1})S_c(z_{i-1} - z_i) \\ V_u &= \quad A(z_{i-1} - z_i)S_y \end{aligned}, \quad h_i \geq z_{i-1} \tag{1a}$$

$$\begin{aligned} V_c &= \quad 0 \\ V_u &= A(h_i - z_i)S_y \end{aligned}, \quad z_{i-1} > h_i \geq z_i \tag{1b}$$

$$\begin{aligned} V_c &= 0 \\ V_u &= 0 \end{aligned}, \quad h_i < z_i \tag{1c}$$

Remaining storage is calculated in the postprocessor readHeads based on computed heads, aquifer layer elevations and storage properties, all of which are read by the postprocessor for a given scenario. ReadHeads collects this information by reading input files for the basic (BAS6), discretization (DIS) and layer-property flow (LPF) packages, and the output file of computed heads. ReadHeads is an expanded version of the program read_discret, which is described below. ReadHeads calculates remaining storage summed over each zone of the model, but also can optionally calculate remaining storage summed over all cells in a layer whose centers lie within a specified distance of a given location. These two capabilities are used to, first, determine the additional appropriation of pumping that will deplete 25 percent of storage in the Ozark aquifer unit in Kansas in 100 years; and, second, to develop a map of available water for appropriation that would deplete 25 percent of storage in the Ozark aquifer unit within two miles of any point on the map, holding all other pumping at authorized quantity.

Table B1 defines stress periods for the extended simulations through 2107 as they are specified for input to the discretization package (file 1950-2107.dis); stress period 14 (2048-2057), with 60 time steps, is simply repeated five times in stress periods 15-19.

Table B1. Model simulation stress periods extended through year 2107 for the DWR model version.

PERLEN (days)	NSTP	TSMULT	SSTR	Stress period	years/ strper	years/ step	starting date	ending date
3287	1	1	SS	1	8.9993	8.999	1/1/1950	12/31/1958
9497	26	1	TR	2	26.0014	1.000	1/1/1959	12/31/1984
1826	5	1	TR	3	4.9993	1.000	1/1/1985	12/31/1989
1826	5	1	TR	4	4.9993	1.000	1/1/1990	12/31/1994
1826	5	1	TR	5	4.9993	1.000	1/1/1995	12/31/1999
1827	5	1	TR	6	5.0021	1.000	1/1/2000	12/31/2004
365	1	1	TR	7	0.9993	0.999	1/1/2005	12/31/2005
120	1	1	TR	8	0.3285	0.329	1/1/2006	4/30/2006
579	1	1	TR	9	1.5852	1.585	5/1/2006	11/30/2007
3653	10	1	TR	10	10.0014	1.000	12/1/2007	11/30/2017
3652	10	1	TR	11	9.9986	1.000	12/1/2017	11/30/2027
3653	10	1	TR	12	10.0014	1.000	12/1/2027	11/30/2037
3652	10	1	TR	13	9.9986	1.000	12/1/2037	11/30/2047
3653	60	1	TR	14	10.0014	0.167	12/1/2047	11/30/2057
3652	60	1	TR	15	9.9986	0.167	12/1/2057	11/30/2067
3653	60	1	TR	16	10.0014	0.167	12/1/2067	11/30/2077
3652	60	1	TR	17	9.9986	0.167	12/1/2077	11/30/2087
3653	60	1	TR	18	10.0014	0.167	12/1/2087	11/30/2097
3652	60	1	TR	19	9.9986	0.167	12/1/2097	12/1/2107

Development of future pumping scenarios

Future scenarios developed by DWR to evaluate availability on the basis of storage represent Kansas pumping differently than the original USGS scenarios in two significant ways. First, pumping from dual-screened wells (i.e., those pumping from both Springfield and Ozark aquifer units) was changed from being equally divided between the two units to being proportional to transmissivity in the two units. In the USGS version, pumping is equally divided between the two aquifer units; in the DWR version to be proportional to transmissivity in the two units. Second, future Kansas pumping is specified in terms of authorized quantity. These changes are discussed below.

Distribution of pumping between layers for dual-screened wells

Nearly all of the appropriated groundwater within the active model domain in Kansas is from the Ozark aquifer. However, some water is pumped from dual-screened wells associated with rights held by Pittsburg (8 wells, 5,247 ac-ft authorized) and Cherokee RWD 2 (4 wells, 105 ac-ft authorized).

In the USGS model, pumping was divided equally between Springfield and Ozark aquifer units. This is consistent with reported use in WRIS, which does not identify how much is pumped from each unit, but instead shows the full reported amount twice, once for each aquifer unit. However, for the DWR model version, we assume that the fraction of pumping from each layer is proportional to transmissivity as a fraction of total transmissivity for the two layers. This approach is suggested in the MODFLOW manual (McDonald and Harbaugh, 1988, p. 8-2) and in Anderson and Woessner (2002, p. 149). For the dual-screened Pittsburg wells, this changes the ratios from a 50/50 split to a distribution of 96 percent pumped from the Ozark and 4 percent from the Springfield. This is a significant change in terms of Kansas pumping, since most of the Pittsburg wells are dual-screened and represent nearly half of average Kansas reported use or appropriation within the model domain, and projected pumping increases are applied only to Ozark pumping.

Representing future Kansas pumping in terms of authorized quantity

Future scenarios used to project storage in the Ozark aquifer were initially devised in terms of pumping data in the original USGS model, which was based on average reported use for Kansas pumping and estimated pumping in Missouri and Oklahoma. For the most recent historical period ending November 30, 2007, Table B2 summarizes the assumed pumping by state and model layer in the USGS model, which is projected into the future for scenario 1 with no increase in water use. It shows a total assumed 7,658 ac-ft/yr pumped by Kansas.

Table B2. Projected pumping in USGS model for each state and layer, ac-ft/yr for Scenario 1.

	Springfield aqf. (L2)		Ozark aqf. (L4)		Both layers		Ozark
state	count	sum	count	sum	count	sum	fraction
KS	36	-1671.3	90	-5986.69	126	-7657.99	0.782
MO	60	-562.517	293	-71831.8	353	-72394.3	0.992
OK	41	-2537.63	27	-4441.48	68	-6979.11	0.636

[source: range i5486:p5490, sheet wells_baseline, file stress_periods.xls, in \gw\Ozark\model]

Future scenarios are defined as they are listed in Table B3. Scenarios 1-5 were reported in Czarnecki et al. (2009); scenarios 1, 4, 6 and 7 were run with the DWR model version as reported in a previous memo (Perkins, 2010, attached). Scenarios 1-7 defined pumping increases in terms of annual percentages listed in Table B3 and ran fifty years into the future through 2057. Remaining storage was not evaluated for these scenarios.

The remaining scenarios 8-15 represented future pumping increases differently from scenarios 1-7. Instead of specifying an annual growth rate as a percent of current pumping, future pumping is specified by a step increase as a multiplying factor that is applied to current pumping and which begins with the first future stress period. For example, in Scenario 8, future Kansas pumping is twice that for the most recent historical stress period. The first three scenarios (1, 1w and 1aq) and scenarios 8-15 were set up to run 100 years into the future, through 2107.

Description of future pumping scenarios

For the future storage depletion simulations, pumping files were composed in an Excel spreadsheet template in which the original USGS representation of pumping in Kansas was replaced by records based on GIS queries of the KDA-DWR Water Rights Information System (WRIS) database, while retaining the USGS representation of pumping in Missouri and Oklahoma. The Excel spreadsheet template provides the option to specify pumping either as an average of reported groundwater use over years 1990-2006 or as authorized quantity for each point of diversion. The option to specify authorized quantity entails an additional complication, namely that water rights often encompass multiple points of diversion. This is handled by uniformly distributing the quantity authorized for each water right over the points of diversion associated with the water right; this is done with an ArcView Avenue script. (Wilson, 1999)

Table B3. List of future scenarios

Scen-ario	pct (KS)	pct (MO, OK)	USGS [1]	DWR [2]	KS factor	MO OK factor	Source of pumping data
1	0	0	y	y			USGS model
1w	0	0	y				DWR WRIS: avg reported use 1990-2006
1aq	0	0	y				DWR WRIS: authorized quantity Sep 2010
2	1	1	y				USGS model
3	0	1	y				USGS model
4	2	2	y	y			USGS model
5	4	4	y				USGS model
6	2	0		y			USGS model
7	2	4		y			USGS model
8aq	0	0			2	1	DWR WRIS: authorized quantity Sep 2010
9aq	0	0			3	1	DWR WRIS: authorized quantity Sep 2010
10aq	0	0			1	2	DWR WRIS: authorized quantity Sep 2010
11aq	0	0			2	2	DWR WRIS: authorized quantity Sep 2010
12aq	0	0			3	2	DWR WRIS: authorized quantity Sep 2010
13aq	0	0			4	2	DWR WRIS: authorized quantity Sep 2010
14aq	0	0			5	2	DWR WRIS: authorized quantity Sep 2010
15aq	0	0			6	2	DWR WRIS: authorized quantity Sep 2010

[1]: Listed in Table 8 of Czarnecki et al. (2009). [2]: Scenarios run under DWR model version and reported in memo on initial model testing.
[Source: sheet pumping_scenarios in file stress_periods_pumping_scenarios_thru_2107.xls, folder \gw\Ozark\thru_2107.]

The average groundwater use in Kansas specified by the revised spreadsheet is 7,522 ac-ft/yr; the USGS model version specifies 7658 ac-ft/yr, which is 136 ac-ft/yr or 1.8 pct greater than the average based on the WRIS database, and is considered a very small discrepancy. The corresponding authorized quantity is 12,196 ac-ft/yr.

Table B4 lists the future pumping scenarios, model run name files, multiplying factors and specified pumping for the states and for Pittsburg. The first scenario (1) uses the pumping data prepared for the Scenario 1 model obtained from the USGS. For the second scenario (1w), the Kansas portion of the pumping data prepared by USGS is replaced by data prepared by DWR, which specifies reported use averaged over years 1990-2006 at current points of diversion, based on a query of WRIS in September, 2010, while pumping data for other states is the same as the USGS model data. Table B4 shows that the specified total pumping in Kansas for Scenarios 1 and 1w differ only slightly. For Scenario 1aq, authorized quantity is specified at each point of diversion. In the case of a water right with multiple pd's, the authorized quantity for the water right is distributed uniformly over its pd's.

For the remaining scenarios, Table B4 lists the factors multiplied by pumping in Kansas and other states; these factors are also included in the scenarios' model run name files. Common to all of the increased pumping scenarios is the assumption that the growth occurs at the pumping locations for the last historical stress period ending in 2007.

Table B4. Summary of pumping for revised future scenarios based on DWR compilation of Kansas pumping data for input to model, and on USGS compilation for other states. Future increases in pumping as multiples of current pumping and projected pumping volume by Kansas, Oklahoma and Missouri (ac-ft/yr).

Scen-ario	name file (extension NAM)	cell h4934	KS factor	OK-MO factor	KS	Pittsburg	OK	AR-MO
1	scen_1_KSfactor_1_MOfactor_1		1	1	7,658	2,916	6,979	72,394
1w	scen_1w_KSfactor_1_MOfactor_1	KSUSE	1	1	7,522	3,158	6,979	72,394
1aq	scen_1aq_KSfactor_1_MOfactor_1	KSAQ	1	1	12,196	5,247	6,979	72,394
8aq	scen_8aq_KSfactor_2_MOfactor_1	KSAQ	2	1	24,070	10,258	6,979	72,394
10aq	scen_10aq_KSfactor_1_MOfactor_2	KSAQ	1	2	12,196	5,247	11,421	144,226
11aq	scen_11aq_KSfactor_2_MOfactor_2	KSAQ	2	2	24,070	10,258	11,421	144,226
12aq	scen_12aq_KSfactor_3_MOfactor_2	KSAQ	3	2	35,944	15,268	11,421	144,226
13aq	scen_13aq_KSfactor_4_MOfactor_2	KSAQ	4	2	47,818	20,278	11,421	144,226
14aq	scen_14aq_KSfactor_5_MOfactor_2	KSAQ	5	2	59,692	25,288	11,421	144,226
15aq	scen_15aq_KSfactor_6_MOfactor_2	KSAQ	6	2	71,566	30,298	11,421	144,226

[from sheet wris_based_cases in stress_periods_storage_projection_thru_2107.xls, folder \gw\Ozark\thru_2107\pumping]

Producing pumping files for input to MODFLOW

Pumping files for the above scenarios were produced in spreadsheet build_scenarios_8-15v2 of Excel file Ozark_pumping_template_thru_2107.xls, folder \gw\Ozark\thru_2107\pumping. After specifying the scenario, the corresponding pumping file was produced by copying and exporting the spreadsheet as a space-delimited file (extension PRN); after exporting, the file extension was changed to WEL to help identify the pumping files for input to MODFLOW.

Scenarios 1aq, 8aq and 10aq-15aq listed in Table B4 are selected in sheet build_scenarios_8-15v2 by specifying the scenario number 1-15 in cell i4934 and “KSAQ” cell h4934. The multiplying factors corresponding to each scenario (Table B6, above) are listed in sheet new_pumping_scenarios, and are referenced by index functions in cells j4934 for KS and k4934 for MO and OK. These factors are then specified in column N (rows 4935:5481) for each corresponding well pumping from the Ozark aquifer (layer 4). For all states, only a factor of one is applied to wells pumping from the Springfield aquifer (layer 2). The range O4935:O5481 specifies the factor to be applied to wells in both layers and all three states for all scenarios 1 and 8-15. Current pumping (cu. ft/day) is specified in range I4935:I5481. Pumping to be read by MODFLOW (cu. ft/day) is given by range D4935:D5481 as the product of current pumping in col. I and the multiplying factor in column O. Column T converts the pumping specified in column I to ac-ft/yr by dividing by 119.26078 [=(43560 sqft/acre) / (365.25 days/yr)].

Results of analysis to determine total available water for appropriation

Verification of future pumping scenario simulations

The USGS postprocessing program ZoneBudget was used to summarize volumetric flow budgets for groundwater model scenarios. The budgets include all flow components and exchanges between zones. For additional background on this topic, refer to the Jan 2010 memo reproduced below (p.). The use of these budgets to verify future scenarios is illustrated by comparing the pumping component of budgets for scenarios 13aq (4x authorized quantity in KS) and 14aq (4x authorized quantity in KS). Figs. B2 and B3 plot groundwater pumping and change in storage for the Ozark aquifer zones corresponding to KS, OK and AR-MO.

For scenario 13aq (4x authorized quantity in KS), the budget summary includes 47,144 afy of future pumping in KS that is maintained through the end of the simulation in 2107, as shown in Fig. B2. Annual change in storage changes smoothly after the step change in pumping occurs at the beginning of future stress periods. Other scenarios with less pumping than under scenario 13aq were also found to maintain specified pumping through the end of simulations.

In contrast, Kansas pumping under Scenario 14aq (5x KS authorized quantity) cannot be maintained. As Fig. B7 shows, KS pumping declines suddenly by 19,437 afy, from 58,931 afy at the end of 2044 to 39,493 afy at the end of 2045. This happens because the imposed pumping causes the piezometric head to drop below the bottom of the Ozark aquifer, creating dry cells in model layer 4. The dry cells are eliminated from the model along with the pumping. Consequently, scenario 14aq cannot be considered a valid scenario for evaluating effect of pumping on storage because such a significant quantity of pumping drops out during the simulation. However, the loss of pumping suggests that Scenario 14aq imposes more pumping than can be sustained.

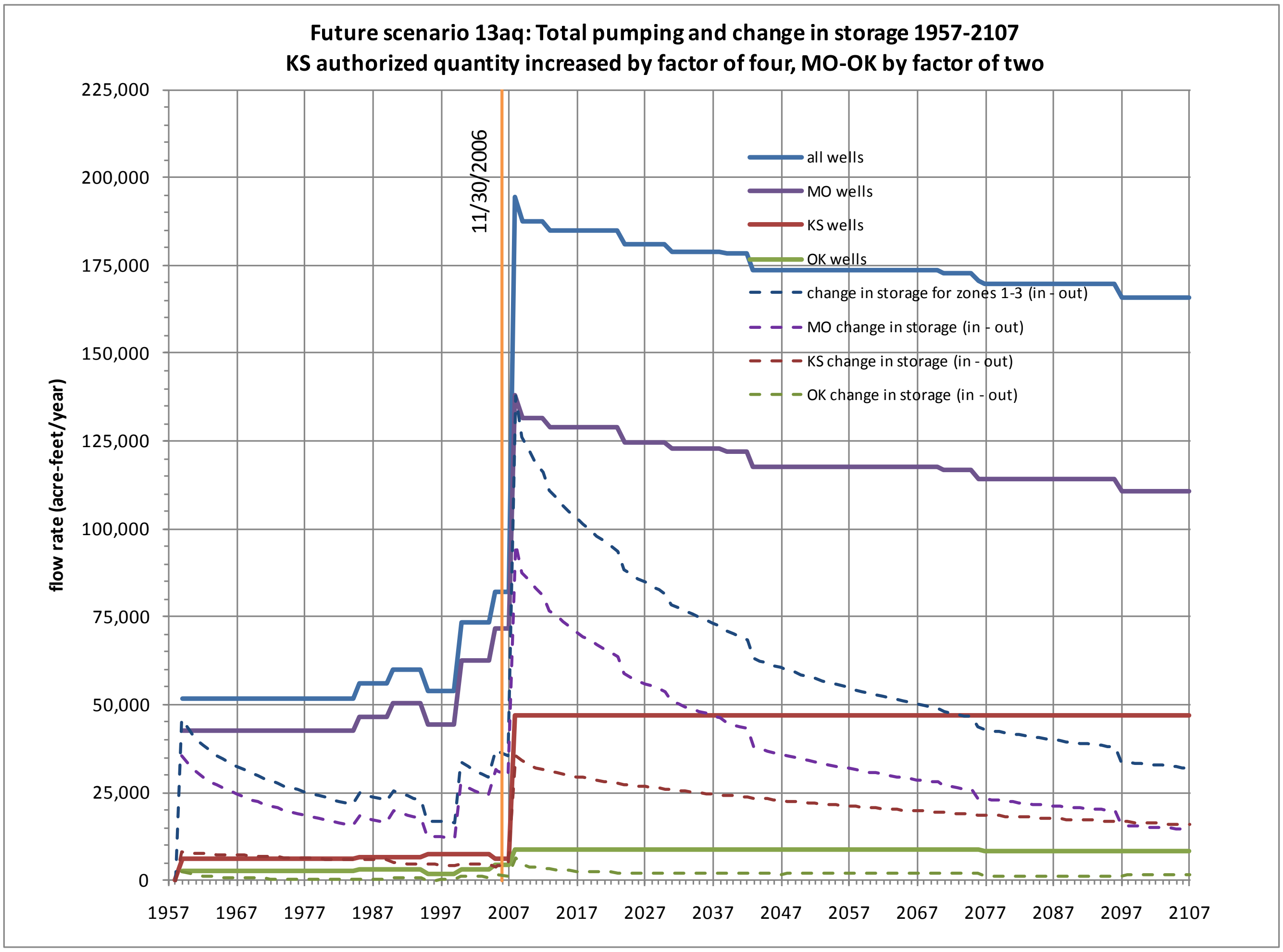

Fig. B2. Pumping and change in storage by state for Ozark aquifer, scenario 13aq (4x KS, 2x MO). [file budget_scen_13aq_KSfactor_4_MOfactor_2.xls, sheet budget_sort_by_zones_AFY at cr10]

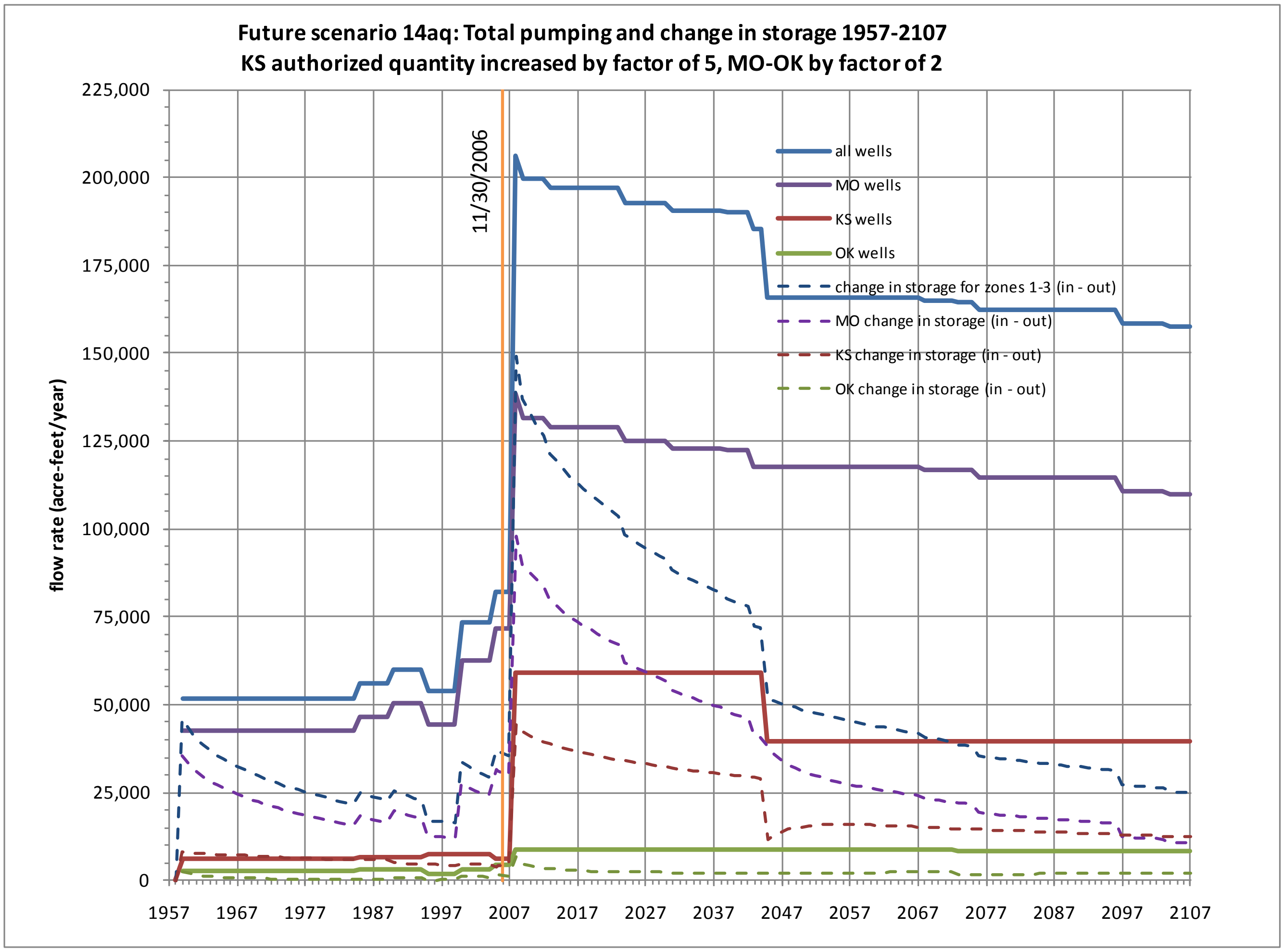

Fig. B3. Pumping and change in storage by state for Ozark aquifer, scenario 14aq (5x KS, 2x MO). [file budget_scen_14aq_KSfactor_5_MOfactor_2.xls, sheet budget_sort_by_zones_AFY at cr10]

Remaining storage in Kansas for future pumping scenarios

The spatial distribution of remaining storage at the end of 2107 as a fraction of current storage is mapped in the figures below for scenarios 12aq and 13aq, listed in Table B6. Fig. B4 shows, for scenario 12aq (3x KS authorized quantity and 2x OK-MO pumping), the storage depletion is less than 25 percent most of the Kansas moratorium zone; depletion exceeds 25 percent for the Pittsburg vicinity, an area just west of the state line east of Joplin, and a thin band south of Pittsburg and extending to the northwest.

Fig. B5 is a map of remaining storage fraction for scenario 13aq (4x KS authorized quantity and 2x OK-MO pumping). Compared to scenario 12aq in Fig. B4, it shows a significant expansion of the areas exceeding 25 percent depletion. Based on the extents of depletion exceeding 25 percent, the specified pumping of 36,000 ac-ft/yr for scenario is considered a reasonable upper limit for authorized quantity in Kansas within the active model domain.

Effect of hydraulic property zones on remaining storage distributions

The maps shown in Figs. B4 and B5 show an apparently artificial feature of the spatial distributions of remaining storage fraction. This feature consists of straight edges bounding classes of remaining storage fraction to the southwest and southeast of Pittsburg. Comparison with Fig. B1 shows that the straight lines coincide with zones of hydraulic properties for the Ozark aquifer layer 4. The boundaries delimit areas with differing hydraulic conductivity, specific storage and specific yield that give rise to the edges in Figs. B4 and B5.

This feature is more pronounced in alternate versions of the maps in Figs. B6 and B7. These display the same distributions of remaining storage fraction, but the classes are generated automatically.

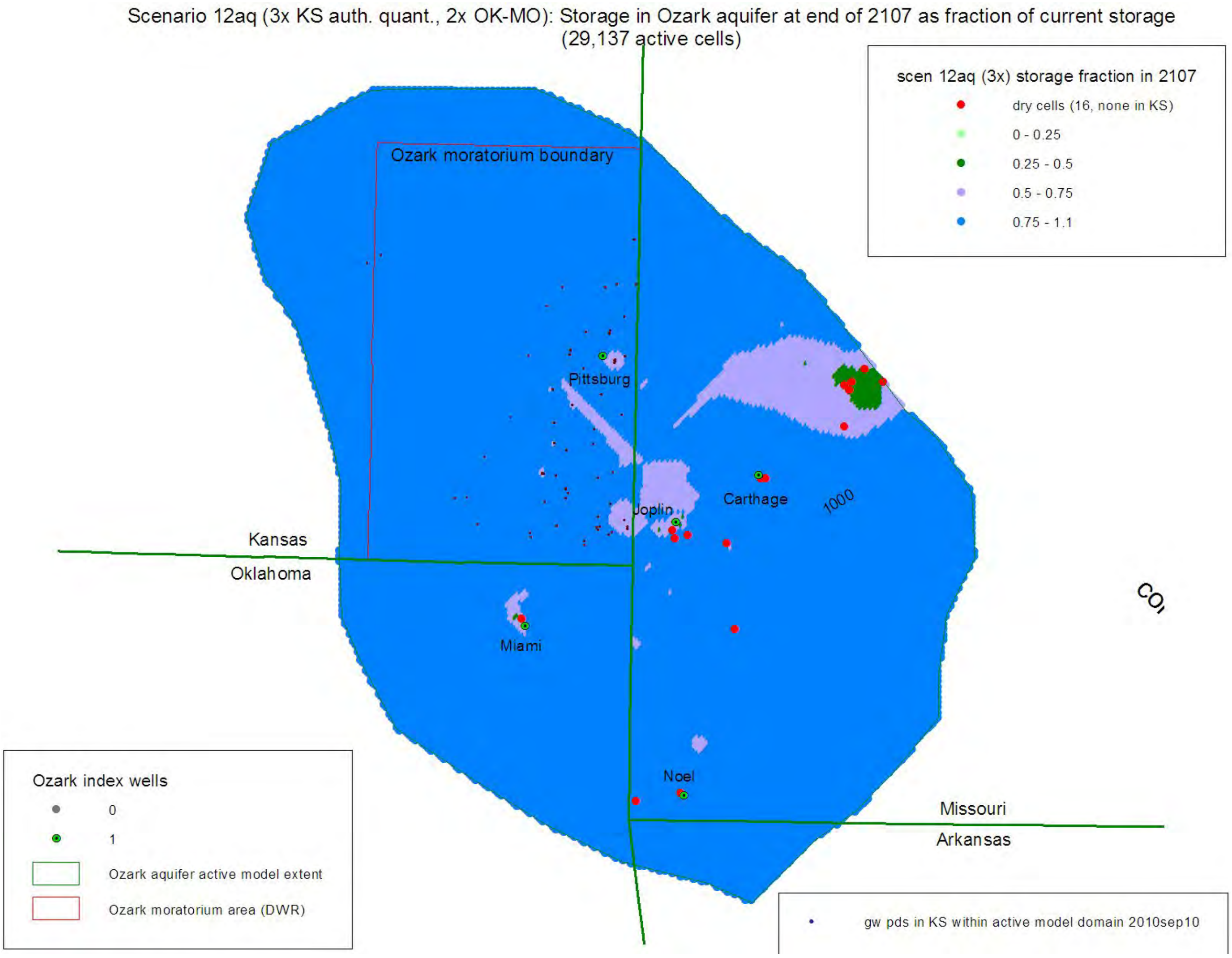

Fig. B4. Remaining storage fraction at end of 2107, scenario 12aq (3x KS authorized quantity, 2x MO pumping). [scen12aq_remaining_storage_fraction.jpg]

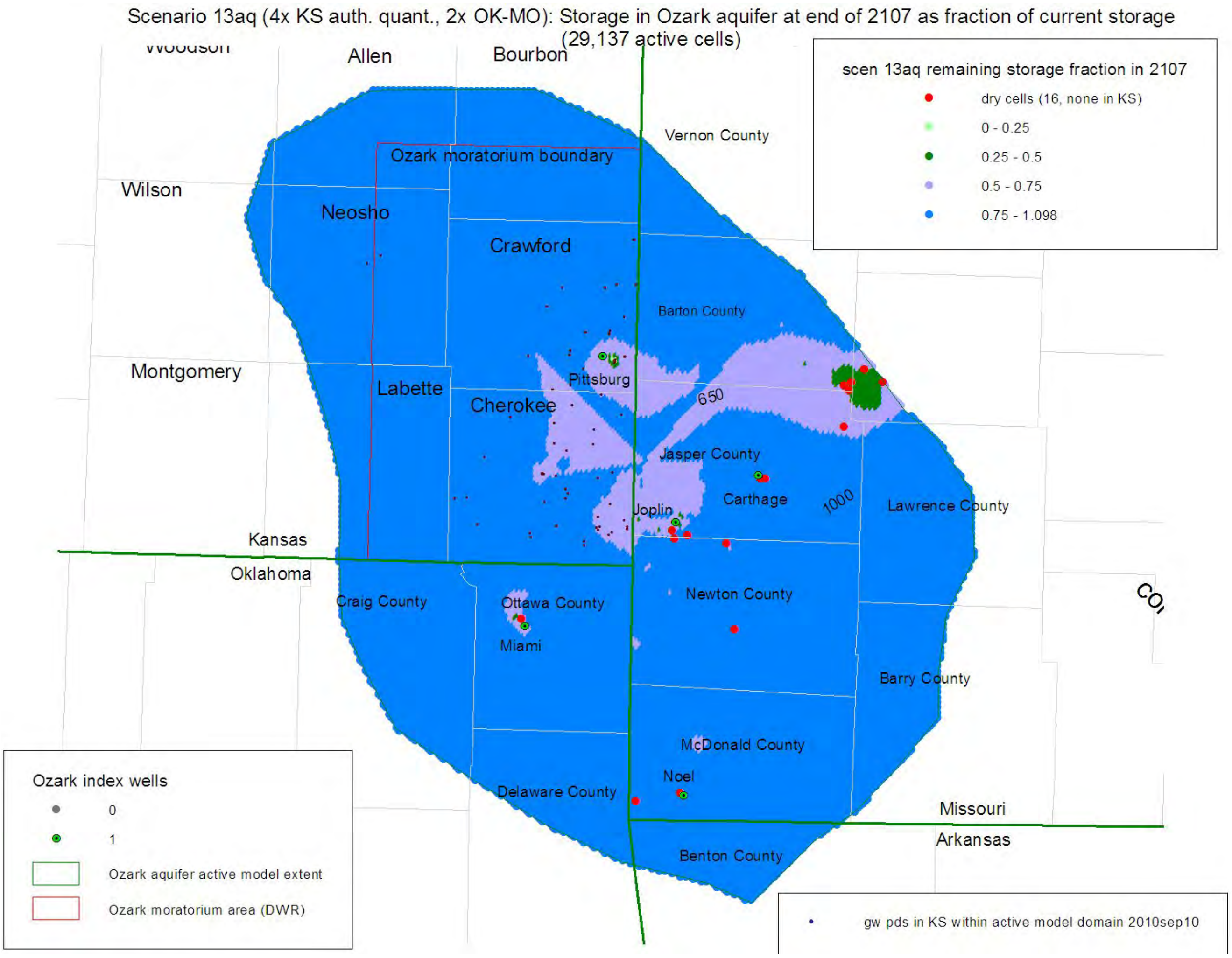

Fig. B5. Remaining storage fraction at end of 2107, scenario 13aq (4x KS authorized quantity, 2x MO pumping). [scen13aq_remaining_storage_fraction.jpg]

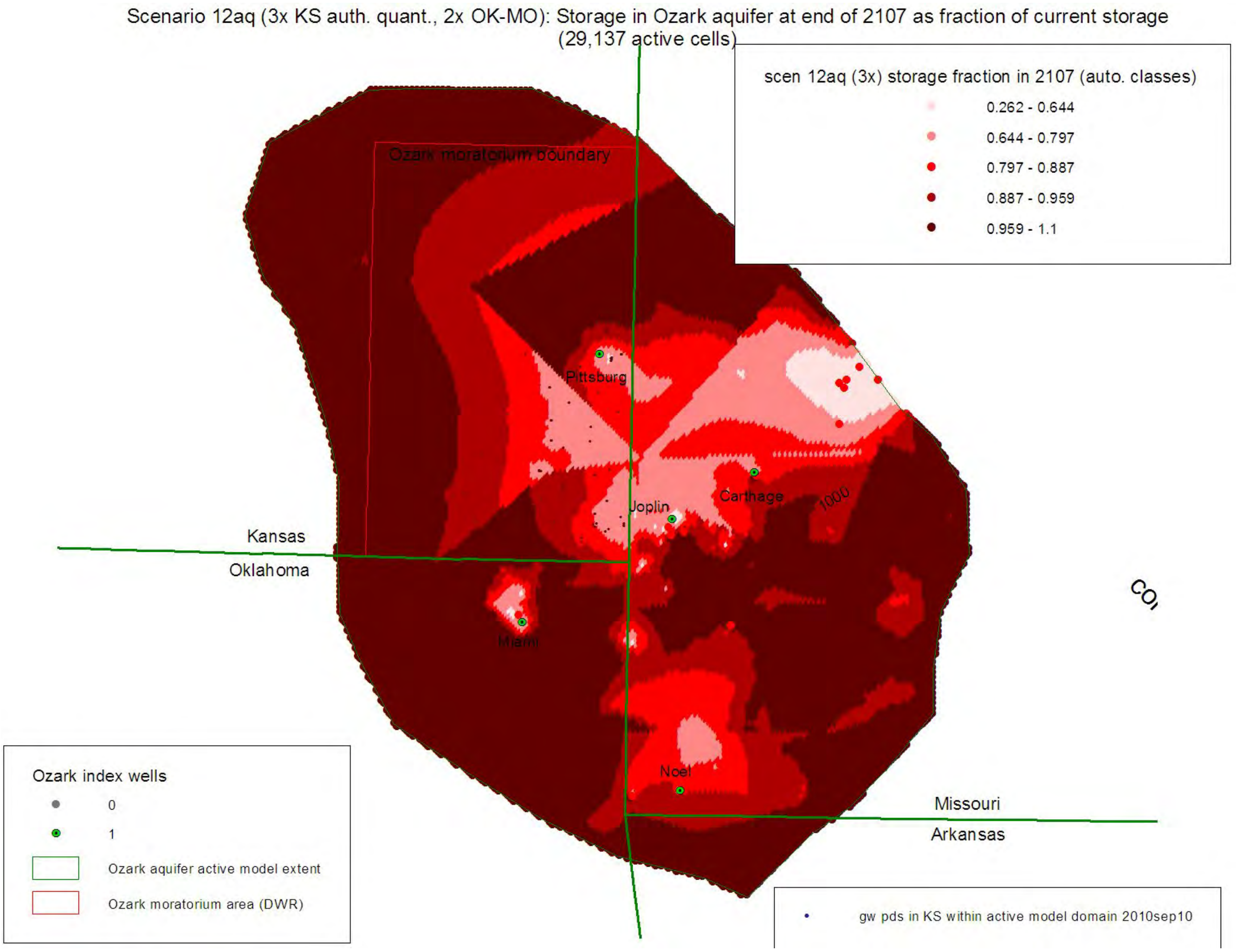

Fig. B6. Remaining storage fraction distribution at end of 2107, with automatically selected classes, for scenario 12aq (3x KS authorized quantity, 2x MO pumping), [scen12aq_remaining_storage_fraction _auto_classes.jpg]

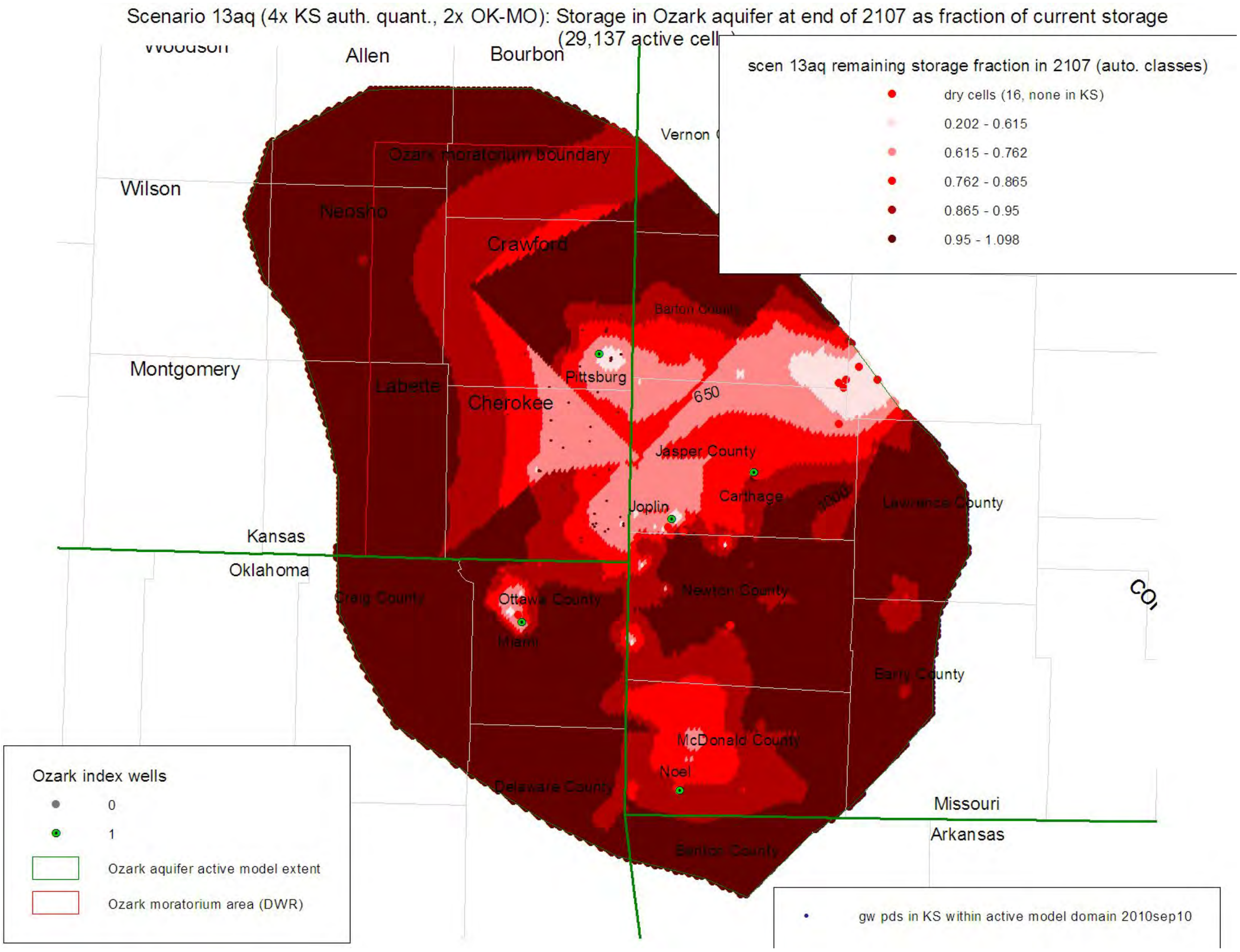

Fig. B7. Remaining storage fraction distribution at end of 2107, with automatically selected classes, for scenario 13aq (4x KS authorized quantity, 2x MO pumping), [scen13aq_remaining_storage_fraction _auto_classes.jpg]

Quantifying local availability of water for appropriation

Remaining storage near Pittsburg: two additional scenarios

To examine the issue of how local availability should be quantified, the remaining storage fraction in the Ozark aquifer was evaluated for a cylindrical volume centered on a Pittsburg well for varying radii (pd for File 17465). Since Pittsburg holds 43 percent of the authorized quantity within the moratorium zone, this was considered the best place to start.

Remaining storage within two miles of the Pittsburg point of diversion is affected not only by Pittsburg pumping but also by other pumping in Kansas, most significantly by the nearby municipalities summarized in Table B5. Scenario 12aq assumes authorized quantity increases by a factor of three at all pd's in the Kansas model area. To see how increased pumping by other rights affects remaining storage near Pittsburg, two additional scenarios were run in which pumping was increased only at the

Pittsburg wells by factors of 3 and 4, holding all other pd’s in Kansas at authorized quantity.

Table B5. Pumping scenarios for Pittsburg and nearby municipalities and for states.

col.	d	e	f	g	h	i	j
Wells	1w (use)	1aq (1x)	11aq (2x)	12aq (3x)	13aq (4x)	12aq (3x Pittsburg wells only)	13aq (4x Pittsburg wells only)
Pittsburg	3,158	5,247	10,258	15,268	20,278	15,268	20,278
Crawford RWD 5	259	524	1,049	1,573	2,098	524	524
Frontenac	335	578	1,157	1,735	2,314	578	578
sum	3,752	6,350	12,463	18,576	24,689	16,370	21,381
Pittsburg/sum	0.842	0.826	0.823	0.822	0.821	0.933	0.948
KS	7,522	12,196	24,070	35,944	47,818	22,216	27,226
OK	6,979	6,979	11,421	11,421	11,421	11,421	11,421
AR-MO	72,394	72,394	144,226	144,226	144,226	144,226	144,226

[range a2:j12, sheet remStg_nr_Pittsburg, file remaining_storage_near_Pittsburg.xls]

Table B6 summarizes remaining storage fraction for key scenarios listed in Table B5 (cols. d-h) and for the additional Pittsburg scenarios (cols. i and j). For Scenario 12aq (col. g), with 35,944 afy pumping in Kansas, remaining storage fraction at the end of 2107 is 0.746 for a radius of two miles. If allowable pumping is evaluated on the basis of remaining storage within this radius, then the imposed pumping under this scenario may represent a reasonable upper limit on authorized quantity in Kansas within the active model domain or the moratorium zone.

Table B6 shows remaining storage fraction for these scenarios in cols. i and j. Comparison of cols. g and i in Table B6 shows that development at other pd’s in Kansas increases storage depletion within two miles of Pittsburg wells by ten percent with 3x pumping (12aq), and by about eighteen percent with 4x pumping (13aq). Taking Scenario 12aq with pumping at all pd’s in Kansas as the basis of evaluating availability suggests that 36,000 afy is a reasonable upper limit on authorized quantity for the moratorium zone.

Table B6. Remaining storage fraction near Pittsburg for varying distance 0.5 to 5 miles.

col.	d	e	f	g	h	i	j
radius* mi	no. cells	1aq (1x)	11aq (2x)	12aq (3x)	13aq (4x)	12aq (3x Pittsburg wells only)	13aq (4x Pittsburg wells only)
0.5	4	0.998	0.830	0.628	0.309	0.741	0.573
1	12	0.999	0.857	0.677	0.431	0.783	0.643
2	52	0.999	0.898	**0.746**	0.560	**0.845**	**0.735**
3	116	0.999	0.926	0.789	0.627	0.884	0.788
3.38514	148	0.999	0.934	0.803	0.647	0.896	0.805
4	207	0.999	0.943	0.821	0.674	0.911	0.827
5	317	0.999	0.951	0.843	0.707	0.925	0.854

(*) distance from point of diversion for File 17465.
[range a15:j23, sheet remStg_nr_Pittsburg, file remaining_storage_near_Pittsburg.xls]

Mapping local availability of water for appropriation

An assumption common to the future pumping scenarios is that increased pumping is assumed to occur at the pumping locations for the last historical stress period ending in 2007. However, increases in appropriation could occur elsewhere within the moratorium zone. To provide a basis for evaluating availability anywhere within the moratorium zone, a method of mapping available quantity for appropriation was devised.

Based on the results of the pumping scenarios for Pittsburg, a reasonable criterion for evaluating availability emerged as the authorized quantity that would deplete storage by 25 percent in 100 years, evaluated for a cylindrical volume with a radius of two miles. We developed a map to represent allowable pumping, holding all other Kansas pumping at current authorized quantity. To evaluate availability as so defined, a set of 45 “response points” was chosen at which to impose additional pumping that would deplete storage by 25 percent.

The selected response points are shown in Fig. B8. Their chosen locations were intended to provide a sufficient coverage to allow contouring the evaluated points. The selection also considered the aquifer property zones for the Ozark aquifer (layer 4). Fig. B8 shows the zones within the Kansas extent of the model. For the corresponding values (hydraulic conductivity, specific storage and specific yield), see Table 6 and Fig. 13 in Czarnecki et al (2009). Response points were selected along boundaries and at vertices of these zones as well as just outside the Kansas state line into Missouri and Oklahoma.

Method of evaluating local availability at response points

The problem is to determine how much pumping at a response point, including any existing pumping within a two-mile radius, will deplete 25 percent of water in storage in the Ozark aquifer; i.e., to solve the inverse of a function $f(p)$ for f=0.75, where p = pumping (ac-ft/yr) and f = remaining storage fraction after 100 years. For a given value of p, $f(p)$ is determined by running the model for the corresponding scenario and then evaluating the change in storage within two miles in 100 years. The inverse function $p(f)$, or $f^{-1}(p)$, can be solved by trial and error, based on evaluating $f(p)$ for a series of values p_i as follows.

At each response point, the required pumping is found by trial and error, but assisted by the secant method once the solution had been bracketed or roughly approximated. The secant method is a variation on Newton’s method of solving for a root in which the derivative is represented numerically (see, for example, Conte and deBoor, 1980, section 3.5; Press et al., 1986, section 9.2). Given a series of trial solution pairs (f_n, p_n) for i=0,1,…,n, the secant method solves for $p(f)$ by

$$p(f) = p_{n-1} + \frac{(f - f_{n-1})}{p'(f)}, \tag{2a}$$

where the derivative in Newton’s method is approximated by the forward difference

$$p'(f) \approx \frac{(p_n - p_{n-1})}{(f_n - f_{n-1})}, \tag{2b}$$

In our case, we set f=0.75. Each secant step at a response point requires a separate model run; however, the solution for a neighboring response point can provide a sometimes good initial guess. The procedure typically required only two trial-and-error steps preceding the secant step. Details of the solution procedure are described near the end of this appendix.

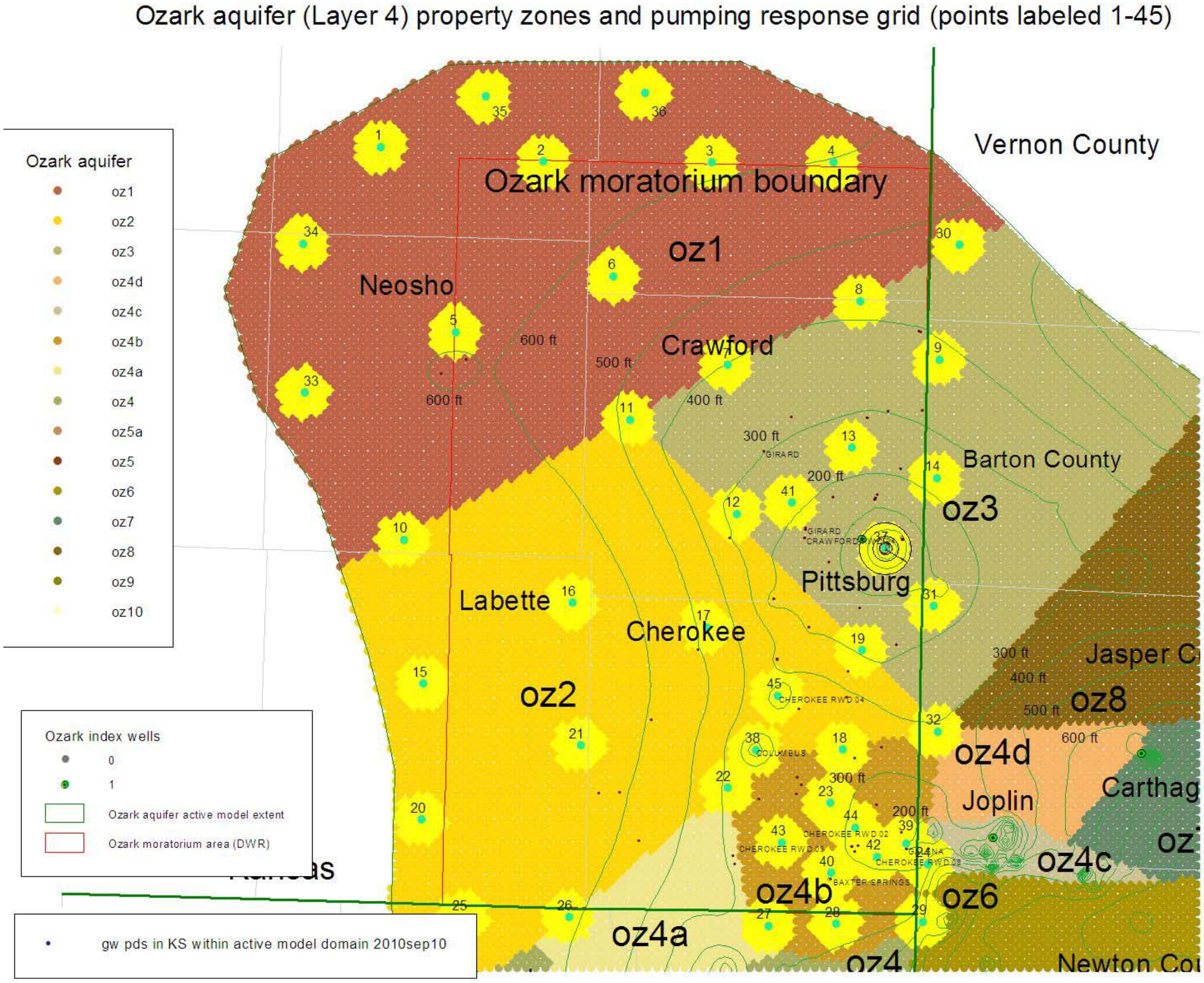

Fig. B8. Response point locations chosen to evaluate availability for appropriation, holding other pumping in Kansas at current appropriation. [file ozark_gw_pumping_response_gridpts.jpg in \gw\Ozark\map\images]

Spatially distributing pumping at a response point over local model grid cells

An important condition in solving for available quantity for appropriation at each of the response points listed is that the imposed pumping must remain active throughout each simulation in the solution series. If this condition is not maintained, then the solution is invalid. However, the solutions given by the quantities listed in column d of Table B9 would quickly create dry cells and disable the imposed pumping if the quantities were imposed at a single node. This was avoided simply by distributing the imposed pumping over a group of model cells, with the condition that the center coordinates of the cells over which the pumping is distributed are within two miles of the specified response point. An initial test of a distribution of imposed pumping over five cells (implemented in a pumping template sheet named build_scenarios_8-15v5) was found to be insufficient. Some experimentation indicated that distributing the pumping over a five-by-five grid of 25 cells centered on the response point would be sufficient to allow all the imposed pumping to be maintained to the end of each simulation. Such a square of cells fits easily within a two-mile circle centered on a response point. A circle with a two-mile radius encloses an area of 8,042 acres. Since model grid cells have an area of 159.225 acres each, a two-mile circle encloses an area corresponding to 50.5 grid cells. For any given location, roughly 50 grid cell centers will be enclosed by a two-mile circle.

The imposed pumping at each response point distributed over a five-by-five grid of cells was implemented in sheet build_scenarios_8-15v6, file Ozark_pumping_template_thru_2107.xls. For each specified response point, the 25 grid cell locations and assigned pumping were automatically generated, given the response well id number 1-45 and the total quantity to be imposed.

To verify that the imposed pumping was maintained to the end of each simulation, the zone budget for model layer 4 was graphed (using the format shown in Figs. A6 and A7) for each trial solution at a response point for which the imposed pumping was greater than previous trial solutions.

Results of evaluating local availability at response points

Table B7 summarizes the evaluation of availability at the 45 response points. The solution series at each point was listed in a separate sheet. Columns b and c give the projected (x,y) coordinates of each response point (UTM-15 NAD 1983 meters). Columns e and f identify the records in the spreadsheet corresponding to subscripts *n*-1 and *n*, respectively, in Eqns. 2a and 2b. Solution pairs are given by columns g and h for step *n*-1, and by columns i and j for step *n*. The numerical derivative (2b) is given by column k, and the solution (2a) is given by column d.

Table B7. Availability evaluated at 45 response points: allowable quantity for appropriation within two miles of each response point, including current appropriation, given by column d.

a	b	c	d	e	f	g	h	i	j	k
rsp_id	xutm_m	yutm_m	P | (f=0.75)	Rec pen (n-1)	Rec last (n)	pump afy p(n-1)	remstg fraction in 2107 f(n-1)	pump afy p(n)	remstg fraction in 2107 f(n)	df/dp
1	290695	4189579	23327	6	7	22000	0.7641	25000	0.7322	-1.06168E-05
37	352228	4140636	20120	10	11	20000	0.7527	22200	0.7027	-2.27621E-05
38	336497	4116067	5057	15	16	5000	0.7529	10000	0.5018	-5.0206E-05
45	339136	4122679	3268	19	20	3000	0.7668	5000	0.6411	-6.28921E-05
19	349359	4128235	8249	24	25	8000	0.7567	10000	0.7028	-2.69573E-05
32	358636	4118281	5783	27	28	6000	0.7447	8000	0.6962	-2.42478E-05
18	347110	4116139	5377	30	31	5000	0.7638	6000	0.7272	-3.65979E-05
22	332978	4111439	6454	33	34	5000	0.8116	8000	0.6845	-4.2346E-05
23	345490	4109587	9490	36	37	8000	0.8032	10000	0.7318	-3.56821E-05
43	339653	4104763	11466	39	40	9000	0.8349	12000	0.7316	-3.44216E-05
44	348566	4106588	7521	42	43	7000	0.7668	10000	0.6700	-3.2251E-05
39	354787	4104658	4434	45	46	4000	0.7646	7000	0.6637	-3.36302E-05
40	345597	4101031	10479	48	49	7000	0.8471	12000	0.7075	-2.79199E-05
42	351272	4103032	6705	51	52	6000	0.7719	7000	0.7409	-3.10269E-05
24	357403	4102115	3502	54	55	3000	0.7765	4000	0.7237	-5.28361E-05

27	337975	4094596	7778	57	58	7000	0.7897	10000	0.6366	-5.10366E-05
28	346295	4094885	10566	60	61	8000	0.8302	11000	0.7364	-3.1265E-05
29	356848	4095111	2013	63	64	1000	0.8163	3000	0.6854	-6.54282E-05
31	358144	4133609	11649	66	67	10000	0.7850	15000	0.6789	-2.12279E-05
12	334132	4144838	16041	69	70	15000	0.7825	18000	0.6888	-3.12416E-05
41	340904	4146222	24339	72	73	20000	0.8705	25000	0.7316	-2.77855E-05
13	348191	4152947	23614	75	76	20000	0.8352	25000	0.7173	-2.35748E-05
14	358538	4149196	20169	78	79	20000	0.7543	21000	0.7287	-2.56204E-05
9	358892	4163661	23518	81	82	20000	0.8512	30000	0.5636	-2.87625E-05
30	361259	4177608	16996	84	85	15000	0.7958	20000	0.6811	-2.29285E-05
8	349225	4170787	18746	87	88	15000	0.8376	20000	0.7207	-2.33787E-05
7	333031	4163008	20076	90	91	15000	0.8099	20000	0.7509	-1.1803E-05
11	321135	4156345	11454	93	94	10000	0.7782	15000	0.6811	-1.9429E-05
17	330502	4130996	3532	96	97	3000	0.7798	5000	0.6678	-5.60427E-05
16	314054	4134024	4411	99	100	3000	0.8252	5000	0.7186	-5.32701E-05
21	315111	4116591	5207	102	103	5000	0.7593	6000	0.7146	-4.46871E-05
26	313649	4095690	4235	105	106	3000	0.8390	5000	0.6949	-7.20921E-05
10	293507	4141680	11535	108	109	10000	0.7827	12000	0.7401	-2.13114E-05
15	295924	4124133	7435	111	112	5000	0.8319	10000	0.6637	-3.3634E-05
20	295722	4107540	9832	114	115	5000	0.8722	10000	0.7458	-2.52841E-05
25	300830	4095609	5030	117	118	5000	0.7515	6000	0.7031	-4.83785E-05
35	303507	4195758	25835	120	121	20000	0.8059	26000	0.7484	-9.58594E-06
36	322954	4196128	23415	123	124	20000	0.7858	25000	0.7334	-1.04725E-05
2	310531	4187791	15206	126	127	15000	0.7533	20000	0.6740	-1.58566E-05
3	331092	4187687	14472	129	130	13000	0.7737	15000	0.7415	-1.61108E-05
4	345925	4187727	14338	132	133	12000	0.7869	15000	0.7396	-1.5771E-05
34	281282	4177792	17872	135	136	15000	0.7898	20000	0.7205	-1.38609E-05
33	281467	4159642	21037	138	139	20000	0.7622	22000	0.7387	-1.1757E-05
5	299868	4167008	13582	141	142	12000	0.7775	15000	0.7253	-1.73933E-05
6	319115	4173814	12823	144	145	10000	0.7993	15000	0.7119	-1.74805E-05

[File Ozark_remaining_storage_summaries_ALyon_spp_2010Dec08.xls, range a1:k47 of sheet sequence_resp_centers]

A contour map based on local availability of water at response points

A contour map of local availability was produced on the basis of the solutions at the response points listed in Table B7. A comma-delimited text file with columns b, c and d from Table B7 defining (x,y,z) coordinates was imported into Surfer and used to produce the contours, which were exported as a 2-d shapefile for use in ArcView or ArcGIS. A map of the availability contours, superimposed on the hydraulic property zones for the Ozark aquifer, is shown in Fig. B1, and is reproduced as Fig. B9.

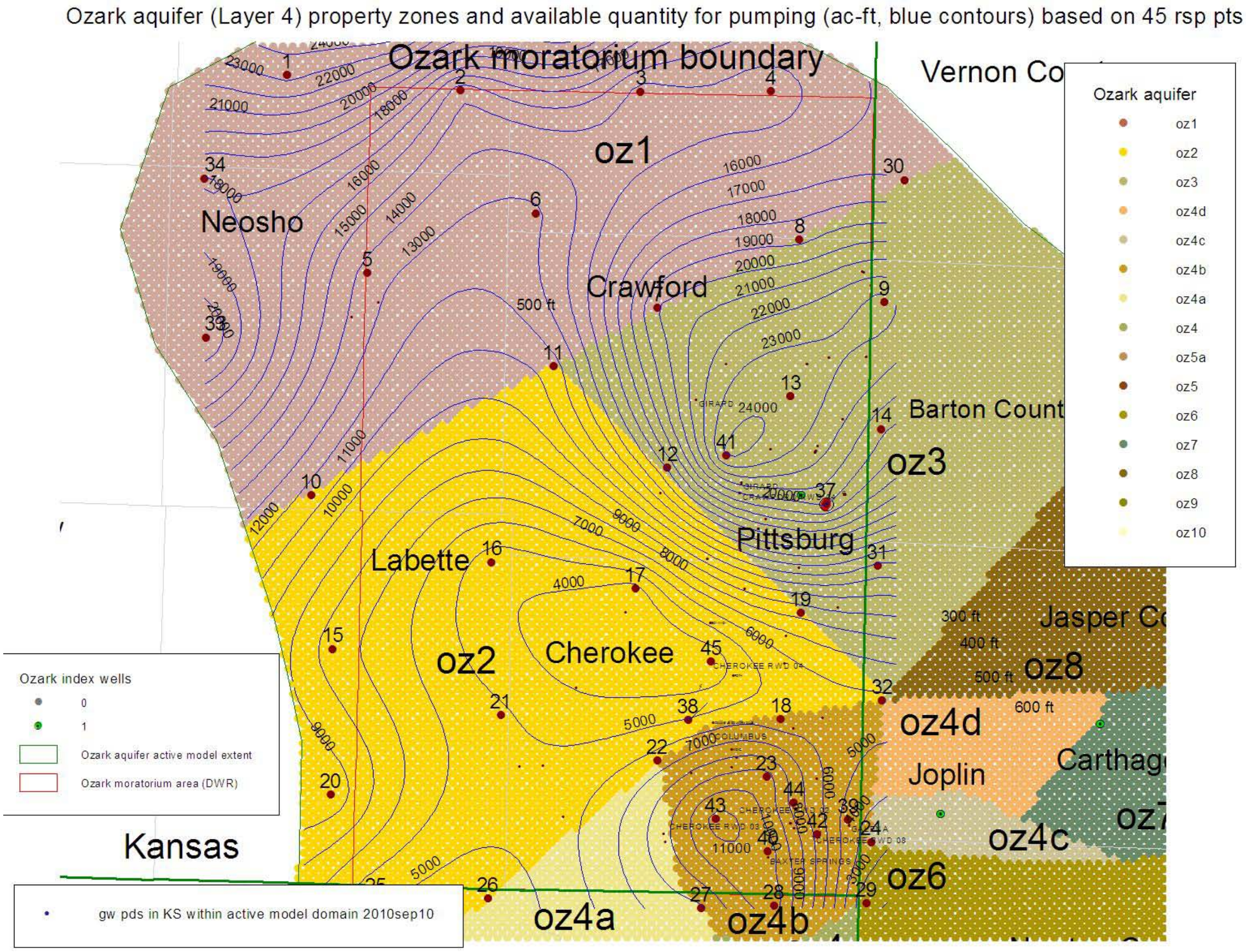

Fig. B9. Map showing contours of local availability of water for appropriation (including current appropriation) based on evaluation at 45 response points (Table B9), and hydraulic property zones for Ozark aquifer (layer 4). [ozark_aquifer_l4_avail_qty_45pts_2010dec03.jpg in \gw\Ozark\map\images]

Remaining storage in all model layers

The metric used to quantify availability of water for appropriation on the basis of depleting 25 percent of current storage in 100 years was reviewed by Steve Larson (SSPA, Inc.). He approved of our metric for this, but pointed out that depletion of the Ozark aquifer in layer 4 would also entail depletion of the layers above it.

In response to Steve's comment, we evaluated remaining storage in all four active model layers for two cases: Scenario 10aq with no additional pumping at a response point, and Scenario 10aq with 20,120 ac-ft/yr pumping specified for response well id no. 37 at Pittsburg. [Scenario 10aq represents Kansas pumping held at current authorized quantity, with other states' pumping at double current pumping specified by the USGS model].

To evaluate storage in all layers, these scenarios were first rerun with modified output control to specify that computed heads be written for the top four layers. A modified version of the postprocessor readHeads was used to summarize storage for each state, for the moratorium region in Kansas and for the two-mile circle around the Pittsburg response well.

Calibration of the USGS model focused on the Ozark confining layer and the Ozark aquifer in layers 3 and 4, as indicated in the discussion of sensitivity analysis (Czarnecki et al., 2009, p. 37). Because of this, it is likely that greater uncertainty is associated with hydraulic parameters and therefore storage volume in the top two layers.

The tables below show confined, unconfined and total (sum of confined and unconfined) storage for each layer. They are color-coded to correspond roughly to the colors in Figs. 5 and 6 of the USGS report as follows:

Layer	color key	Geologic unit
1	WIPCU	Western Interior Plains confining unit
2	Spgfld	Springfield Plateau aquifer
3	OzCU	Ozark confining unit
4	Ozark	Ozark aquifer

In each table, remaining storage is summarized at the end of the year in column 2. From left to right, the columns summarize confined storage (layers 1-4) followed by unconfined storage (layers 1-4) and then total storage (sum of confined and unconfined, layers 1-4).

Tables B8 and B9 summarize storage within two miles of a response well at Pittsburg: T. B8 with no pumping assigned at the response well, and T. B9 with 20,120 ac-ft/yr assigned within 2 mi of the response well. The rightmost column of these tables shows total remaining storage at end of years 2057 and 2107 as fractions of storage at the end of 2007. This fraction is 0.7526 in 2107 for A11, so 20,120 ac-ft is about the maximum allowed appropriation within two mi of response well 37 at Pittsburg.

Comparing Tables B8 and B9, the remaining storage in the Ozark confining unit changes only slightly in response to the increased pumping for T. B9; this change occurs only for the confined storage in layer 3, while layer 3's unconfined storage isn't affected at all.

Table B10 shows confined, unconfined and total remaining storage in each layer for the entire KS moratorium extent. It shows that Springfield and Ozark remaining storage are pretty similar. In 2107: for confined, about 4 MAF in Springfield and 6 MAF in Ozark; for unconfined, about 19 MAF in Springfield and 17 MAF in Ozark; for total (sum of confined and unconfined), about 22.7 MAF in Springfield and 22.5 MAF in Ozark.

Table B8. Ozark storage (ac-ft) within 2mi of response well 37 at Pittsburg; no pumping specified for rsp37.

1	2	51	66	81	21	52	67	82	22	53	68	83	23		
aq+rsp37	year	cnf RSP 1 af	cnf RSP 2 af	cnf RSP 3 af	cnf RSP 4 af	unc RSP 1 af	unc RSP 2 af	unc RSP 3 af	unc RSP 4 af	tot RSP 1 af	tot RSP 2 af	tot RSP 3 af	tot RSP 4 af	tot RSP af	remfrc_L4
0	1958	685	5,437	266	592	329,228	256,233	11,843	115,874	329,913	261,670	12,109	116,466	720,158	
0	1984	615	4,646	255	523	329,179	256,233	11,843	115,874	329,794	260,879	12,098	116,397	719,167	
0	2007	89	2,370	196	392	322,131	254,173	11,843	115,874	322,220	256,543	12,039	116,266	707,068	
0	2057	225	3,850	152	111	325,078	256,233	11,843	115,874	325,303	260,083	11,995	115,985	713,365	0.9976
0	2107	191	3,689	139	56	324,782	256,233	11,843	115,851	324,974	259,922	11,982	115,907	712,785	0.9969

Table B9. Ozark storage (ac-ft) within 2mi of response well 37 at Pittsburg; 20,120 ac-ft/yr pumping specified for rsp37.

1	2	51	66	81	21	52	67	82	22	53	68	83	23		
aq+rsp37	year	cnf RSP 1 af	cnf RSP 2 af	cnf RSP 3 af	cnf RSP 4 af	unc RSP 1 af	unc RSP 2 af	unc RSP 3 af	unc RSP 4 af	tot RSP 1 af	tot RSP 2 af	tot RSP 3 af	tot RSP 4 af	tot RSP af	remfrc_L4
20120	1958	685	5,437	266	592	329,228	256,233	11,843	115,874	329,913	261,670	12,109	116,466	720,158	
20120	1984	615	4,646	255	523	329,179	256,233	11,843	115,874	329,794	260,879	12,098	116,397	719,167	
20120	2007	89	2,370	196	392	322,131	254,173	11,843	115,874	322,220	256,543	12,039	116,266	707,068	
20120	2057	163	3,575	119	0	323,656	256,233	11,843	97,011	323,818	259,808	11,962	97,011	692,599	0.8344
20120	2107	143	3,492	118	0	323,136	256,233	11,843	87,504	323,280	259,725	11,961	87,504	682,470	0.7526

Table B10. Ozark storage (ac-ft) within Kansas moratorium zone.

1	2	39	54	69	9	43	58	73	13	47	62	77	17
aq+rsp37	year	cnf KSM1 af	cnf KSM2 af	cnf KSM3 af	cnf KSM4 af	unc KSM1 af	unc KSM2 af	unc KSM3 af	unc KSM4 af	tot KSM1 af	tot KSM2 af	tot KSM3 af	tot KSM4 af
0	1958	63125	4375731	184041	6645855	113732576	18597810	6348028	16877830	113795344	22973534	6532159	23523590
0	1984	63004	4374292	183876	6637892	113732480	18597708	6348028	16877830	113795128	22971980	6531966	23515622
0	2007	60172	4325504	177331	6366838	113705968	18572940	6348028	16877830	113765824	22898440	6525454	23244628
0	2057	59359	4259313	167307	5925425	113690808	18539000	6348028	16862934	113749960	22798318	6515414	22788314
0	2107	58385	4194040	161517	5657036	113668160	18512518	6348028	16839540	113726368	22706516	6509646	22496508

[from sheet 10aq_remstg_rsp37_Pitts_all, file Ozark_remaining_storage_summaries_ALyon_spp_2010Dec08.xls, folder \gw\Ozark\thru_2107\remaining_storage]

Procedure to evaluate local availability at a response point

This section describes the procedure followed at 45 individual response points (see Fig. B8) to evaluate availability of water within a two-mile radius of each response point. For an explanation of the method and resulting map, see the section “Mapping local availability of water for appropriation.”

This procedure is described in terms of an example for response point 19, Fig. B8 shows this point is located in northeast Cherokee County along the boundary between zones oz2 and oz3 of the Ozark aquifer hydraulic properties.

Choose initial pumping; base guess on nearby response pt
Pt is along boundary between L4 property zones oz2 and oz3. Previously evaluated pts 37 (Pittsburg: 20,120 af) and 45 (Cherokee RWD 04: 3268 af). Try 5000 af (5 KAF).

Create Well package input file for Modflow (mf2005).
Sheet remStg_nr_rsp_centers: on record 21, begin sequence of records for rsp id 19.
Open pumping template sheet; use build_scenarios_8-15v6 , file Ozark_pumping_template_thru_2107.xls in C:\gw\Ozark\thru_2107\pumping.
In cell g5543, enter id no. 19, and in cell h5543 enter initial guess 5000. Sheet then shows 4.1 af currently appropriated within 2 mi of the response point, which is subtracted from the guess of 5000 af to give the additional pumping of 4996 af; this is equally distributed over an array of 25 test wells located at model grid cell centers within the 2-mi circle; 199.84 af is assigned to each of these wells. Records 5508-5532 show the assigned pumping for these wells. Rec. 5507 represents the location of the response point (id 19), but with no pumping; all pumping associated with the response well is distributed over the 25 test wells. Distances from response well to each test well are given in miles by col. AG.

Export (COPY of) sheet build_scenarios_8-15v6 to separate file.
Copy & paste entire sheet by value. Delete columns S:Z and AB:AF, which leaves some identifying fields intact for the future stress periods, including a sequential index to each pd, the “Last_name” field and distance in miles from the response well location and each pd.
Save sheet as space-delimited text file (ext. prn) in folder ..\in
Change extension to WEL, so that the resulting file to be read by Modflow is `scen_10aq_RSP19_5KAF_MOfactor_2.wel` in folder in\.

Create Name file to run Modflow (mf2005)
In folder ..\nam:

Copy and revise previous name file; for the initial rsp id 19 run, open file `scen_10aq_RSP45_5KAF_MOfactor_2.nam` and rename as `scen_10aq_RSP19_5KAF_MOfactor_2.nam`; make corresponding changes to file, i.e. change all occurrences of the string “`RSP45_5KAF`” to “`RSP19_5KAF`”, and associated description in the first few lines. First line is a comment that includes the command to run mf2005 for this case; copy the line beginning with the string “`\gw\bin\mf2005`”, which is followed by the file pathname. In the console window, navigate to the folder C:\gw\Ozark\thru_2107; paste the command line into the console window and run the program by pressing “Enter”. Successful program execution should list simulated time steps through stress period 19, time step 60, then show ending date and time, elapsed time and print “Normal termination of simulation”.

Postprocessing: ZoneBudget and ReadHeadsv2:
Specify input files in folder ..\post. Start with input files from previous run; for rsp id 19, start with files for rsp id 45 specifying 3 KAF.

Run ZoneBudget to see if specified pumping at response point stays active

We're using version 3.01, released Dec 18, 2009.

Open file scen_10aq_RSP45_5KAF_MOfactor_2_Zonebudget.par in post\ and save as scen_10aq_RSP19_5KAF_MOfactor_2_Zonebudget.par. Change file contents from the string "RSP45_5KAF" to "RSP19_5KAF". Resulting contents of file are as follows:

Listing of redirected input file to program zonbud

```
budgets/scen_10aq_RSP19_5KAF_MOfactor_2 CSV2
out/scen_10aq_RSP19_5KAF_MOfactor_2.ccf
scenario 10aq for future 2008-2107: RSP19_5KAF, KS pumping factor 1, MO-OK factor 2
../zones/zonefile.txt
A

to run from /gw/Ozark/thru_2107> /gw/bin/zonbud <
            post/scen_10aq_RSP19_5KAF_MOfactor_2_Zonebudget.par >
            post/scen_10aq_RSP19_5KAF_MOfactor_2_Zonebudget.jnl
```

The program **zonbud** reads only the first five lines of the input file; these are followed by a line showing how the program is run for this case. The line begins with "`to run from C:/gw/Ozark/thru_2107>`". Copy the remainder of this string, beginning with " `/gw/bin/zonbud`", which refers to the program's executable file name; the remainder of the line refers to redirected input and output files (with extensions .par and .jnl, respectively). The program is actually interactive; the characters "<" and ">" redirect the standard i/o (keyboard input and terminal prompts or responses) so they are read from a text file and written to a text file. Redirected output to the file with extension jnl shows how the run proceeded. The output file of interest is scen_10aq_RSP19_5KAF_MOfactor_2.2.csv, which is comma-delimited. Open Excel file budget_scen_10aq_RSP45_5KAF_KSfactor_1_MOfactor_2.xls for zone budgets of previous case for RSP45 with 5 KAF pumping specified. Rename as scen_10aq_RSP19_5KAF_MOfactor_2_Zonebudget.xls. Import comma-delimited file into sheet import_budget. Copy range a2:an1201 into sheet budget_sort_by_zones_cfd at cell b2 (into range b2:ao1201). Select range b1:ao1201 (to include header record). Sort this range based on two keys: first key = zone (col. e), second key = total time, days (col. b). If this proceeds correctly, then sheet budget_sort_by_zones_AFY shows the sorted data, converted from cu.ft/day to ac-ft/yr, and the graph at cr10 plots two budget components (pumping and change in storage) for each state (zones 1-3) within the Ozark aquifer. The plot of total pumping in Kansas is used to indicate whether the specified pumping stays active through the end of the simulation, which it must if the model run is to be included in the trajectory of coordinate pairs (pumping, remaining storage).

Run ReadHeadsv2 to evaluate remaining storage within 2 mi of response well

Open file scen_10aq_RSP45_5KAF_MOfactor_2_readHeadsv2.par in post\ and save as scen_10aq_RSP19_5KAF_MOfactor_2_readHeadsv2.par. Change file contents from the string "RSP45_5KAF" to "RSP19_5KAF". Resulting contents of file are as shown below (indented lines in this report are continuations of previous lines in source file):

Listing of input file to program readHeadsv2

```
to run from \gw\Ozark\thru_2107> ..\bin\readHeadsv2
post\scen_10aq_RSP19_5KAF_MOfactor_2_readHeadsv2.par >
post\scen_10aq_RSP19_5KAF_MOfactor_2_readHeadsv2.log
in/1950-2107.dis
..\baseline\baseline.ba6
..\baseline\baseline.lpf
```

```
in/baseline_19SP.rch
../zones/zonefile.txt
../grid/ozark_counties.csv
../grid/ozark_grid_2009_counties.csv
2,363129.741,3993526.08,-45, Lenuni_prj (1:ft, 2:meters),x0,y0,rotdeg
1,1,1,read options opt_discret (y=1,n=0); opt_zone (y=1,n=0); opt_remstg (y=1,n=0)
Ozark_layers.out
remaining_storage/scen_10aq_RSP19_5KAF_MOfactor_2_summary.out
pumping/Ozark_gw_response_wells.csv
19,19,2,num_gwrsp,id_rsp,remstg_distmi
5,nprt
out\scen_10aq_RSP19_5KAF_MOfactor_2.hed
heads\scen_10aq_RSP19_5KAF_MOfactor_2_L24_
F                                    !heads file is formatted
1 (1f8.1)                            !LBLSAV, FMTOUT
0 1 0 1 0                            !(laysav(k),k=1,5): read only layers 2 and 4,
            consistent with oc file
1,1,idxper,idxstp
2,1
9,1
14,60
19,60,idxper,idxstp
```

Complete input requirements for program readHeadsv2 are documented in greater detail elsewhere. The first line of the above file that is read but not used by the program. It shows how to run the program for this case. To run the program, copy the text of the first line beginning with the executable file path, and paste this into a console prompt window after navigating to `\gw\Ozark\thru_2107>`. Program readHeadsv2 expects to read this input file; i.e. it is not redirected keyboard input, hence, no "<" appears following the executable file name in the command line.

Program readHeadsv2 reads input data from several packages and writes the cell-by-cell data to file Ozark_layers.out, which is incidental to the purpose for running the program here. The program reads computed heads from file `out\scen_10aq_RSP19_5KAF_MOfactor_2.hed`, and writes formatted heads for layers 2 and 4 for selected stress periods and time steps listed at the end of the file: (sp,ts)=(9,1) corresponds to current time (end of 2007), and (sp,ts)=(19,60) corresponds to end of simulation (end of 2107). Program writes summary output, including remaining storage within two miles of response point, to file `remaining_storage/scen_10aq_RSP19_5KAF_MOfactor_2_summary.out`.

Summary of response points

The summary output file from program readHeadsv2 is input to an Excel file used to solve for available water with remaining storage fraction=0.75, file Ozark_remaining_storage_summaries.xls. It is imported into spreadsheet 10aq_RSP19_stg_summaries corresponding to response point 19.

Solution trajectory coordinates for each trial solution are entered into sheet remStg_nr_rsp_centers; Once solution at remaining storage=0.75 is roughly approximated or bracketed, Newton (secant) step is taken; solution is considered found, and no more model runs are required for this response point.

Sheet sequence_resp_centers summarizes location coordinates and inverse solution for all 45 response points; contents are listed in Table B7. When completed, this sheet was exported from Excel; imported into Surfer as (x,y,z) file; then gridded and contoured. Contours were exported from Surfer as 2-d shapefile for input to ArcView or ArcGIS for mapping as shown in Fig. B9.

Model recharge data: summary over Kansas moratorium area

Precipitation recharge data as specified for input to the top model layer was summarized over the extent of the moratorium region in Kansas. The DWR postprocessor readHeads was used to extract the recharge data from model input files. This program reads a number of model input files, including that for the recharge package, prior to reading computed heads for a specified model run.

Fig. B10 is a map of precipitation recharge zones over the Kansas moratorium area based on the model input data. [Comparing Fig. B10 with Fig. 7 in the USGS report, the recharge zones appear consistent but the legends are at odds. After examining the recharge data in GMS, John Czarnecki confirmed in private communication that Fig. B10 and its legend are correct, and that the legend in Fig. 7 of the USGS report is in error.]

Fig. B10 shows that the eastern parts of Cherokee and Crawford counties receive a little under one-half inch/year of recharge, while the western parts of these counties receive less than one-tenth inch/year, or almost nothing. Table B11 lists the values of the recharge parameters, which are also listed in Table 7 of the USGS report. Table B11 also lists, for each recharge zone, the annual volume of recharge within a circle two miles in radius, the number of active model cells in the top layer within the moratorium area, and the annual volume of recharge within the moratorium.

Aside from dual-screened wells, nearly all groundwater within the active model domain in Kansas has been appropriated from the Ozark aquifer and an insignificant quantity from the Springfield Plateau aquifer. The Springfield is represented as layer 2 of the model, under the Western Interior Plains confining unit, but the Springfield is the top active layer for a southeast corner of Cherokee County; see Fig. 6 in Czarnecki et al. (2009). Fig. B10 also shows this part of the model area highlighted in yellow.

Table B11. Precipitation recharge applied to top active model layer, and annual volume over Kansas moratorium zone.

id	rchid	rch file values	r_ft/d	r_in/yr	r ac-ft/yr 2mi circle	no. active cells moratorium	recharge ac-ft/yr	STATES
1	80	0.0008	8.00E-04	3.5064	2350	0	0	AR
2	82	0.000768204	7.68E-04	3.367038	2257	0	0	MO
3	79	0.000434611	4.35E-04	1.9049	1277	0	0	MO
4	81	0.000111397	1.11E-04	0.488253	327	0	0	MO
5	77	0.000110243	1.10E-04	0.483195	324	1675	10,739	MO KS OK
6	78	1E-04	1.00E-04	0.4383	294	1772	10,305	KS
7	76	2E-05	2.00E-05	0.08766	59	4700	5,467	KS
					moratorium:	8147	26,511	KS

recharge, no Western Interior Plains confining unit (highlighted in Fig. 1):

77	0.000110243	1.10E-04	0.483	324	271	1,737	KS (se CK Co.)

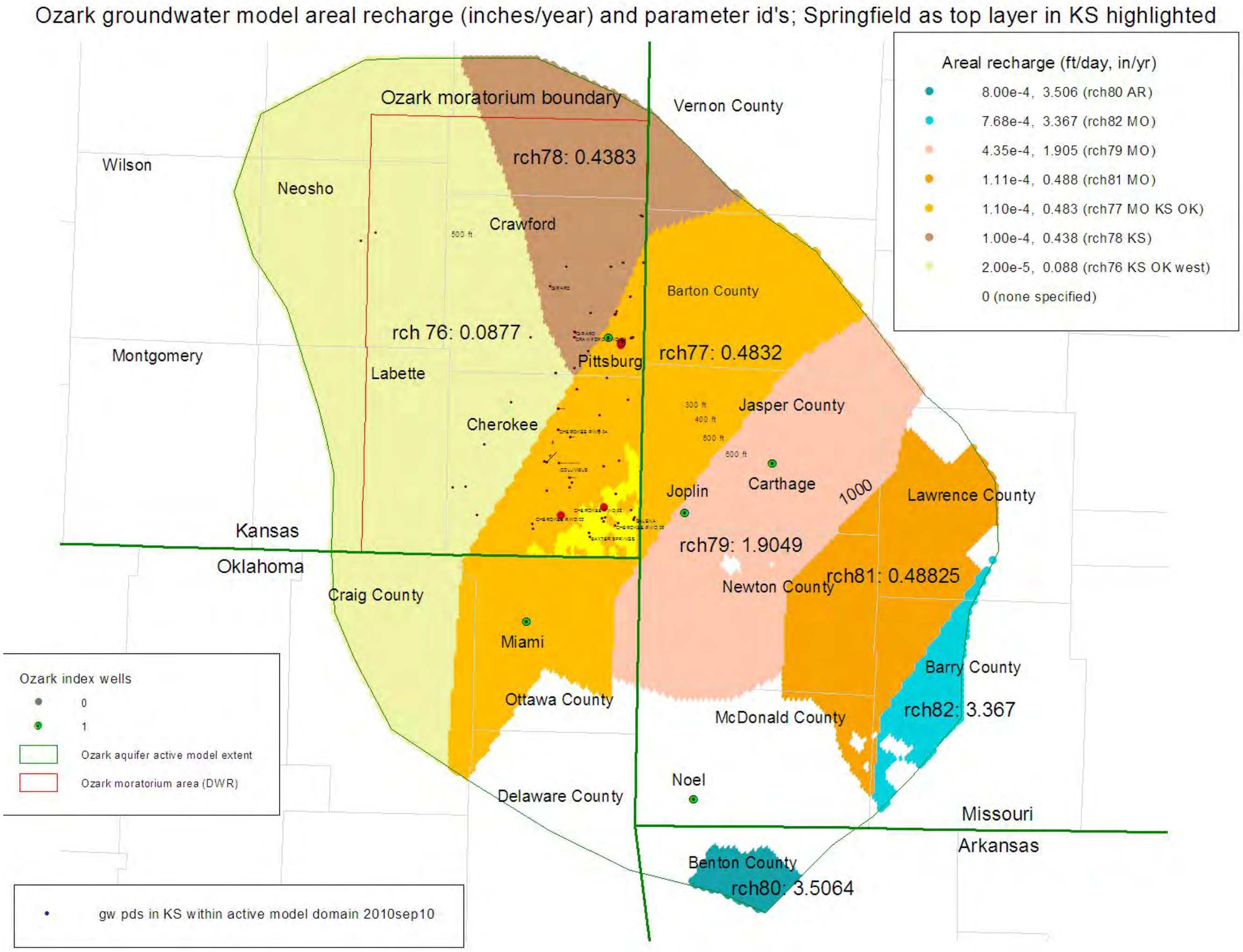

Fig. B10. Map of recharge spatial distribution (corrected version of Fig. 6 in Czarnecki et al., 2009).

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Ozark groundwater model: DWR operation and comparison with USGS model (Memo)

KANSAS DEPARTMENT OF AGRICULTURE
Division of Water Resources
M E M O R A N D U M

TO: David Barfield, Chris Beightel, Lane Letourneau, Katie Tietsort, Andy Lyon, Paul Graves

FROM: Sam Perkins

DATE: January 6, 2010

RE: Ozark groundwater model: DWR operation, comparison with USGS model, additional cases

We obtained the Ozark groundwater model from John Czarnecki, USGS groundwater modeler, Little Rock, AR, in September 2009. The model was provided as a set of computer files organized into folders corresponding to scenarios 1-5 as defined in the USGS report (Czarnecki et al., 2009). Model input files for Scenarios 1-5 were provided in a form that requires licensing under Groundwater Modeling System (GMS), which is a proprietary version of Modflow-2000 (mf2k) and related software. Scenario 1, which assumes no change in future pumping by Kansas, Missouri and Oklahoma, was also provided in a format that could be run under a version of Modflow-2005 (mf2005) that is in the public domain.

This memo documents work at DWR to run the Ozark groundwater model under the public domain version of mf2005 for two of the original scenarios (1 and 4), compares results from the DWR model runs with USGS model results, and presents additional scenarios that test the sensitivity of computed heads in Kansas to the projected rate of pumping increase in Missouri. The documentation contained herein is intended as a guide for setting up and running the remaining scenarios 2, 4 and 5 for comparison with USGS results in order to gain some experience with the model.

Postprocessing: Produce contour shapefiles in Surfer and maps in ArcView. Read computed heads using program ReadHeads. In Surfer, open xyz-format, comma-delimited heads file with extension txt. Construct grid files of saturated thickness, delimited by active model domain in Kansas with a blanking file. Export contours as ESRI 2-d shapefiles, import into ArcView and produce maps.

Additional work: saturated thickness maps (figs. 7a-7c); additional scenarios 6 and 7 (sensitivity of computed heads in Kansas to change in rate of pumping growth in MO and OK).

[file Memo_DWR_operation_of_OzarkModel_spp2010Jan06.doc]

Georeference model grid

USGS mapped model grid using UTM-15 NAD 1983 meters
Transformations:grid cells, nodes, cell id, model grid cel center coordinates (xg,yg), ft; UTM coordinates

Node number and cell id

The grid cell node number as calculated in Modflow can be used as a unique record identifier for spreadsheets and database Tables associated with shapefiles. The node number is calculated for a grid of size (ncol,nrow,nlay) using the equation

$$\text{node} = \text{ncol}\left[\text{nrow}\left(k-1\right)+(i-1)\right]+j\,, \tag{1}$$

with indices (j,i,k) corresponding to grid column, row and layer. For a single layer, this reduces to

$$\text{cellid} = \text{ncol}(i-1)+j \tag{2}$$

Inverse calculation: The number of nodes per layer is nrow*ncol. Row and column indices can be calculated from the cell id using

$$\text{row} = \text{int}\left[\left(\text{cellid}-1\right)/\,\text{ncol}\right]+1 \tag{3a}$$

$$\text{column} = \text{mod}\left(\text{cellid}-1,\text{ncol}\right)+1 \tag{3b}$$

As specified by the model discretization files (see, for example, baseline.dis), the Ozark model grid has 5 layers, 253 rows and 180 columns (nlay=5, nrow=253, ncol=180) of regular grid cells for a total 227,700 nodes, and 45,540 nodes/layer. The model is specified using feet as units of length (LENUNI=1) and days as units of time (ITMUNI=4).
Model layers represent aquifer units as follows: (1) Western Interior Plains confining unit; (2) Springield Plateau aquifer and mine zones; (3) Ozark confining unit; (4) Ozark aquifer; (5) a no-flow boundary layer representing St. Francois confining unit, St. Francois aquifer or basement confining unit. Since all model cells in layer 5 are specified as no-flow, the model has only four active layers and is described as a four-layer model in Czarnecki et al. (2009).

Grid cell dimensions are Δx = 2630.93395 ft, or 801.908669 m; and Δy = 2636.27282 ft, or 803.535955 m (~0.5 mi on a side). Cell dimensions Δx and Δy are specified by delr and delc, respectively, by the discretization input file. delr is cell width along rows, one value for each of ncol columns; delc is cell width along columns, one value for each of nrow rows. Grid coordinates are expressed in units of meters by

$$x_{gj} = x_{g0} + \Delta x\left(j-0.5\right) \;\; \text{(m)} \tag{4a}$$

$$y_{gi} = y_{g0} + \Delta y\left[\text{nrow}-\left(i-0.5\right)\right] \;\; \text{(m)}, \tag{4b}$$

with origin in grid coordinates (x_{g0},y_{g0}) = (0,0).

Inverse calculation: Real-valued (column,row) coordinates are expressed in terms of (x_g,y_g) by

$$\text{Real}(j) = 0.5 + x_g\,/\,\Delta x \tag{5a}$$

$$\text{Real}(i) = \text{nrow} + 0.5 - y_g\,/\,\Delta y \tag{5b}$$

Integer-valued (column, row) coordinates are obtained either by rounding the real-valued coordinates to the nearest integer, or directly using:

$$j = \text{Int}\left[1+\left(x_j - x_0\right)/\,\Delta x\right] \tag{6a}$$

$$i = \text{Int}\left[\text{nrow}+1-\left(y_i - y_0\right)/\,\Delta y\right] \tag{6b}$$

The model grid is georeferenced to the UTM-15 projection (NAD 1983) with distance in meters. The projected grid origin is (x_0,y_0) = (363129.741, 3993526.08) with rotation angle θ = –45.00 deg, measured from a line through (x_0,y_0) and parallel to the rows to an east-west axis through (x_0,y_0). For θ = –45.00 deg or –0.78539816 radians, cosθ = sinθ = –0.70710678. To transform from grid coordinates (x_g,y_g) to projected coordinates (x,y), apply

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} + \begin{pmatrix} c\theta & s\theta \\ -s\theta & c\theta \end{pmatrix}\begin{pmatrix} x_g \\ y_g \end{pmatrix}, \tag{7}$$

Or equivalently

$$x = x_0 + x_g \cos\theta + y_g \sin\theta \quad \text{(m)} \tag{7a}$$

$$y = y_0 - x_g \sin\theta + y_g \cos\theta \quad \text{(m)} \tag{7b}$$

Inverse calculation: To transform from projected to grid coordinates, apply

$$\begin{pmatrix} x_g \\ y_g \end{pmatrix} = \begin{pmatrix} c\theta & -s\theta \\ s\theta & c\theta \end{pmatrix} \begin{pmatrix} x - x_0 \\ y - y_0 \end{pmatrix}, \tag{8}$$

Or equivalently

$$x_g = (x - x_0)\cos\theta - (y - y_0)\sin\theta \quad \text{(m)} \tag{8a}$$

$$y_g = (x - x_0)\sin\theta + (y - y_0)\cos\theta \quad \text{(m)} \tag{8b}$$

Extract model discretization data (Program read_discret)

Program read_discret was written to extract data from model input files for discretization (DIS) and basic (BA6) packages, and write georeferencing and model data to a text file for input to Surfer, Excel or GIS. The program does the following:

Read discretization input file:
nlay, nrow, ncol, nper, itmuni, lenuni
(laycbd(k),k=1,nlay), dx, dy
Top 2-d array of elevations of top layer
Botm 2-d array of bottom elevations for each layer
Read for each stress period iper=1 to nper:
Perlen,nstp,tsmult,sstr

Read basic input file:

Ibound	2-d integer array for each layer to define active model domain;
Hnoflo	real value representing heads for inactive cells;
Strt	2-d real array of starting head elevations for each layer

Calculate model grid coordinates (x_g,y_g) for each cell center both in units of ft and m (eqns. 4a-4b). The version in feet corresponds to model dimensions, and the version in meters is transformed to projected coordinates.

For each model grid cell:
Calculate projected coordinates (x,y) from model grid coordinates (x_g,y_g) (eqns. 7a-7b).
Cell id, row I, column j;
Grid cell center coordinates (xg,yg), ft;
Projected cell center coordinates (xutm,yutm), meters;
Top elevation
For each layer 1 to 5:
Ibound, starting heads, bottom elevation

The output file written by this program was imported into Excel file Ozark_GridCells_2009Dec.xls in I:\gw\Ozark\grid, sheet baseline.out. Ozark_gridcells_2009, and then exported from Excel in comma-delimited format without the layer identifiers as follows (file Ozark_gridcells_2009.csv in folder I:\gw\Ozark\grid):

For each model grid cell id=1 to45,540:

Id, I, j, xgft_j, ygft_i, xutm_m, yutm_m, topft, (ibound(j,I,k),k=1,5)

After re-naming the file extension from csv to txt, it was imported into an ArcView project to verify that the model grid was correctly georeferenced.

Fig. 1 shows a map of the model domain in the UTM-15 projection (NAD 1983, meters). [The note about re-projection from Lambert applies only to the grid box and its vertices labeled 1-4. The base map includes state and county boundaries for a four-state subset of shapefiles that were downloaded from the NationalAtlas.gov website and projected from decimal degrees to UTM-15 (NAD 1983, meters). The pumping centers are approximated by the locations of the corresponding cities, which are represented in a point shapefile of cities, also downloaded from NationalAtlas.gov and projected. Also shown is the Ozark moratorium boundary in Kansas.

A variation on the above file, Ozark_gridcells_2009.csv in folder I:\gw\Ozark\grid, included two additional fields corresponding to a zone associated with each cell, idZone, and a two-character state abbreviation, ST. This file was read by the program writeBudgetZones, which was used to write arrays to define zones for the ZoneBudget program (see description below). This file was also exported from sheet Ozark_gridcells_2009 of file Ozark_GridCells_2009Dec.xls in I:\gw\Ozark\grid.

Test model execution under MF2005 for baseline case (scenario 1)

The groundwater model delivered to DWR by USGS includes the following:

- a GMS version of input and output files for scenarios 1-5 and executable files for the GMS version of Modflow-2000 (mf2k);
- a version of input and output files for the baseline case (scenario 1) that John converted to run under mf2005, and an executable file, mf2005.exe
- file readme.pdf, a description of folders and files included in the delivery; see this file for more details about the delivered model.

Test runs under mf2005 at DWR

The latest version of Modflow 2005 (mf2005) was downloaded from the USGS website. I am using the executable file mf2005.exe that came with the download. John also sent an executable file, which works about as well except that it does not incorporate the hydmod package, which we use to extract computed head hydrographs at specified locations. I have also used Lahey Fortran 95 v7.1 to compile the source code, which includes c code for a particular solver, and link the object files to create an executable file that will run the models. However, execution is slower by about a factor of five than with the executable file downloaded from USGS. This effect may be due to the choice of compiler switches specified in the compilation as suggested in USGS documentation.

Initial run with same temporal discretization as USGS model run

I began by attempting to run the baseline case under mf2005 as it was delivered to us, except for renaming files from ts81_mine_sc1_baseline_v2_zone.mfn to baseline.*. For this run, with name file baseline.nam, the solution failed to converge for stress period (SP) 13. In comparing output with the delivered files, I saw that John's standard version of the baseline run under mf2005 also failed to converge at the same place in the simulation. On the other hand, the GMS version of the baseline run achieved convergence through the end of the run. For SP 13, volumetric budget flow rates show about 0.01 pct discrepancy between input and output for both standard and GMS versions of the run. A key difference between the two versions may be that, for the GMS version, a GMS-specific input file with the extension asp specifies the option NOSTOP=1, which enables a mass balance override; i.e., if the maximum iteration limit has been reached but the mass balance discrepancy as a percent (equal to 100*|total input – total output|/[(total input + total output)/2] is less than a specified threshold; the RRCA model specifies 1 pct. It may be that the mass balance override has been applied starting with SP 13, although the output shows no warning about nonconvergence. The code for an earlier GMS version, which we possess for the MidArk model, shows that a warning is issued when an override is applied; see mainline mf2k.f (“`CONTINUE EXECUTION, BUT WRITE MESSAGE(S) REGARDING NONCONVERGENCE`”).

Model changes to obtain convergence and provide additional results

We need the model solution to converge through the end of SP 14 (2057). Options that can be applied in-house to obtain convergence include increasing the number of time steps per stress period (a standard approach in numerical solution of differential equations); modifying solver parameters, which include increasing head closure criterion and maximum number of iterations allowed; and introducing code for a mass balance override, following the code used for the RRCA model. Fortunately, a combination of the first two options has resulted in completed simulations for scenarios 1 and 4 as well as two variations on scenario 4.

Discretization: The number of time steps per stress period was increased as specified by the input file `baseline_alt_steps.dis`. The original model versions use only one time step per stress period. During testing, the number of time steps per stress period was increased successively for SP 13 and 14. Table 1 lists the number of time steps per stress period that were settled upon for the model runs. In addition to SP 13 and 14, the number of time steps was increased for the remaining stress periods so that most time steps are one year (see column “yrs/step”). For SP 14, two-month time steps (6/yr) are specified.

Table 1. Summary of stress periods as specified by input to the discretization package for modified model runs (file baseline_alt_steps.dis).

strper	PERLEN	NSTP	TSMULT	SSTR	yrs/sp	yrs/step	starting date	ending date	Future years*
1	3287	1	1	SS	8.999	8.999	1/1/1950	12/31/1958	
2	9497	26	1	TR	26.001	1.000	1/1/1959	12/31/1984	
3	1826	5	1	TR	4.999	1.000	1/1/1985	12/31/1989	
4	1826	5	1	TR	4.999	1.000	1/1/1990	12/31/1994	
5	1826	5	1	TR	4.999	1.000	1/1/1995	12/31/1999	
6	1827	5	1	TR	5.002	1.000	1/1/2000	12/31/2004	
7	365	1	1	TR	0.999	0.999	1/1/2005	12/31/2005	
8	120	1	1	TR	0.329	0.329	1/1/2006	4/30/2006	
9	579	1	1	TR	1.585	1.585	5/1/2006	11/30/2007	
10	3653	10	1	TR	10.001	1.000	12/1/2007	11/30/2017	5.00
11	3652	10	1	TR	9.999	1.000	12/1/2017	11/30/2027	15.00
12	3653	10	1	TR	10.001	1.000	12/1/2027	11/30/2037	25.00
13	3652	10	1	TR	9.999	1.000	12/1/2037	11/30/2047	35.00
14	3653	60	1	TR	10.001	0.167	12/1/2047	11/30/2057	45.00

Notes: Table 1 columns labeled PERLEN, NSTP, TSMULT and SSTR are read from input file `baseline_alt_steps.dis` by the discretization package. PERLEN specifies stress period length, in days, and NSTP specifies the number of time steps into which the stress period is divided equally (since TSMULT=1). Column SSTR specifies that the first stress period is really a steady-state model run, followed by a transient model run for SP 2–14. (See mf2005 manual for further details). Table 10 comes from range a1:i15 of sheet stress_periods in file stress_periods.xls, folder I:\gw\Ozark\model. (*) “Future years” represents the time from the beginning of stress period 10 (12/1/2007) to the midpoint of the future stress periods (denoted by Δt below).

Solver: Parameters for the PCG package (preconditioned conjugate polynomial solver) were modified (file `baseline_alt.pcg`). The head closure criterion was increased from 0.01 ft to 0.02 ft; the maximum number of outer iterations was increased from 10 to 100, and the maximum number of inner iterations was increased from 50 to 100. The damping and relaxation factors were not modified, but adjusting these might help improve convergence (see manual for details).

Additional changes to model input files

Discretization: The discretization file provided by John as part of the baseline model case that can be run with the public domain version of mf2005 contains the arrays for the top elevation of the top layer and the bottom elevations of each layer. This format was modified by moving the arrays to separate files in a “static” folder; and referencing these files from the discretization input file

Output control: In conjunction with increasing the number of time steps per stress period, output control was modified to write computed head and cell-by-cell flows at the end of every time step for SP 1–13, and at the end of time steps that are a multiple of six for SP 14, so that computed heads are generally written at the end of each year for years 1959-2057; SP 1, 8 and 9 are the exceptions.

The output control file was also modified to specify how computed heads are saved in order to coordinate with the postprocessor named readHeads, which was written to do just that; see description below. Changes to the output control file include the following:

(1) The first line of the file was changed from “`HEAD save FORMAT (1f8.1)`” to” `HEAD save FORMAT (1f8.1) LABEL`”. With this change, computed heads that are written to an output file are preceded by a label record that clearly identifies the time step, stress period and layer of heads following the label.
(2) The command to save heads was changed from “`SAVE HEAD`” to “`SAVE HEAD 2 4`”, so that only layers 2 and 4 of computed heads, corresponding to Springfield and Ozark aquifer layers, are written. This reduces the size of the resulting files for current model runs from 222 MB to 89 MB.

The output control file baseline_alt_steps_fmtHeads_L24.oc includes the changes noted above, both to coordinate with the discretization file on the number of time steps specified per stress period and how heads are saved.

Hydrographs: The HYDMOD package is incorporated into the latest mf2005 executable version downloaded from USGS; the package is in source file gwf2hydmod7.f, and the mainline on source file mf2005.f specifies ‘HYD ‘ in a data statement for array CUNIT to indicate the availability of HYDMOD. Instructions for this package are not included in the mf2005 documentation, but are available separately. This package was invoked in order that computed water level hydrographs could be specified for the same locations used for the hydrographs shown in the USGS report for Scenarios 1-5 in Figs. 26, 28, 30, 32 and 34.

The map in Fig. 1 shows approximate locations in terms of model grid (row, column) indices that were initially used to specify water level hydrographs to be written by the HYDMOD package. I received a note from John with the following correct locations: {Pittsburg: 114, 121; Carthage: 166, 126; Joplin: 159, 101; Noel: 210, 50; Miami: 145, 53} Table 2 shows the data for HYDMOD to specify these hydrographs. The data listed in Table 2 was exported from sheet hydrograph_coordinates in file Ozark_discret.xls, folder I:\gw\Ozark\grid, to a text file in space-delimited format, which is read as file hydrograph_defs.hyd by mf2005.

Table 2. data for HYDMOD to specify computed water level hydrographs for comparison with USGS model scenarios (Figs 26, 28, 30, 32 and 34 in Czarnecki et al., 2009).

layer	Xg, ft	Yg, ft	label	(row, col coordinates

```
BAS   HD   C          4   317027.5   367760.0      Pittsburg_KS      (r114,c121)
BAS   HD   C          4   138124.0   286035.6      Miami_OK          (r145,c053)
BAS   HD   C          4   264408.8   249127.8      Joplin_MO         (r159,c101)
BAS   HD   C          4   330182.2   230673.9      Carthage_MO       (r166,c126)
BAS   HD   C          4   130231.2   114677.9      Noel_MO           (r210,c050)
```

Future pumping scenarios (WEL package)

The pumping input file for the baseline case (scenario 1) was used exactly as it was provided, except for a name change (from ts81_mine_sc1_baseline_v2_zone.wel to baseline.wel). This file was then used as the basis for generating pumping input files for other pumping scenarios, since we did not obtain versions of these for input to mf2005. This is just as well, since we need to be able to generate our own pumping files for additional scenarios.

Table 3 lists pumping scenarios and the assumed annual increases in future pumping from the Ozark aquifer. The first five scenarios are those listed in Table 8 of the USGS report, which defines the pumping increases with respect to the year 2006. 1, 4, 6 and 7 have been run by DWR; Scenarios 6 and 7 are variations on scenario 4, in which increases in Kansas pumping are held fixed at 2 pct, and pumping increases in OK and MO are varied about the annual increases for scenario 4 by +/- 2 pct.

To generate our own version of the scenarios, we apply the corresponding annual rates to the midpoints of the stress periods with respect to the beginning of stress period 10. These time periods, Δt (years) are listed in the right-hand column of Table 1, beginning with five years for SP 10. For an annual rate increase, p (pct), the corresponding increase in pumping is given by $f = (1 + p/100)^{\Delta t}$. For annual rate increases of 1, 2 and 4 pct, the three righthand columns of Table 4 list the increases in pumping with respect to baseline conditions for SP 10-14. These factors are applied selectively to pumping within each state according to scenarios 2-7 for future stress periods 10-14. Calculations are made in spreadsheet versions of the pumping files; for example, the pumping input file for scenario 4 is set up in sheet wells_scenario_4 in file stress_periods.xls, which is exported to a space-delimited text file (extension PRN) that is renamed scenario_4.wel in folder I:\gw\Ozark\pumping.

Table 3. DWR versions of future scenarios for future years 2008-2057 (stress periods 10-14).

Scenario	pct (KS)	pct (MO, OK)	USGS [1]	DWR [2]	Spreadsheet file with imported results for case
1	0	0	y	y	I:/gw/Ozark/baseline/budget_baseline_alt_steps.xls
2	1	1	y		
3	0	1	y		
4	2	2	y	y	I:/gw/Ozark/scenarios/budget_scenario_4_alt_steps.xls
5	4	4	y		
6	2	0		y	I:/gw/Ozark/scenarios/budget_scenario_6_alt_steps.xls
7	2	4		y	I:/gw/Ozark/scenarios/budget_scenario_7_alt_steps.xls

[1] Listed in Table 8 of Czarnecki et al. (2009); [2] additional scenarios that have been run under the DWR model version. Table is from range a1:e8 of sheet pumping_scenarios in file stress_periods.xls, folder I:\gw\Ozark\model.

Table 4. Summary of pumping for input to model for baseline case (Scenario 1); pumping for stress period 10 is repeated for SP 11-14.

Stress period	Springfield aquifer ac-ft/yr	Ozark aquifer ac-ft/yr	Total pumping ac-ft/yr	Fractional increase over previous year	Pump incr. factor, f, at 1 pct/year	Pump incr. factor, f, at 2 pct/year	Pump incr. factor, f, at 4 pct/year
1	788	0	788				
2	4,379	51,888	56,267				
3	4,523	56,002	60,525				

4	5,044	60,143	65,187				
5	3,964	53,858	57,823				
6	4,364	73,194	77,557				
7	4,771	82,252	87,023				
8	4,771	82,177	86,948				
9	4,771	82,225	86,996	0.0005794			
10	4,771	82,260	87,031	0.0004291	1.05102	1.10410	1.21669
11					1.16098	1.34589	1.80099
12					1.28244	1.64063	2.66591
13					1.41661	1.99992	3.94619
14					1.56482	2.43789	5.84133

Under the assumed annual increases of 1, 2 and 4 percent/year, pumping after 50 years will increase by factors of 1.56, 2.44 and 5.84, respectively, as listed in Table 4.

Postprocessing programs

Postprocessing programs: Zonbud, Hydfmt, ReadHeads

Zonbud (USGS)

Zone budget analysis was used for the USGS model results. Zones were defined as follows. Zones 1-3 correspond to cells in the Ozark aquifer layer 4 that are within KS (1), OK (2) or MO and AR (3);zone 4 includes all cells in the Ozark confining unit (model layer 3); see Fig. 35 in Czarnecki et al. (2009). Tables 10-12 of the USGS report list budget summaries for zones 1-3 (KS, OK and AR-MO).

This definition was expanded to assign zones to all model grid cells so that the corresponding zone budgets would include the complete model budget. Table 5 lists the definitions of nine zones, where the first four zones correspond to the four zones defined in the USGS report. Zones 5, 6 and 7 correspond to the Springfield aquifer divided among states, and zone 8 includes all cells in the top model layer. Zone 9, the bottom layer, includes only inactive, or no-flow cells, so no budget flows are associated with zone 9.

Table 5. Definition of zones.

zone	state	layer	
1	KS	4	Ozark aquifer in KS
2	OK	4	Ozark aquifer in OK
3	MO, AR	4	Ozark aquifer in MO and AR
4	all	3	Ozark confining unit
5	KS	2	Springfield Plateau aquifer in KS
6	OK	2	Springfield Plateau aquifer in OK
7	MO, AR	2	Springfield Plateau aquifer in MO and AR
8	all	1	Western Interior Plains confining unit
9	all	5	no-flow boundary

The program writeBudgetZones was written to define model zones for the USGS ZoneBudget program (or zonbud). It reads the file Ozark_gridcells_2009.csv in folder I:\gw\Ozark\grid (described at the end of the section “Extract discretization data”), which includes fields corresponding to a zone associated with each cell, idZone, and a two-character state abbreviation, ST. Program writeBudgetZones writes 2-d integer zone arrays for layers 2 and 4 (files Springfield_zones.txt and Ozark_zones.txt). The text file zoneFile.txt defines all nine zones for the Zone Budget program, and references the zone array files for layers 2 and 4; these files are in folder I:\gw\Ozark\zones.

The latest available Zone Budget program version (3.0) was downloaded from USGS. Zone Budget reads the unformatted cell-by-cell flow file written by mf2005. The 3.0 version of Zone Budget has two spreadsheet-style options in addition to the formatted table option, which is similar to Tables 10-12 in the USGS report. A spreadsheet-style option was chosen, indicated by the description “CSV” which writes a complete version of the budget for each active zone (1-8) to a comma-delimited file. Each record written includes all flow components, and interzone flows, for a given stress period, time step and zone. I import this file into Excel, then apply a two-key sort (first key: zone, second key: time). Budget flow terms for model runs are in cubic feet per day (based on specifying ITMUNI=4 (days) and LENUNI=1 (feet) in the discretization package. A second version of the sorted budget output sheet converts the flows to acre-feet/year. For example, zone budgets for the baseline case were written to file baseline_alt_steps.bud in folder I:\gw\Ozark\baseline\out. This file was imported into sheet import_budget of Excel file budget_baseline_alt_steps.xls in folder I:\gw\Ozark\baseline, then copied into sheet baseline_alt_steps. This sheet was copied to sheet baseline_alt_steps_sorted, which was sorted as described above. A second version of this sheet, baseline_alt_steps_sorted_AFY, was produced to convert the flow rates to acre-feet/day.

A graph in this sheet compares model results with those shown in Table 10 of the USGS report (flows between Ozark aquifer confining unit and Ozark aquifer in Kansas); see results.

Hydfmt (USGS)

HYDMOD writes an unformatted file that contains computed heads at the locations specified in Table 2 for each stress period and time step. This file can be read by running the postprocessor hydfmt; the source code for this program was included in the mf2005 download in folder I:\gw\bin\MF2005.1_7\src\hydprograms. Hydfmt is interactive, but input data can be supplied by a text file that is specified as redirected keyboard data.

Results imported into sheet baseline_hydrographs and graphed

ReadHeads (DWR)

The program ReadHeads is a modified version of the program Read_discret, which was written to extract model discretization data as described above. Program ReadHeads is coordinated with formatted heads written by mf2005 as specified by the output control file baseline_alt_steps_fmtHeads_L24.oc, which specifies that only layers 2 and 4 of computed heads are written to a formatted file, and that the heads are preceded by a label record to identify the stress period, time step and layer.

ReadHeads was written with the option to read unformatted heads, but this option does not yet work. If it did work, it would read the entire model array. With the formatted option, the output control file can specify which layers are to be written. The ReadHeads program assumes that only layers 2 and 4 were written to the files that it reads.

ReadHeads writes heads to data files corresponding to selected stress period and time step, specified in chronological order; stress period and time step are encoded in the file name. Files are written in “xyz” format as defined for Surfer (a Golden Software trademark), where x and y represent cell center projected coordinates (UTM-15, NAD 1983, meters, eqns. 7a and 7b), and z represents computed head elevation (feet); heads for both layers 2 and 4 are written to the same file for a specified stress period and time step.

The program ReadHeads also has the option to write heads in a “grid” format as defined for Surfer (see GS ASCII Grid File Format described in Surfer manual Appendix C). The resulting files are defined in grid coordinates (xg,yg), meters, according to eqns. 4a and 4b. Surfer also appears to have the capability to do the required transformation (rotation and translation) to the projected coordinates (xutm,yutm) as given by eqns. 7a and 7b. However, Surfer does not appear to apply this transformation as expected, so I'm working only with the "xyz" version of the output from ReadHeads.

The xyz files is imported into Surfer for gridding and used to produce elevation contour maps. I have gridded the heads in the xyz data file using 200 rows by 200 columns, which takes about a minute to execute. Alternatively, the files can be imported into Excel, exported as comma-delimited files and then imported into GIS (with the extension txt). Additionally, contours constructed in Surfer can be exported as shapefiles that can be used in ArcGIS or ArcView. Fig. 6 (below) shows an ArcView map image that includes computed head elevation contours that were produced in Surfer and exported as a shapefile.

Batch model runs

Batch file run_scenario_7_alt_steps.bat, listed below, was used to run mf2005, zonbud, hydfmt and readHeads for model scenario 7 from folder I:\gw\Ozark\scenarios. The batch file refers to folder /gw/bin for the executable files. Programs mf2005 and readHeads are each followed by the name of an input file that the program reads as command line arguments. The other two programs, zonbud and hydfmt, are interactive, and expect responses to be typed in at a keyboard (standard input). For these programs, responses are supplied by a text file whose name follows the redirected input symbol, "<". For all except mf2005, log files are specified with names following the redirected output symbol, ">", so that the log files capture program output that would otherwise be written to the terminal screen (standard output).

```
rem file run_scenario_7_alt_steps.bat
rem run from folder i:/gw/Ozark/scenarios>
rem run mf2005
rem
/gw/bin/mf2005 scenario_7_alt_steps.nam
rem
rem run Zonebudget
rem
/gw/bin/zonbud < zonbud_scenario_7_alt_steps.inp > zonbud_scenario_7_alt_steps.log
rem
rem run Hydmod postprocessor hydfmt
rem
/gw/bin/hydfmt < hydfmt_scenario_7_alt_steps.inp > hydfmt_scenario_7_alt_steps.log
rem
rem read heads at end of steady state solution and at end of stress periods 9
(2007) and 14 (2057):
rem
..\bin\readHeads readHeads_scenario_7_formatted_L24.par
               > readHeads_scenario_7_formatted_L24.log
```

Compare results from USGS and DWR model runs

USGS results for model scenarios 1-5 were published in Czarnecki et al. (2009). Results from corresponding model runs were extracted using the postprocessors Zonbud for cell-by-cell flows, Hydfmt for computed head hydrographs at specified locations, and ReadHeads for spatial distributions of computed heads.

Table 6 is an expanded version of Table 3 that lists Excel files into which results from cases run by DWR have been imported; scenarios 1, 4, 6 and 7 have been run. Tables 7a and 7b compare results from USGS and DWR model runs, respectively, on the basis of volumetric flow budgets for zone 1 (Ozark aquifer in Kansas). Table 7a is a modified version of Table 10 in Czarnecki et al. (2009) in which net flows are shown for each budget term. Table 7b (not yet complete) shows corresponding results based on DWR model runs. Comparison of Tables 7a and 7b shows that the USGS and DWR versions of model runs for scenarios 1 and 4 yield very similar, but not identical, budgets for Zone 1.

Table 6. DWR versions of future scenarios for future years 2008-2057 (stress periods 10-14).

Scen-ario	pct (KS)	pct (MO, OK)	USGS [1]	DWR [2]	Spreadsheet file with imported results for case
1	0	0	y	y	I:/gw/Ozark/baseline/budget_baseline_alt_steps.xls
2	1	1	y		
3	0	1	y		
4	2	2	y	y	I:/gw/Ozark/scenarios/budget_scenario_4_alt_steps.xls
5	4	4	y		
6	2	0		y	I:/gw/Ozark/scenarios/budget_scenario_6_alt_steps.xls
7	2	4		y	I:/gw/Ozark/scenarios/budget_scenario_7_alt_steps.xls

Fig. 1. Base map of model domain with model grid cell centers showing active model domain for the Ozark aquifer layer 4 (green). Also shown: approximate locations of pumping centers for comparison of water level hydrographs (to be extracted from DWR model runs) against USGS report for scenarios 1-5. [pumping_center_locations_estimated_from_city_locs.jpg]

Fig. 2. Contours of Ozark aquifer bottom elevation (ft) displayed in Surfer; based on groundwater model discretization package input file. Axis coordinates are in UTM-15 (NAD 1983, meters. [file Ozark_aquifer_layer_L4_bottom_elevation_ft_contours_surfer.jpg in I:\gw\Ozark\images]

Scenario 1 (baseline conditions): figs. 3-7

Compare Tables 7a and 7b: predevelopment (steady state) and Scenario 1 (baseline conditions).

Fig. 3. Annual pumping rates (acre-feet per year) from Kansas, Oklahoma and Missouri components of Ozark aquifer (defined as zones 1-3, respectively) for baseline conditions (scenario 1, with no change in pumping after 2007).

Fig. 4. Flow exchange between Zones1 (Ozark aquifer in KS) and 4 (Ozark confining layer) for Scenario 1 (baseline), DWR model run and comparison with USGS model run from Table 10 of USGS report.

Fig. 5. Baseline (scenario 1) simulation water level altitudes at nodes near five cities; compare with Fig. 26 of USGS report.

Fig. 6. Computed Ozark aquifer water levels at end of 2057 (stress period 14) for scenario 1 (baseline).

Figs. 7a-7c to do: open file heads_scenario_1.csv in Surfer and construct images.

Fig. 7a. Computed Ozark aquifer saturated thickness for predevelopment conditions (solution for steady-state stress period 1 of scenario 1. [file ozark_aquifer_scenario_1_satthk_contours_2057.jpg in I:\gw\Ozark\images]

Fig. 7b. Computed Ozark aquifer saturated thickness at end of 2007 (stress period 9, time step 1) for scenario 1. [file ozark_aquifer_scenario_1_satthk_contours_2057.jpg in I:\gw\Ozark\images]

Fig. 7c. Computed Ozark aquifer saturated thickness at end of 2057 (stress period 14, time step 60) for scenario 1. [file ozark_aquifer_scenario_1_satthk_contours_2057.jpg in I:\gw\Ozark\images]
Scenario 4: figs 8-9

Compare Tables 7a and 7b: Scenario 4.

Fig. 8. Annual pumping rates (acre-feet per year) from Kansas, Oklahoma and Missouri components of Ozark aquifer (defined as zones 1-3, respectively) for scenario 4.

Fig. 9. Flow exchange between Zones1 (Ozark aquifer in KS) and 4 (Ozark confining layer) for Scenario 4, DWR model run and comparison with USGS model run from Table 10 of USGS report.

Fig. 10. Scenario 4 simulation water level altitudes at nodes near five cities; compare with Fig. 32 of USGS report. Chart at o2 in sheet scenario_4_hydrographs in budget_scenario_4_alt_steps.xls, folder i:\gw\Ozark\scenarios.

Additional scenarios 6 and 7

Sensitivity of computed water level in Ozark aquifer in Kansas near Pittsburg, KS to pumping rate of increase in Missouri: Figs. 10-12.

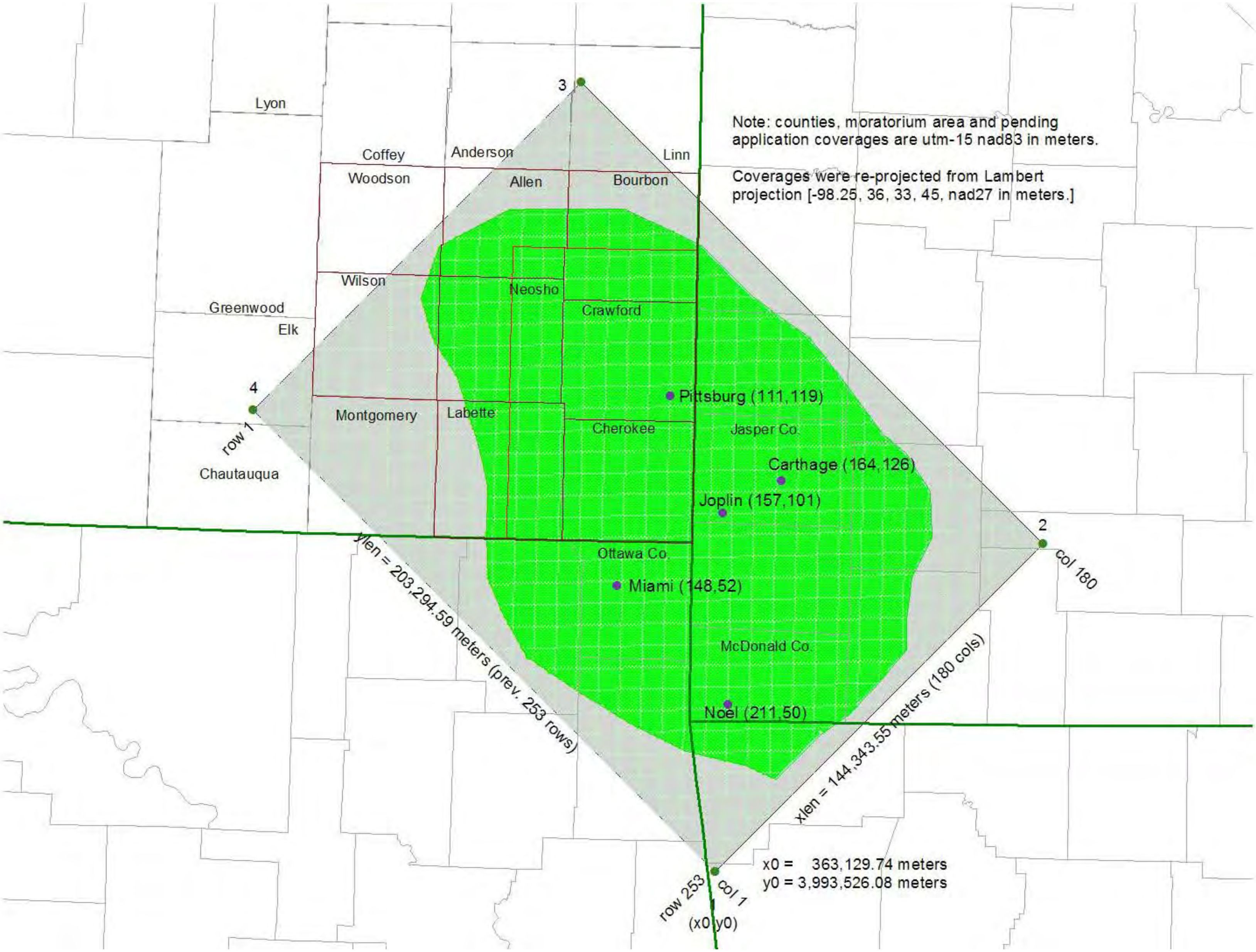
Fig. 11: Computed water level at node near Pittsburg, KS for Scenarios 1, 4, 6 and 7.

Fig. 12. Change in computed water level with respect to Scenario 4 at node near Pittsburg for Scenarios 6 and 7.

Fig. 13. Cumulative frequency distributions of changes in water level under scenarios 6 and 7 with respect to scenario 4.

Fig. 14a. Projected difference in computed water level in Ozark aquifer for Scenario 6 with respect to Scenario 4 at end of simulation period (2057): effect of decreasing annual pumping growth rate in MO and OK from 2 pct/yr to 0 pct/yr, holding KS pumping growth rate at 2 pct/yr.
[file ozark_head_difference_contours_scen6-scen4.jpg in I:\gw\Ozark\images]

Fig. 14b. Projected difference in computed water level in Ozark aquifer for Scenario 7 with respect to Scenario 4 at end of simulation period (2057): effect of increasing annual pumping growth rate in MO and OK from 2 pct/yr to 4 pct/yr, holding KS pumping growth rate at 2 pct/yr.
[file ozark_head_difference_contours_scen7-scen4.jpg in I:\gw\Ozark\images]



Note: counties, moratorium area and pending application coverages are utm-15 nad83 in meters.

Coverages were re-projected from Lambert projection [-98.25, 36, 33, 45, nad27 in meters.]

x0 = 363,129.74 meters
y0 = 3,993,526.08 meters

Fig. 1. Base map of model domain with model grid cell centers showing active model domain for the Ozark aquifer layer 4 (green). Also shown: approximate locations of pumping centers for comparison of water level hydrographs (to be extracted from DWR model runs) against USGS report for scenarios 1-5. [pumping_center_locations_estimated_from_city_locs.jpg]

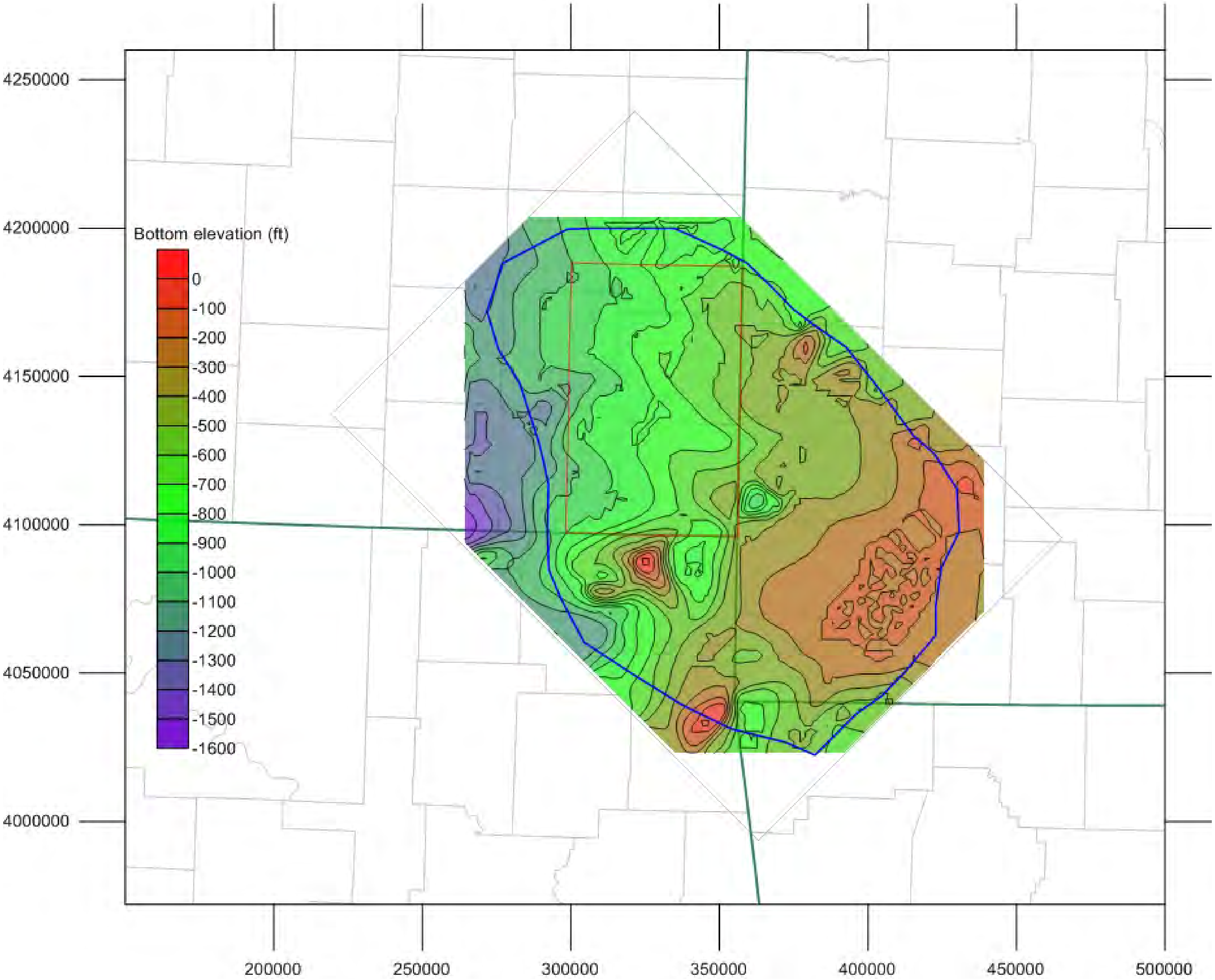


Fig. 2. Contours of Ozark aquifer bottom elevation (ft) displayed in Surfer; based on groundwater model discretization package input file. Axis coordinates are in UTM-15 (NAD 1983, meters. [file Ozark_aquifer_layer_L4_bottom_elevation_ft_contours_surfer.jpg in I:\gw\Ozark\images]

Table 7a. Results from USGS model runs: Ozark aquifer model zone budget for Kansas (Zone 1) for predevelopment conditions and water use percent annual increase scenarios 1-5. A modified version of Table 10, Czarnecki et al. (2009) that also shows net flow for each budget term.

Flow component	Predevel. (no water use)		Scenario 1 KS: 0; MO, OK: 0		Scenario 2 KS: 1; MO, OK: 1		Scenario 3 KS: 0; MO, OK: 1		Scenario 4 KS: 2; MO, OK: 2		Scenario 5 KS: 4; MO, OK: 4	
IN:	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct
Release from storage	0	0	3,148	26	6,963	36	5,426	34	10,782	42	26,431	53
General heads	200	4	259	2	328	2	297	2	368	1	594	1
OK to KS (2 to 1)	489	10	668	6	858	4	721	5	1,018	4	1,783	4
MO to KS (3 to 1)	2,701	58	3,051	25	4,622	24	3,476	22	5,864	23	10,093	20
overlying unit down to KS (4 to 1)	1,274	27	4,945	41	6,500	34	5,930	37	7,528	29	10,536	21
Total	4,665		12,071		19,271		15,850		25,560		49,437	
OUT:	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct
General heads	1,752	38	777	6	699	4	719	5	686	3	618	1
Wells	0	0	6,100	51	10,064	52	6,173	39	13,543	53	30,010	61
KS to OK (1 to 2)	606	13	1,023	8	1,497	8	1,641	10	1,846	7	2,978	6
KS to MO (1 to 3)	1,191	26	3,672	30	6,515	34	6,822	43	8,988	35	15,336	31
KS up to overlying unit (1 to 4)	1,116	24	499	4	495	3	495	3	496	2	494	1
Total	4,665		12,071		19,271		15,850		25,560		49,437	
Net (IN - OUT):	ac-ft/yr	pct*	ac-ft/yr	pct*	ac-ft/yr	pct*	ac-ft/yr	pct*	ac-ft/yr	pct*	ac-ft/yr	pct*
Release from storage	0	0	3148	26	6963	36	5426	34	10782	42	26431	53
General heads	-1,552	-33	-518	-4	-371	-2	-422	-3	-318	-1	-24	0
Wells	0	0	-6100	-51	-10064	-52	-6173	-39	-13543	-53	-30010	-61
OK to KS (2 to 1)	-117	-3	-355	-3	-639	-3	-920	-6	-828	-3	-1,195	-2
MO to KS (3 to 1)	1,510	32	-621	-5	-1,893	-10	-3,346	-21	-3,124	-12	-5,243	-11
overlying unit down to KS (4 to 1)	158	3	4,446	37	6,005	31	5,435	34	7,032	28	10,042	20
Total (IN - OUT):	0	0	0	0	0	0	0	0	0	0	0	0

[range a1:s29 of sheet budget_zone_1_AFY_USGS_runs in budget_baseline_alt_steps.xls

(*) for Net (IN - OUT), percent of Total IN or OUT.

Table 7b. Results from KDA-DWR model runs: Ozark aquifer model zone budget for Kansas (Zone 1) for predevelopment conditions and water use percent annual increase scenarios 1-5; compare with T. 6a (above) or T. 10, Czarnecki et al. (2009).

Flow component	Predevel. (no water use)		Scenario 1 KS: 0; MO, OK: 0		Scenario 2 KS: 1; MO, OK: 1		Scenario 3 KS: 0; MO, OK: 1		Scenario 4 KS: 2; MO, OK: 2		Scenario 5 KS: 4; MO, OK: 4	
IN:	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct
Release from storage	0	0	3,026	26					11,975	44		
General heads	205	4	266	2					436	2		
OK to KS (2 to 1)	490	10	675	6					1,139	4		
MO to KS (3 to 1)	2,691	58	2,739	23					5,802	21		
overlying unit down to KS (4 to 1)	1,260	27	4,992	43					8,006	29		
Total	4,647		11,697						27,357			
OUT:	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct	ac-ft/yr	pct
General heads	1,752	38	735	6					661	2		
Wells	0	0	5,987	51					14,595	53		
KS to OK (1 to 2)	586	13	988	8					1,975	7		
KS to MO (1 to 3)	1,186	26	3,482	30					9,624	35		
KS up to overlying unit (1 to 4)	1,124	24	506	4					501	2		
Total	4,647		11,697						27,357			
Net (IN - OUT):	ac-ft/yr	pct*	ac-ft/yr	pct*	ac-ft/yr	pct*	ac-ft/yr	pct*	ac-ft/yr	pct*	ac-ft/yr	pct*
Release from storage	0	0	3,026	26					11,975	44		
General heads	-1,547	-33	-470	-4					-226	-1		
Wells	0	0	-5,987	-51					-14,595	-53		
OK to KS (2 to 1)	-96	-2	-313	-3					-837	-3		
MO to KS (3 to 1)	1,506	32	-743	-6					-3,823	-14		
overlying unit down to KS (4 to 1)	136	3	4,486	38					7,505	27		
Total (IN - OUT):	0	0	0	0					0	0		

[range a1:s29 of sheet budget_zone_1_AFY_DWR_runs in budget_baseline_alt_steps.xls

(*) for Net (IN - OUT), percent of Total IN or OUT

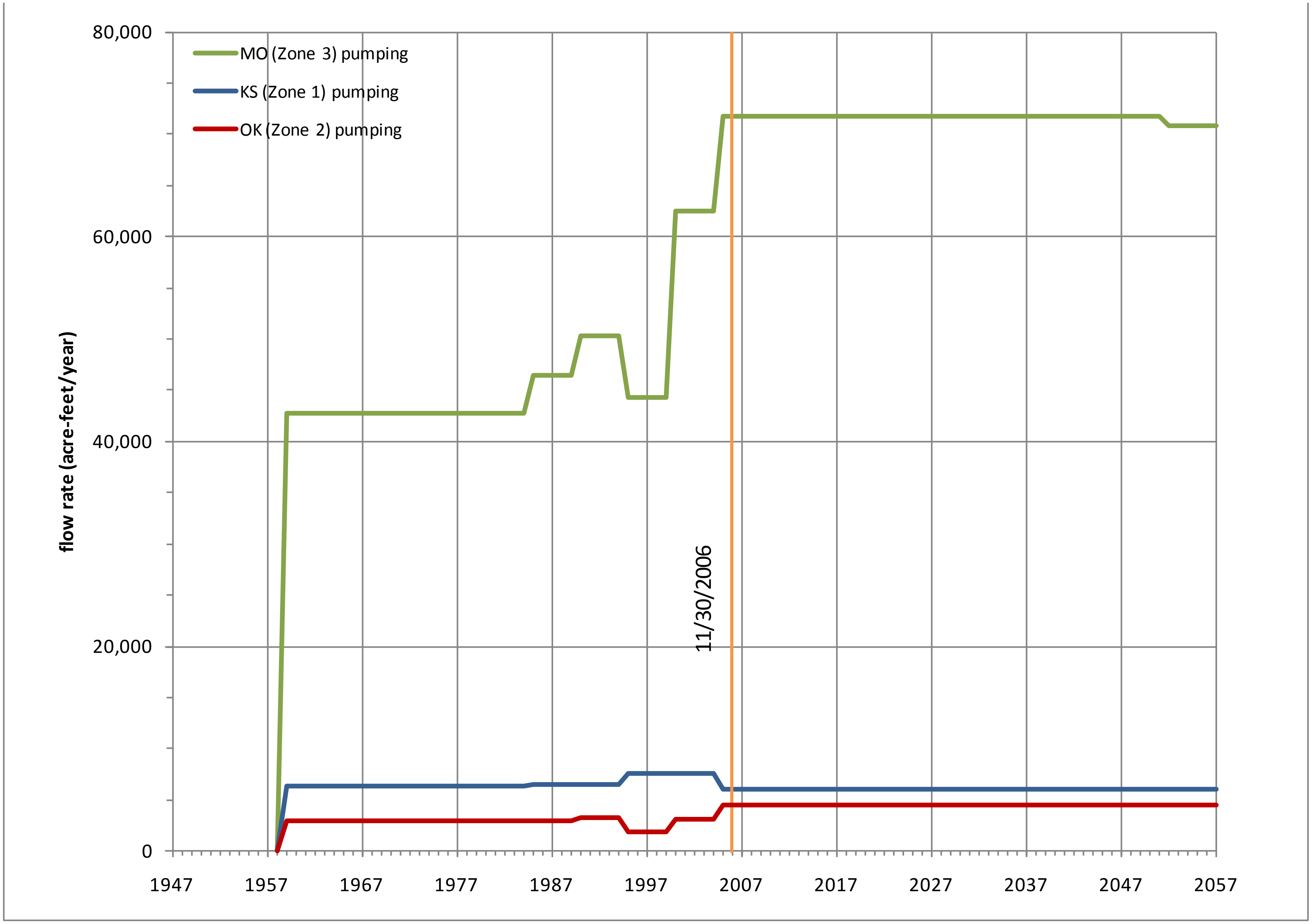
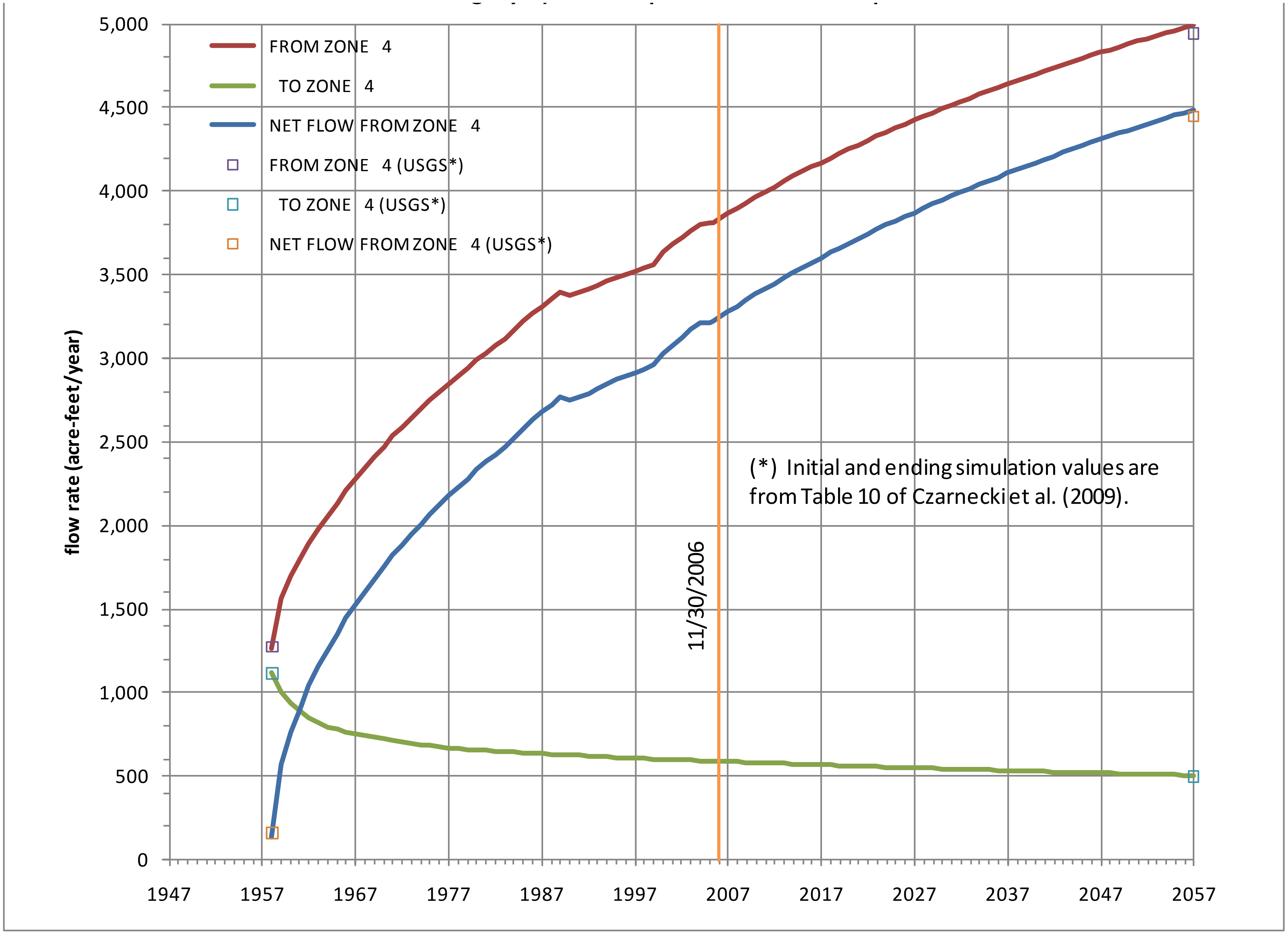


Fig. 3. Annual pumping rates (acre-feet per year) from Kansas, Oklahoma and Missouri components of Ozark aquifer (defined as zones 1-3, respectively) for baseline conditions (scenario 1, with no change in pumping after 2007). From chart at bw10 in sheet baseline_alt_steps_sorted_AFY, file budget_baseline_alt_steps.xls in i:\gw\Ozark\baseline.



(*) Initial and ending simulation values are from Table 10 of Czarnecki et al. (2009).

Fig. 4. Flow exchange between Zones1 (Ozark aquifer in KS) and 4 (Ozark confining layer) for Scenario 1 (baseline), DWR model run and comparison with USGS model run from Table 10 of USGS report. Chart at bj9, sheet baseline_alt_steps_sorted_AFY in budget_baseline_alt_steps.xls

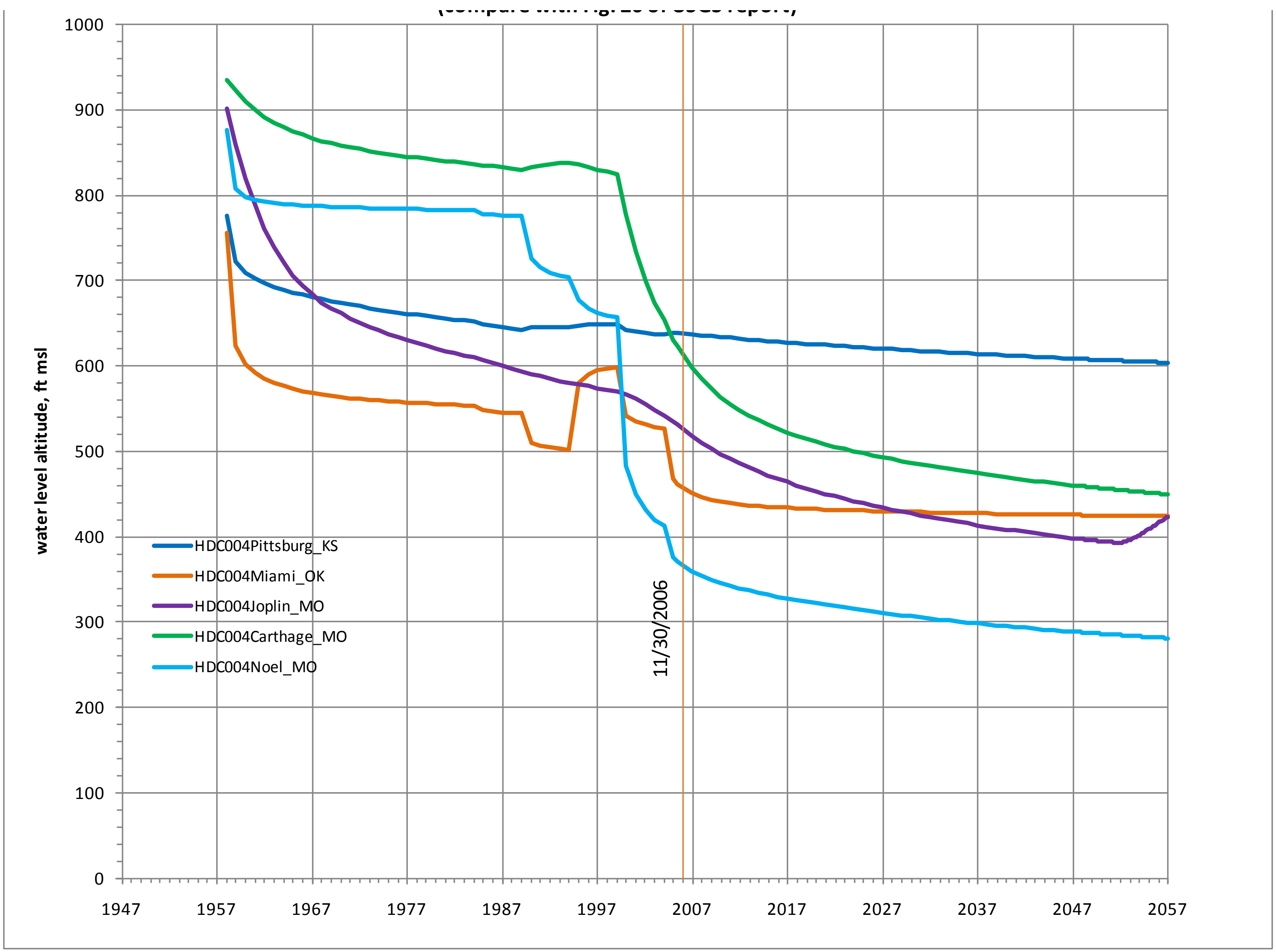


Fig. 5. Baseline (scenario 1) simulation water level altitudes at nodes near five cities; compare with Fig. 26 of USGS report. Chart at o2 in sheet baseline_hydrographs in budget_baseline_alt_steps.xls, folder i:\gw\Ozark\baseline.

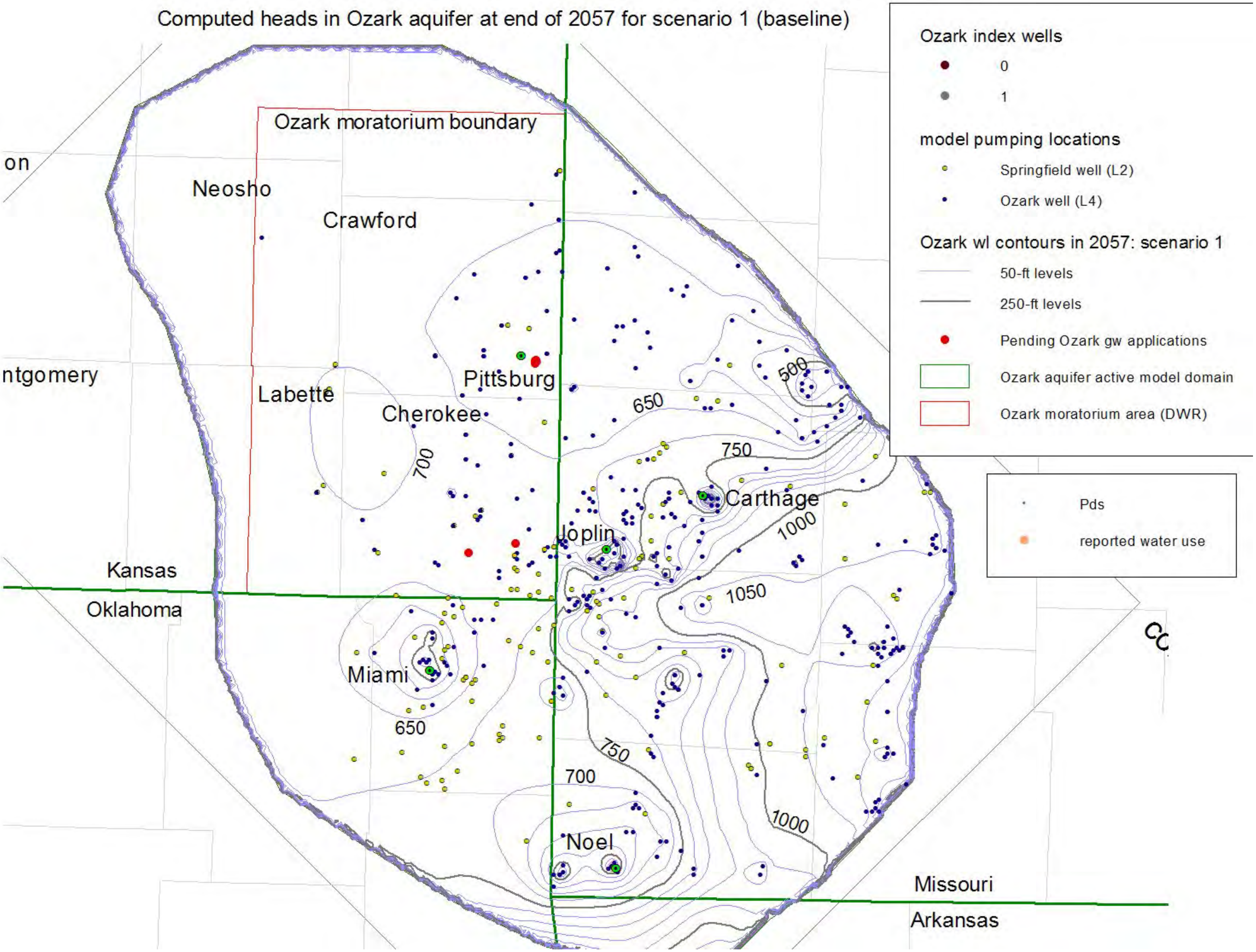


Fig. 6. Computed Ozark aquifer water levels at end of 2057 (stress period 14) for scenario 1 (baseline).
[file ozark_aquifer_scenario_1_wl_contours_2057.jpg in I:\gw\Ozark\images]

Fig. 7a. Computed Ozark aquifer saturated thickness for predevelopment conditions (solution for steady-state stress period 1 of scenario 1. [file ozark_aquifer_scenario_1_satthk_contours_2057.jpg in I:\gw\Ozark\images]

Fig. 7b. Computed Ozark aquifer saturated thickness at end of 2007 (stress period 9, time step 1) for scenario 1. [file ozark_aquifer_scenario_1_satthk_contours_2057.jpg in I:\gw\Ozark\images]

Fig. 7c. Computed Ozark aquifer saturated thickness at end of 2057 (stress period 14, time step 60) for scenario 1. [file ozark_aquifer_scenario_1_satthk_contours_2057.jpg in I:\gw\Ozark\images]

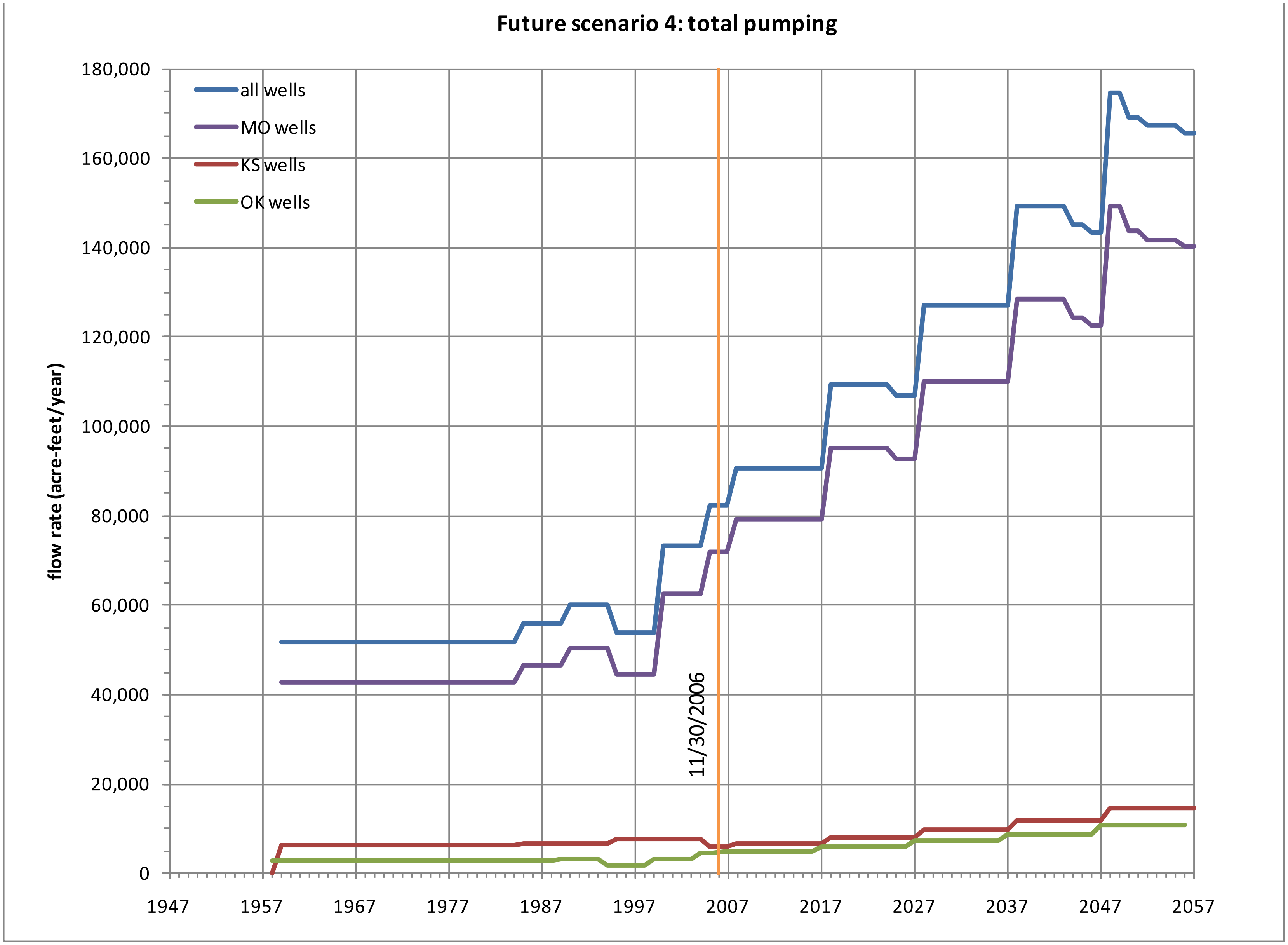


Fig. 8. Annual pumping rates (acre-feet per year) from Kansas, Oklahoma and Missouri components of Ozark aquifer (defined as zones 1-3, respectively) for scenario 4. From chart at bw10 in sheet scenario_4_sort_by_zones_AFY, file budget_scenario_4_alt_steps.xls in i:\gw\Ozark\scenarios.

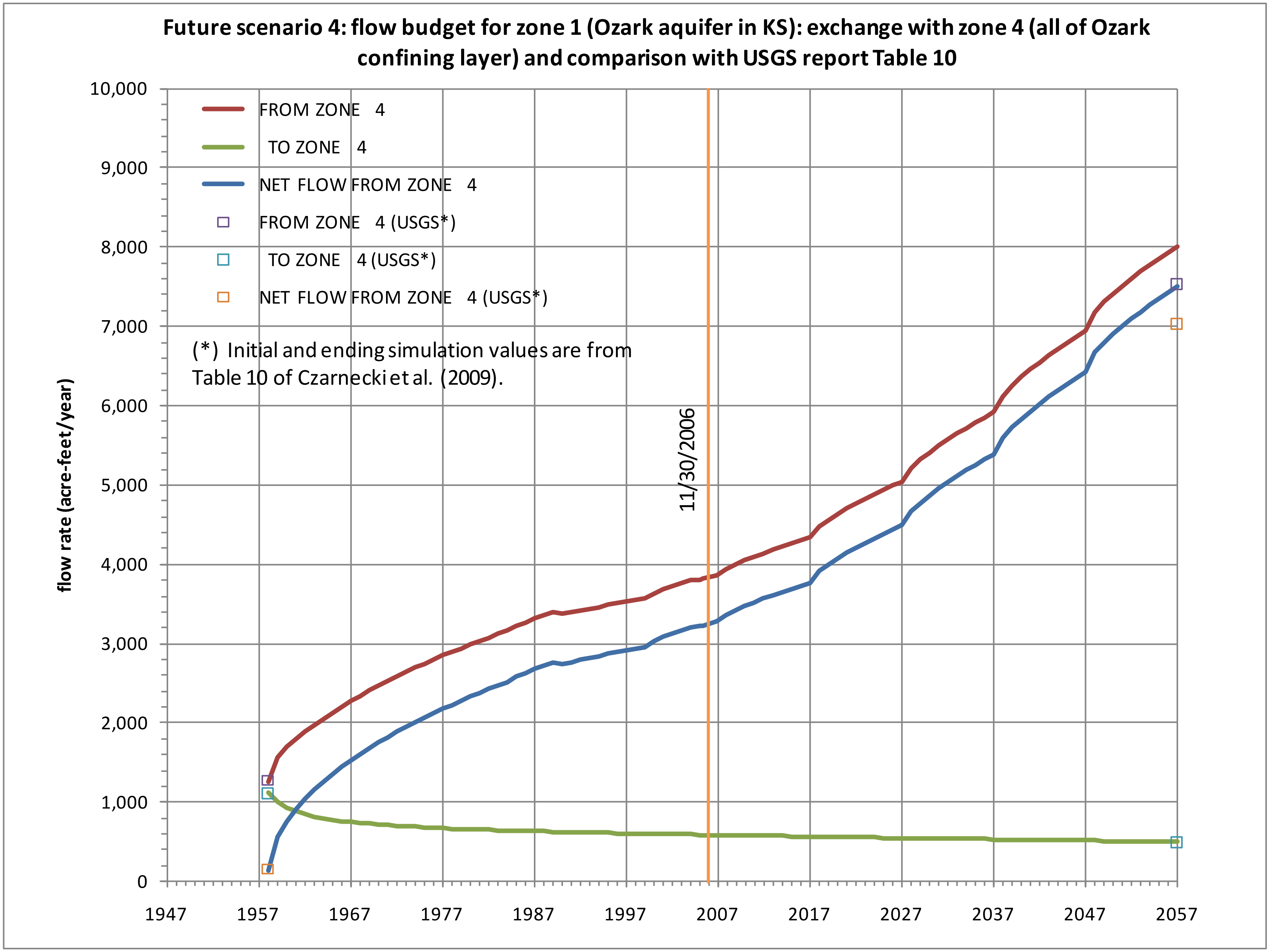


Fig. 9. Flow exchange between Zones1 (Ozark aquifer in KS) and 4 (Ozark confining layer) for Scenario 4, DWR model run and comparison with USGS model run from Table 10 of USGS report. Chart at bj9, sheet scenario_4_sort_by_zones_AFY in budget_scenario_4_alt_steps.xls.

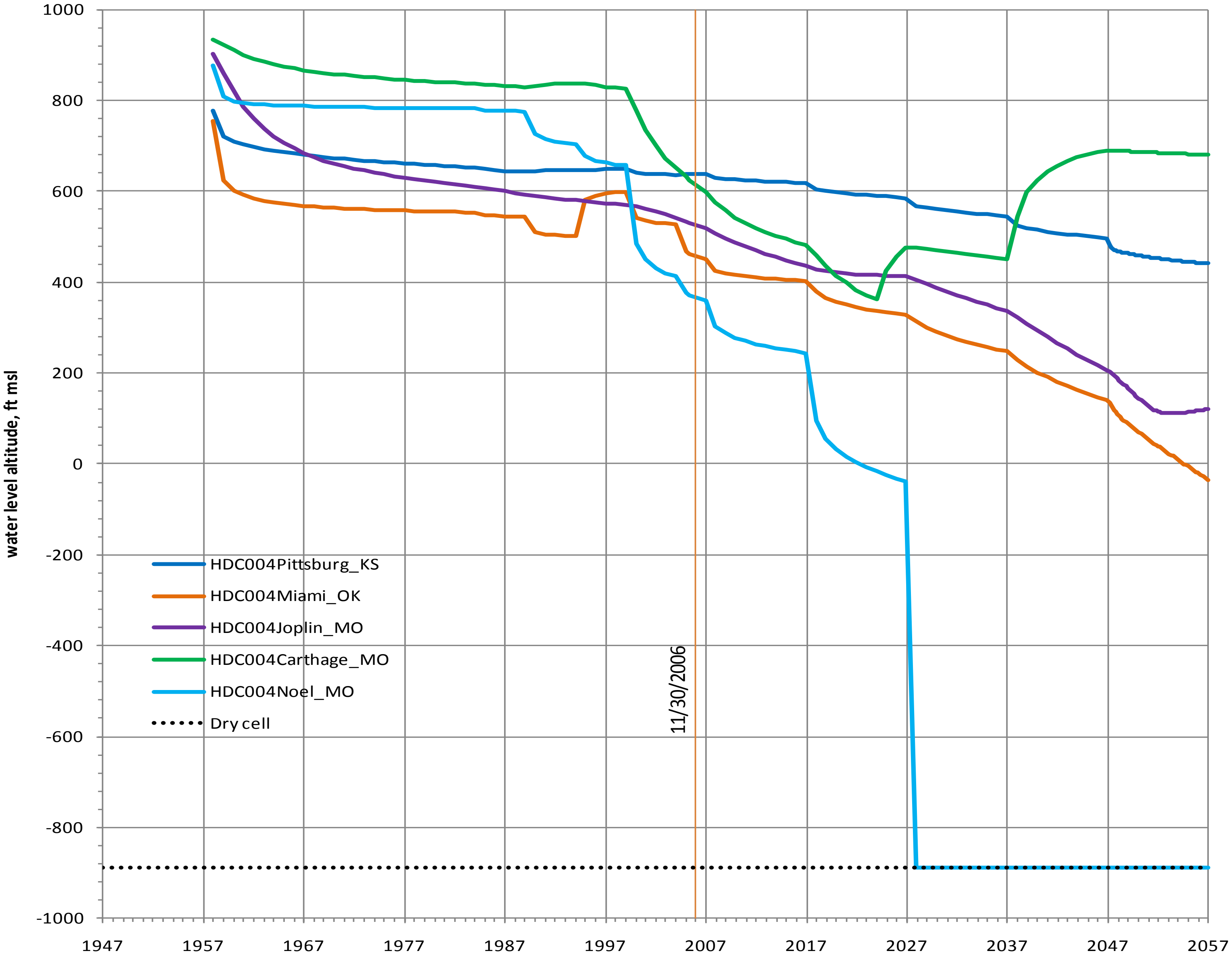


Fig. 10. Scenario 4 simulation water level altitudes at nodes near five cities; compare with Fig. 32 of USGS report. Chart at o2 in sheet scenario_4_hydrographs in budget_scenario_4_alt_steps.xls, folder i:\gw\Ozark\scenarios.

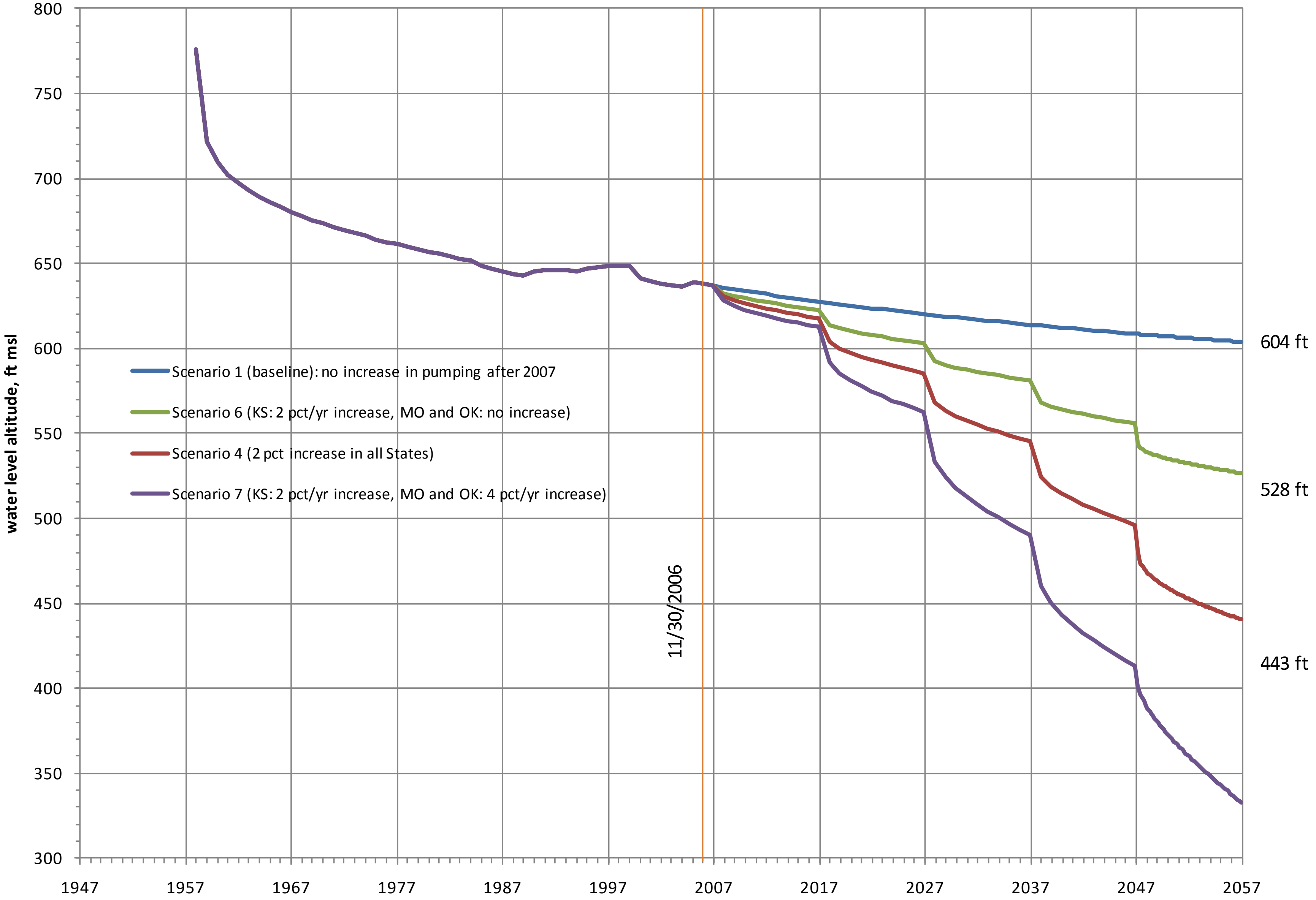


Fig. 11. Simulated water level at node near Pittsburg, KS for Scenarios 1 (baseline), 4, 6 and 7. Chart at O2 in sheet Pittsburg_hydrographs in

budget_baseline_alt_steps.xls.

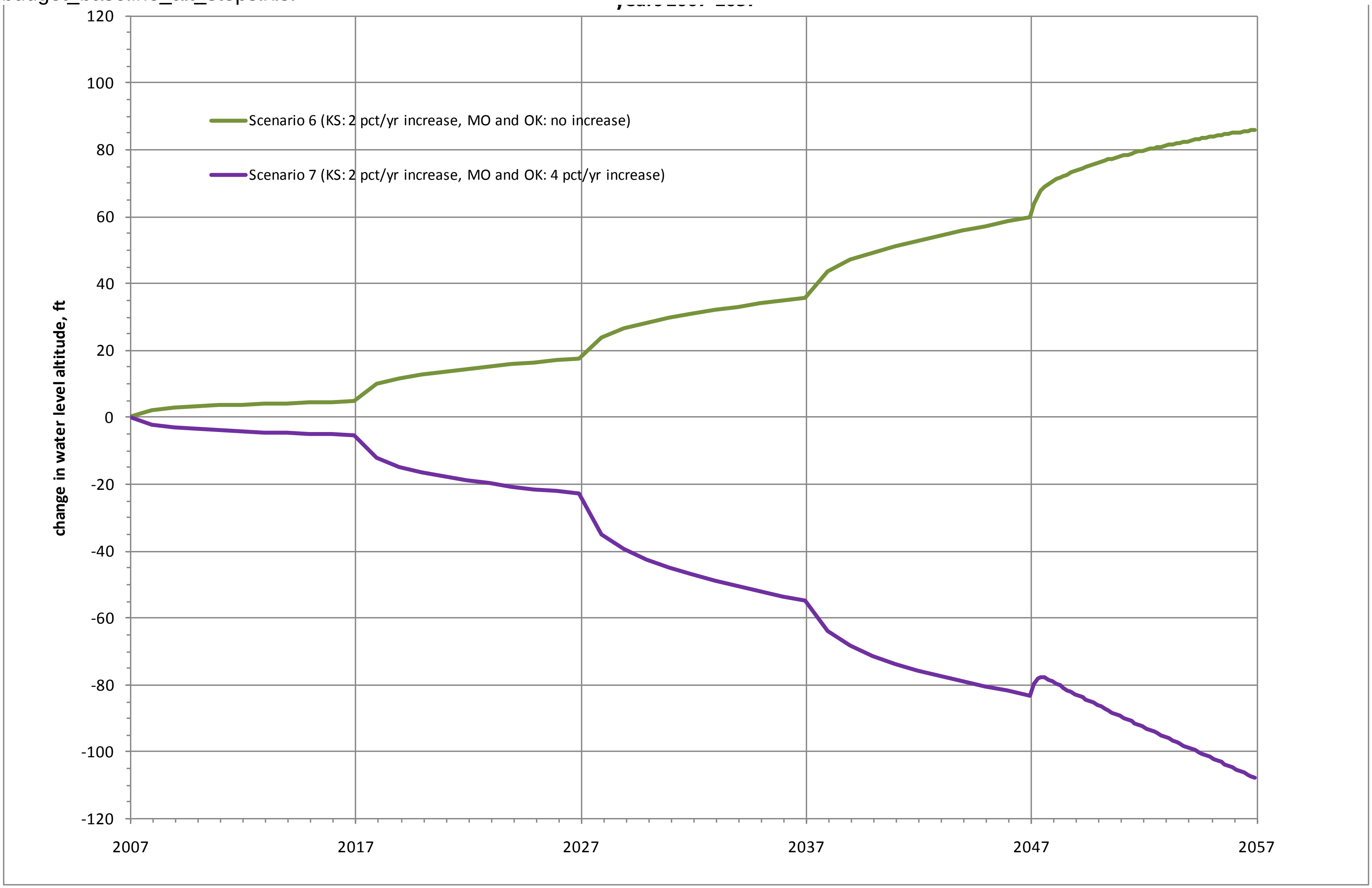


Fig. 12. Change in simulated water level with respect to Scenario 4 at node near Pittsburg, KS for years 2007-2057: Scenarios 6 and 7. Chart at aw2 in sheet Pittsburg_hydrographs in budget_baseline_alt_steps.xls.

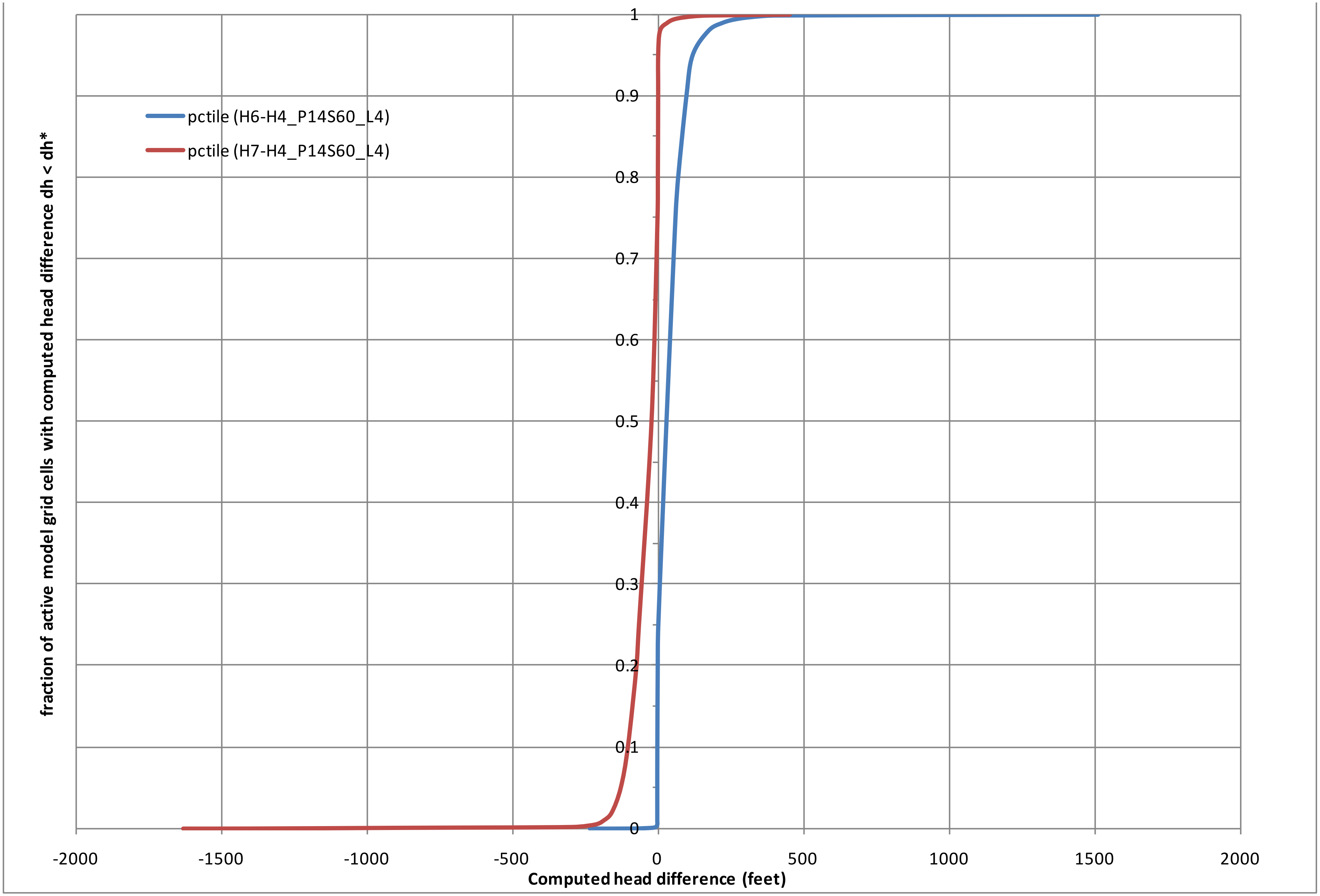
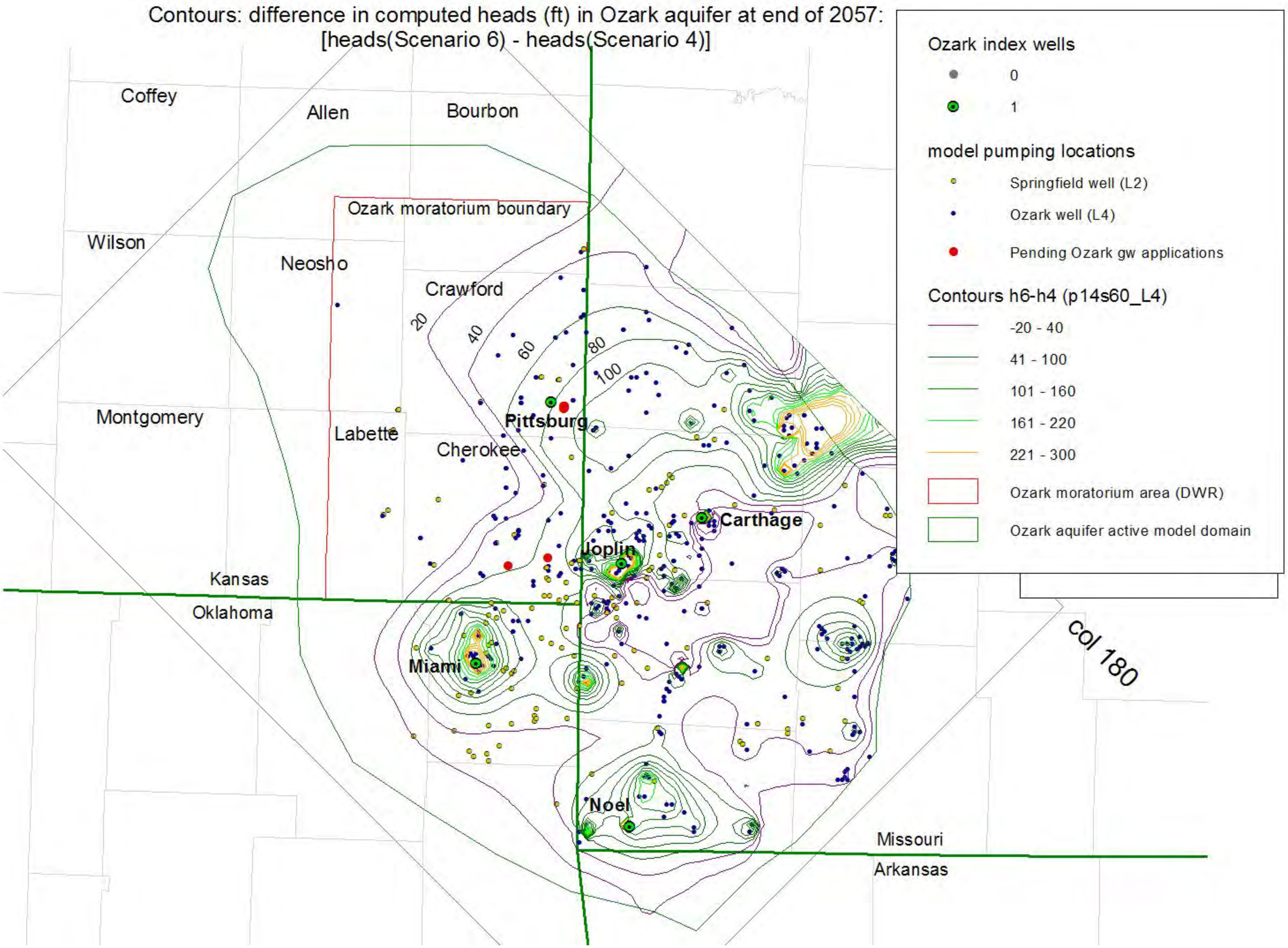


Fig. 13. Cumulative frequency distributions of changes in water level under scenarios 6 and 7 with respect to scenario 4. [Chart at f1 in sheet percentiles in file scenarios_4_6_7_active_heads_L4.xls in i:\gw\Ozark\grid]



Contours: difference in computed heads (ft) in Ozark aquifer at end of 2057: [heads(Scenario 6) - heads(Scenario 4)]

Fig. 14a. Projected difference in computed water level in Ozark aquifer for Scenario 6 with respect to Scenario 4 at end of simulation period (2057): effect of decreasing annual pumping growth rate in MO and OK from 2 pct/yr to 0 pct/yr, holding KS pumping growth rate at 2 pct/yr. [file ozark_head_difference_contours_scen6-scen4.jpg in I:\gw\Ozark\images]

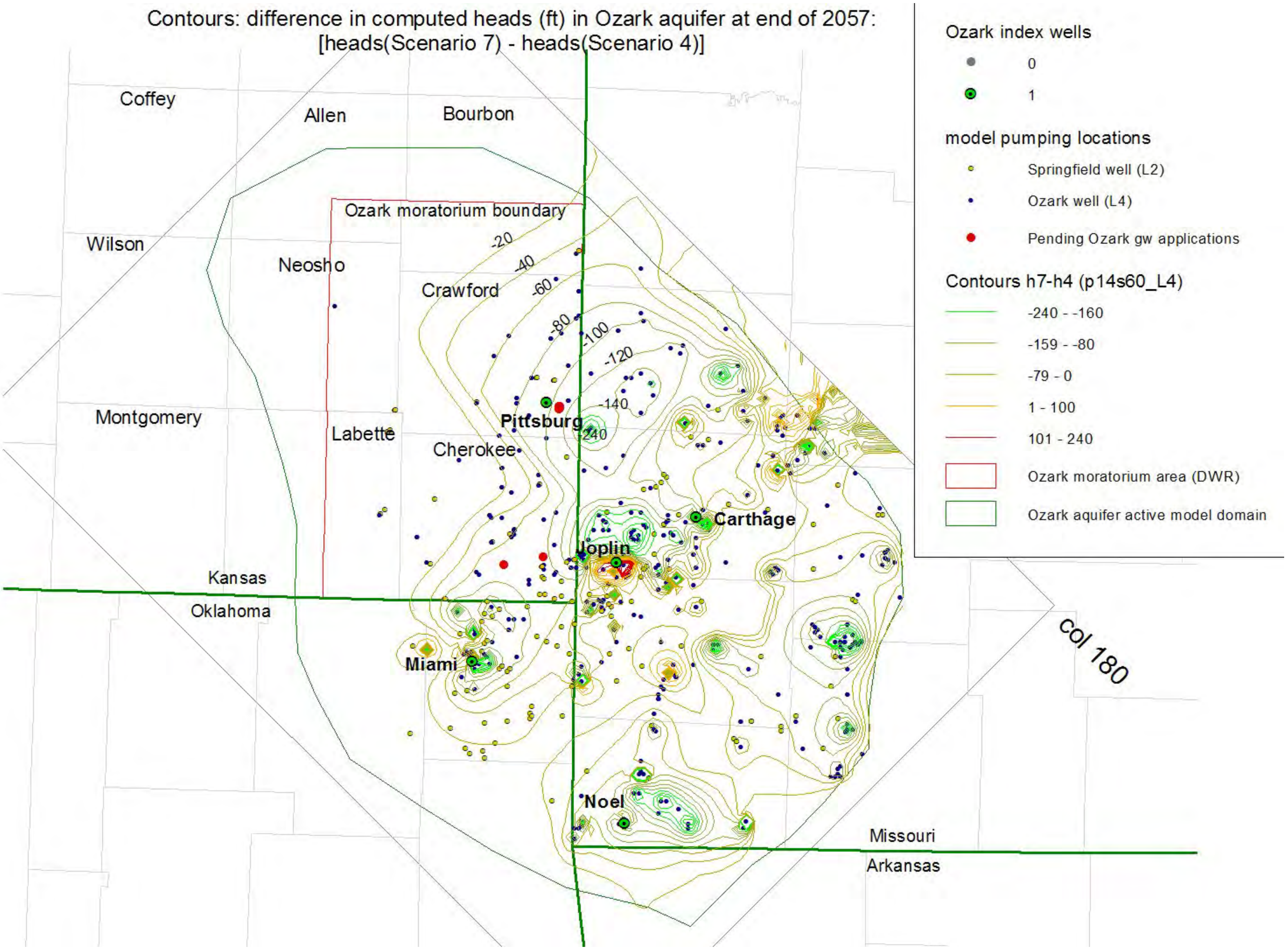


Fig. 14b. Projected difference in computed water level in Ozark aquifer for Scenario 7 with respect to Scenario 4 at end of simulation period (2057): effect of increasing annual pumping growth rate in MO and OK from 2 pct/yr to 4 pct/yr, holding KS pumping growth rate at 2 pct/yr. [file ozark_head_difference_contours_scen7-scen4.jpg in I:\gw\Ozark\images]

Comparison of computed heads from GMS and MF2005 runs (Czarnecki, 2008)

[In this note, John compared baseline model results run using mf2k in GMS and the public-domain version of mf2005.]

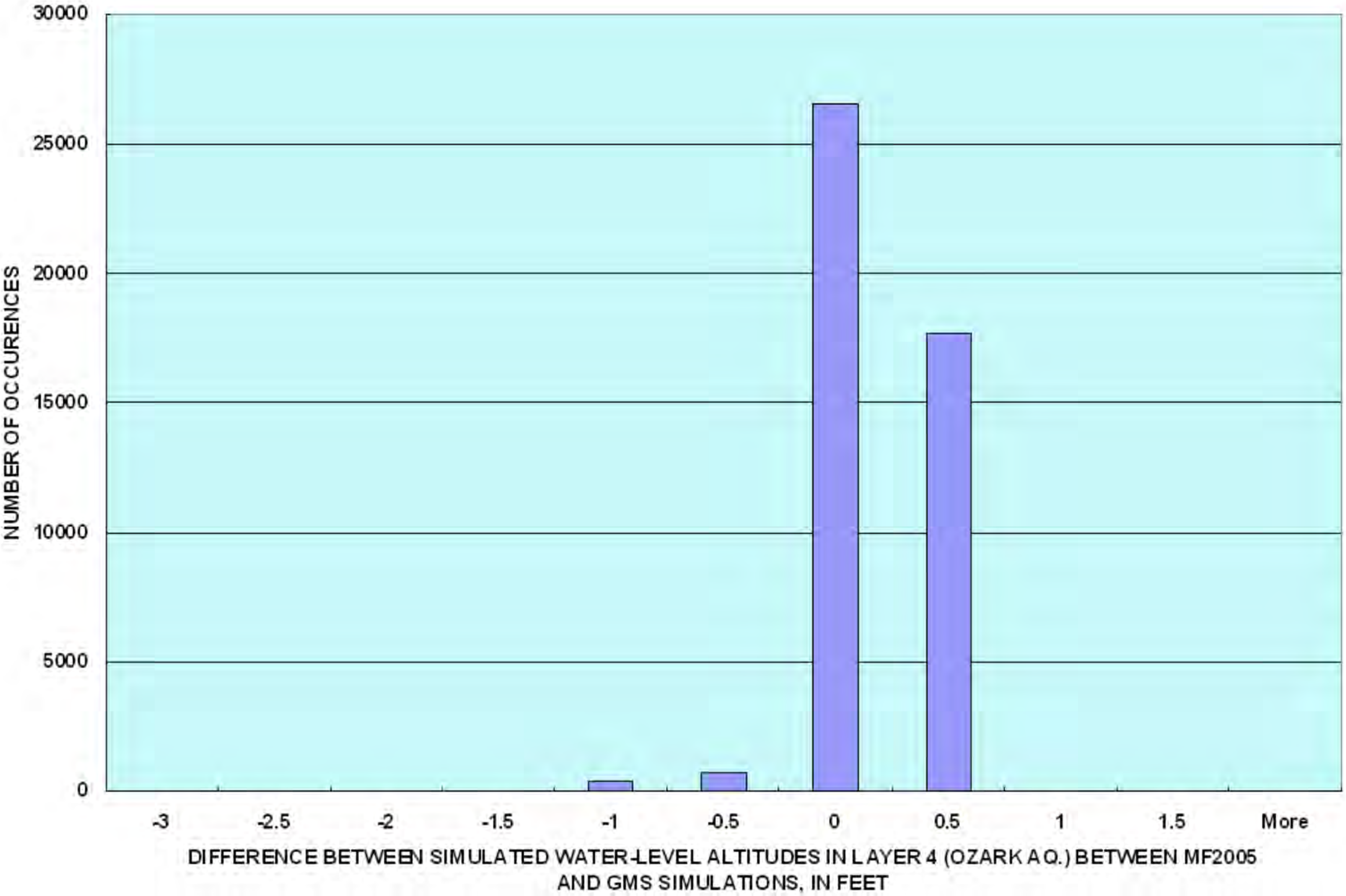
From: John B Czarnecki [mailto:jczarnec@usgs.gov]
Sent: Friday, December 05, 2008 2:53 PM
To: Perkins, Sam
Cc: Walter R Aucott
Subject: evaluation of ss stress period heads in gms and mf2005 runs (Tristate model)

Sam,

You'll be interested to know that I was successful in getting the Tristate model in GMS to run under MODFLOW 2005 (MF2005). Although I was able to finally get the native modflow 2000 files exported from GMS to run using MF2005, I thought it necessary to see what differences there might be between the runs using the two separate codes. The largest discrepancies occur at the location of cells that go dry in one version and not the other in the top three layers. Layer 4 (Ozark aquifer) has no cells that go dry. Differences in that layer in most cells are generally less than 0.5 ft. See histogram [below].

Part of the reason why there is any difference between thses two data sets is what is occurring in the upper layers with differences in cells going dry, and the effect propagating down into layer 4. There are likely differences related to improvements in the solver. Without going into an exhaustive evaluation, I would say that this likely will have minimal effect on KWO using the model outside of GMS for their various scenarios. I know that the MF developers wrestled with cells going dry and developed various 'fixes' that ended up in MF2005. Another check would be to look at the mass balance of all the various flow components to see which ones are affected the most between the two versions of Modflow. Having said all of this, it has been a substantial effort to get the current model to run outside of GMS on an external version of Modflow. Note that although there is a difference in the actual model values, the differences are substantially less than the mean absolute error associated with observed and simulated hydraulic heads.

John Czarnecki, Ph.D.
Hydrologist
U.S. Geological Survey Arkansas Water Science Center


30000
25000
20000
15000
10000
5000
0
NUMBER OF OCCURENCES
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
More
DIFFERENCE BETWEEN SIMULATED WATER-LEVEL ALTITUDES IN LAYER 4 (OZARK AQ.) BETWEEN MF2005
AND GMS SIMULATIONS, IN FEET