Kansas Geological Survey

Equus Beds Groundwater Management District No. 2 Sustainability Assessment

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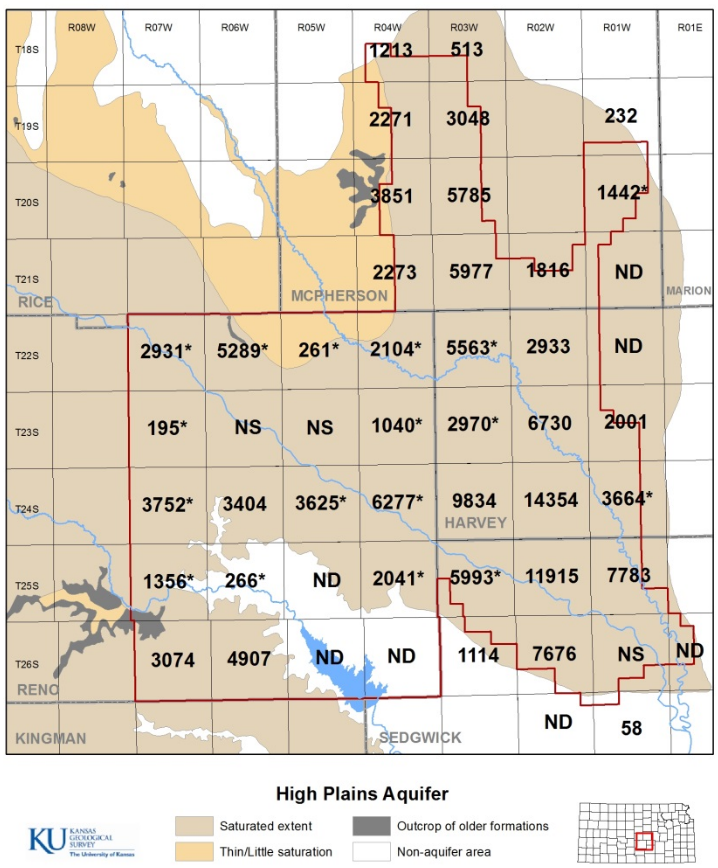
Average Sustainable Water Use, in Acre-Feet, by Township
* indicates the township is heavily dependent on infrequent high inflow years



Kansas Geological Survey Open-File Report No. 2017-3
January 2017

GEOHYDROLOGY

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KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 2017-3

Acknowledgments

We are grateful for the assistance of Steve Flaherty and other members of the staff of Equus Beds Groundwater Management District No. 2 (GMD2). John Woods of the Kansas Geological Survey (KGS) assisted with data processing, and Julie Tollefson of the KGS edited the report. This project was funded by GMD2 and the Kansas Water Plan.

Executive Summary

The objective of this study was to assess the prospects for sustainability of the portions of the High Plains aquifer (HPA) in the Equus Beds Groundwater Management District No. 2 (GMD2) in south-central Kansas. For the purposes of this report, sustainability is defined as being achieved when spatially averaged water levels are stable with time, i.e. the average annual water-level change over an area is zero for a period of several years. Given the temporal variability in annual precipitation and groundwater use, there will be year-to-year rises and falls in spatially averaged water levels across GMD2. However, those changes will average out to zero over a period of several years if the aquifer is being pumped at a sustainable level. The specific purpose of this study was to determine the average annual water use that would produce stable areally averaged water levels over a given area. That annual water use is defined as Q_{stable} in this report.

The water-balance approach used here for assessing the sustainability of the HPA in GMD2 was recently developed at the Kansas Geological Survey to take advantage of conditions common to the HPA in Kansas. This data-driven approach uses annually collected data on groundwater levels and reported water use that can be readily processed to directly calculate Q_{stable}. The approach considers the complete picture of aquifer inflows and outflows at a scale of tens to thousands of square miles and was specifically developed for seasonably pumped aquifers, i.e. aquifers for which irrigation is the main water use, that are at a mature stage of development. All components of the water budget contributing to Q_{stable} (recharge from the land surface, inflow from streams, etc.) are lumped into one term to significantly reduce data requirements and considerably reduce the level of uncertainty relative to alternative approaches. Over time, the resulting analyses can be readily updated to account for changing climatic and hydrologic conditions. In this study, the approach was applied at four spatial scales: that of the entire district, the portions of individual counties lying within the district, the portions of townships lying within the district, and areas defined by GMD2 staff (henceforth, defined areas).

The major conclusion of this study is that the average annual water use over much of the HPA in GMD2 has been close to a sustainable level during the periods considered here (1996–2014 and 2005–2014). This conclusion is consistent with the maps of water-level changes over these periods, which show modest water-level declines over most of the area with relatively large water-level increases restricted to an area that primarily lies within Harvey County. The relative sustainability of the HPA within GMD2, however, varies with the scale and location of the analysis. The major findings of the sustainability assessment for the different scales of analysis are as follows:

1. District-level assessment—The average annual reported water use appears to have been very close to the sustainable level for both assessment periods. Considering the results from all analyses, the average Q_{stable} is 180,308 ac-ft/yr, 1.2% below the average annual reported water use for GMD2.
2. County-level assessment—The findings of this assessment vary among the counties. All but McPherson County are at least somewhat dependent on infrequent years of high inflow to maintain near stable water levels.
   a) Harvey County—The average annual reported water use is very close to (0.2% above) Q_{stable} (48,060 ac-ft/yr), consistent with the water-level rises and modest water-level declines observed during the periods of analysis.

b) McPherson County—The average annual reported water use is above (8.0%) Q_{stable} (29,485 ac-ft/yr), consistent with the water-level declines observed during the periods of analysis.

c) Reno County—The average annual reported water use is slightly above (2.6%) Q_{stable} (59,695 ac-ft/yr), consistent with the modest water-level declines observed during the periods of analysis.

d) Sedgwick County—The average annual reported water use is close to (0.5% above) Q_{stable} (41,343 ac-ft/yr), consistent with the water-level rises and modest declines observed during the periods of analysis.

3. Township-level assessment—The findings of this assessment vary among the township-range units within GMD2.

a) Harvey County—Portions of nine township-range units in this county lie within GMD2, eight of which have sufficient data for analysis. In general, the aquifer in these units has an average annual water use that is slightly above to very slightly below the sustainable level, consistent with the water-level rises and modest water-level declines observed during the analysis periods. However, three of the nine township-range units (T22S-03W, T23S-03W, and T24S-01W) appear to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the average annual water use would be appreciably above the sustainable level in these areas.

b) McPherson County—Portions of 12 township-range units in this county lie within GMD2, 11 of which have sufficient data for analysis. In general, the aquifer in these units has an average annual water use that is much further above the sustainable level than in the other counties in GMD2, consistent with the relatively large water-level declines observed during the analysis periods. This is likely a reflection of lower natural recharge and less stream-aquifer interaction as a result of low permeability material between the land surface and the water table and the absence of major streams in most areas of the county.

c) Reno County—Twenty township-range units in this county lie within GMD2, 17 of which have sufficient data for analysis. In general, the aquifer in these units has an average annual water use that is very slightly to somewhat above the sustainable level, consistent with the modest water-level declines observed during the periods of analysis. Twelve of the township-range units appear to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the average annual water use would be considerably above the sustainable level in those units, many of which are crossed by the Arkansas or Little Arkansas rivers.

d) Sedgwick County—Portions of nine township-range units in this county lie within GMD2, seven of which have sufficient data for analysis. In general, the aquifer in these units has an average annual water use that is very slightly to somewhat above the sustainable level, consistent with the water-level rises and modest declines observed during the periods of analysis. One of the township-range units (T25S-03W) appears to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the average annual use would be considerably above the sustainable level in that unit.

e) Western expansion area in Reno County—There are four full townships and one partial township in this expansion area. Three of the townships have sufficient data for analysis, but a trend in water use in one of these prevented the attainment of statistically significant relationships. The portion of the aquifer in the two other townships (22S-08W and 25S-08W) appears to be developed for an average annual water use that is somewhat above the sustainable level, although the continued increase in water use in these townships indicates that these areas may still be in a relatively early stage of development. In both townships, the system appears to be dependent on inflows produced by years of high precipitation following drought years.

4. Defined area assessment—The findings of the assessment vary among the 45 defined areas within GMD2. In general, the results for the defined areas are consistent with the results for the townships in which they are located, so results from only nine of the 45 areas will be summarized here. Three of these areas are those for which statistically significant results could not be obtained at the township level (Group 1) and six are areas along the eastern boundary of GMD2 (Group 2). The findings are summarized here by these two groupings.

   a) Group 1—The common factor linking these three areas is that they have a much higher proportion of industrial water use (Arkansas River Hutchinson and Arkansas River Wichita defined areas) or non-irrigation use that is neither industrial nor municipal (Maize defined area) than other areas. Moreover, in all three areas, the monitoring wells are primarily located in areas dominated by irrigation pumping. The portions of the aquifer dominated by irrigation pumping appear to be operating with an average annual water use that is somewhat above the sustainable level and, in all cases, appear to be heavily dependent on infrequent high inflow years to maintain the aquifer reasonably close to near stable water levels. The lack of monitoring wells in areas dominated by non-irrigation pumping prevents estimation of Q_{stable} for those portions of the defined areas.

   b) Group 2—The common factors linking these six defined areas are their location along the eastern border of GMD2 and their relatively small number of monitoring wells. These areas appear to be operating with an average annual water use that is slightly to considerably above the sustainable level (Q_{stable} is 0.4% to 13.5% below the average annual water use). Two of the areas (Dog Ear and East Little Arkansas River South defined areas) appear to be heavily dependent on infrequent high inflow years to maintain the aquifer reasonably close to near stable water levels. One area (Park City to Valley Center) is dominated by municipal pumping and has no monitoring wells in the easternmost portion of the area where groundwater use is relatively high.

The calculations for and the results from these analyses, as well as the underlying data, are provided in the appendices accompanying this report. The approach used here is complementary to groundwater flow model simulations of an aquifer's response to various future scenarios, as the Q_{stable} estimates and the insights into aquifer behavior obtained from these analyses can be used to help reduce the uncertainty in the modeled future responses.

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I. Introduction

A. Overview of Equus Beds Groundwater Management District No. 2

Equus Beds Groundwater Management District No. 2 (GMD2) extends across 1,384 mi^2 in south-central Kansas and includes parts of Harvey (262 mi^2), McPherson (219 mi^2), Reno (728 mi^2), and Sedgwick (174 mi^2) counties (fig. I.A.1). The portion of McPherson County in GMD2 lies within the Wellington-McPherson Lowlands physiographic province of Kansas; part of Harvey County in GMD2 also lies within this province. The rest of Harvey County, much of Reno County, and essentially all of Sedgwick County within GMD2 are in the Arkansas River Lowlands physiographic province; the rest of Reno County is within the High Plains province.

Groundwater resources in GMD2 occur primarily in unconsolidated Quaternary deposits of the Equus Beds area of the eastern extension of the High Plains aquifer (HPA). Depths to groundwater can range from less than 10 ft to up to 110 ft below land surface (GMD2: http://www.gmd2.org/AboutUs2.html). The Arkansas River passes through Reno and Sedgwick counties in the district; the principal tributary to the river within GMD2 is the Little Arkansas River, which extends through northeast Reno, western Harvey, and part of Sedgwick counties in GMD2. The North Fork of the Ninnescah River passes through southern Reno County but is not as important to alluvial groundwater resources as the Little Arkansas River because much of its valley in GMD2, including the areas around Cheney Reservoir, are directly underlain by bedrock.

The bedrock underlying the HPA in GMD2 is Lower Permian in age and includes primarily siltstones and shales, some of which contain the evaporite minerals gypsum, anhydrite, and halite. Intrusion of groundwater affected by dissolution of these minerals from the bedrock into the overlying High Plains aquifer, primarily in Reno County and the northwest corner of Sedgwick County within GMD2, renders some of the HPA groundwater saline. Discharge of the saline water from the alluvium of the Arkansas River and small tributaries into the river impacts the salinity of groundwater in the river alluvium through stream-aquifer interactions in the southwestern corner of Harvey County and through Sedgwick County within GMD2.

Oilfield brine contamination has also increased the salinity of the HPA in local areas, particularly near Burrton in western Harvey County (including a portion of eastern Reno County), the Hollow-Nikkel oilfield area in northwestern Harvey County, and other smaller oilfield areas in south-central McPherson County. The Burrton contamination lies within an Intensive Groundwater Use Control Area (IGUCA) and the Hollow-Nikkel oilfield area within a Special Water Quality Use Area. Another IGUCA in GMD2 is in central McPherson County; this IGUCA was developed to control substantial water-level declines caused by pumping.

The climate of the GMD2 area is subhumid; the normal (1981–2010) annual precipitation ranges from 31.2 inches in Reno County to 33.2 inches in Sedgwick County within GMD2. The annual precipitation for the period of 1996–2014 used in this study ranged from a low of 19.6 inches in Reno County in 2011 to a high of 41.8 inches in Sedgwick County in 2005 (fig. I.A.2). Drought years included 2001, 2006, 2011, and 2012. Particularly wet periods occurred in 2005, 2007, 2008, and 2013. In general, the rainfall extremes became greater with time during the study period.

Equus Beds Groundwater Management District No. 2

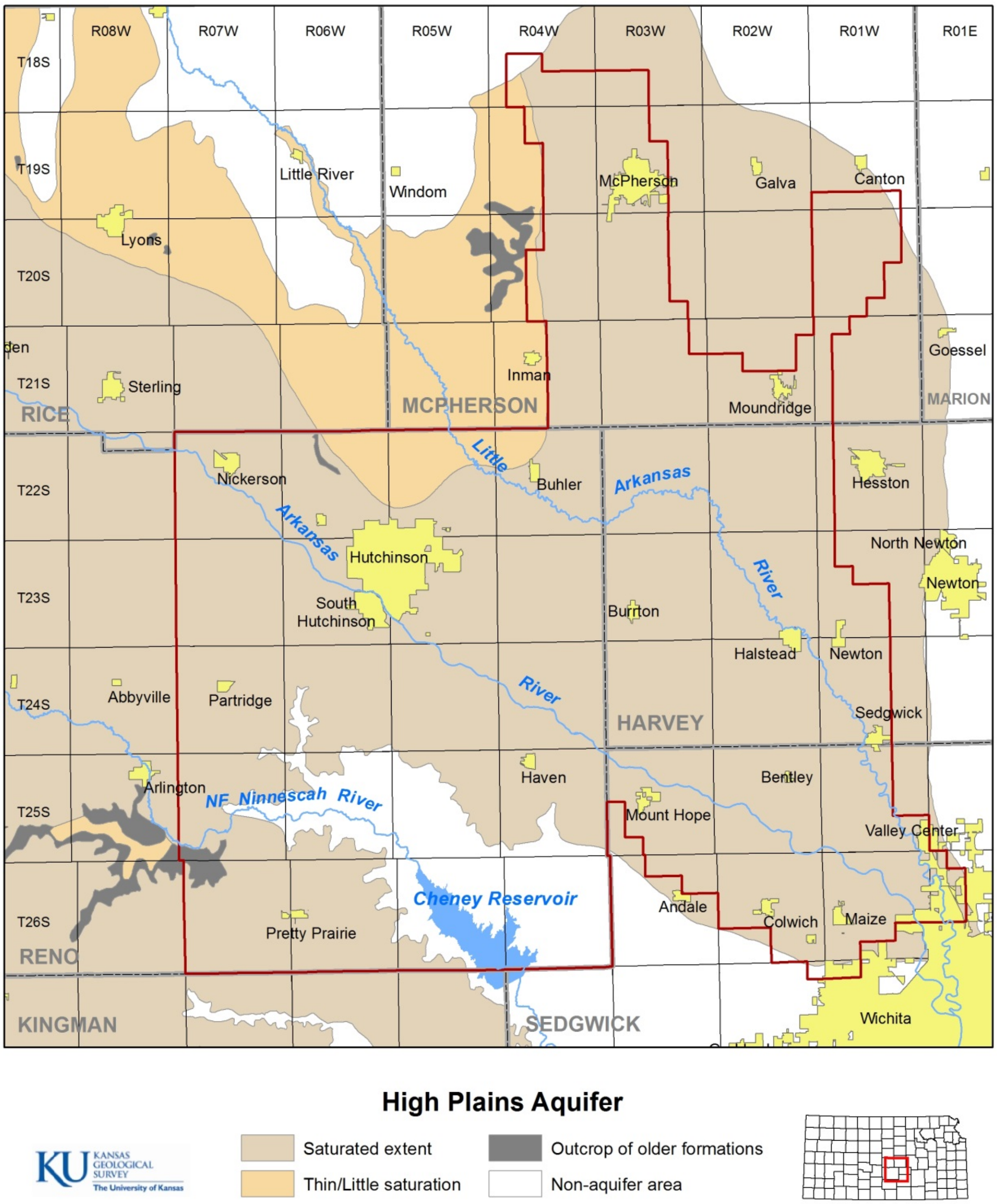

Figure I.A.1. Map of the region including GMD2 showing the major rivers, cities, and the extent of the High Plains aquifer. County lines are denoted by dashed black lines overlying a gray line, township boundaries by thin black lines, and the GMD2 boundary by a red line.

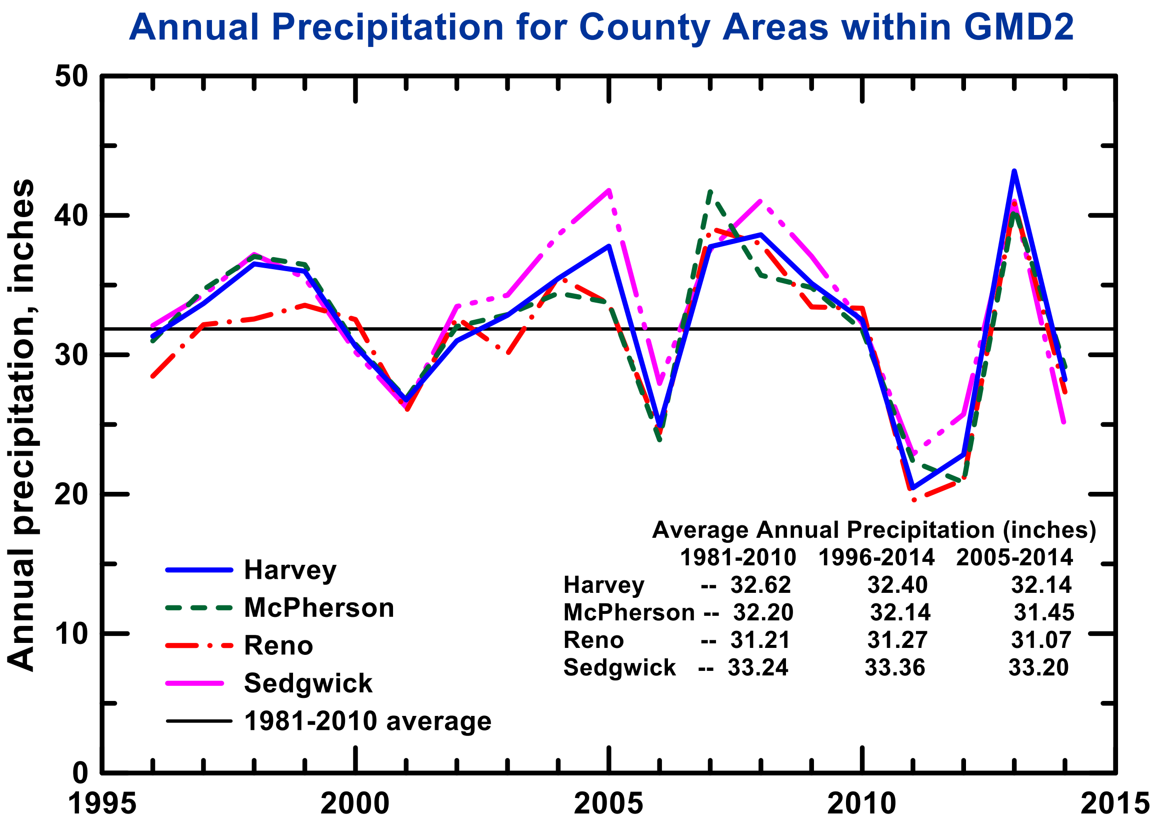

Figure I.A.2. Annual precipitation for the county areas within GMD2 during the study period of 1996–2014 compared to the normal annual precipitation of 1981–2010 for the area of all four counties within GMD2. Average annual precipitation for the time periods of the analyses of this study (1996–2014 and 2005–2014) are given in the table.

Currently, GMD2 manages its groundwater resources using a safe-yield approach. When a new water right application is received, GMD2 staff calculate the current annual pumping allocation within a circle of two miles in radius centered on the proposed location. If the proposed location is within two miles of the Little Arkansas or Ninnescah rivers, the annual volume allocated to support base flow in the river is added to the pumping allocation. The total is then compared to the defined annual recharge volume for the total area of the circle. The defined annual recharge per unit area is 6 inches for Harvey and Sedgwick counties and most of Reno County and 3 inches for McPherson County. The defined annual recharge per unit area has recently been reduced inside the enhanced well spacing area in portions of southern and western Reno County (see K.A.R. 5-22-2 for description of affected areas [GMD2 and DWR, 2011]); the defined annual recharge per unit area within that area is set to 2 inches north of and 3 inches south of the North Fork of the Ninnescah River. For this application, recharge is considered as "the natural infiltration of surface water or rainfall into an aquifer from its catchment area" and is calculated by multiplying the recharge percentage—6.667% in the enhanced well spacing area north of the North Fork of the Ninnescah River, 10% in McPherson County and in the enhanced well spacing area south of the North Fork of the Ninnescah River, and 20% for the rest of the district—times the average annual precipitation of 2.5 feet per year (GMD2 and DWR, 2016). In comparison, the potential natural recharge map of the Division of Water Resources of the Kansas

Department of Agriculture indicates recharge of 2 to 3 inches for most of McPherson and Reno counties within GMD2 and recharge of about 3 inches for the area of Harvey and Sedgwick counties within GMD2 (DWR, 2010). The inherent uncertainty in these estimated recharge values, coupled with concerns about their appropriateness for sustainability assessments, prompted the study described here.

B. Study Objective

The objective of this study is to assess the prospects for sustainability of the portions of the High Plains aquifer in GMD2 based on a data-driven approach. For the purposes of this report, sustainability is defined as being achieved when spatially averaged water levels are stable with time, i.e. the average annual water-level change over an area is zero for a period of several years. Given the temporal variability in annual precipitation (fig. I.A.2) and groundwater use, there will be year-to-year rises and falls in spatially averaged water levels in GMD2. However, those changes will average out to zero over a period of several years if the aquifer is being pumped at a sustainable level. The specific purpose of this study is to determine the average annual water use that would produce stable areally averaged water levels over a given area. That annual water use is defined as Q_{stable} in this report.

The primary approaches used for assessing the prospects for aquifer sustainability are based on the aquifer water-balance equation:

Water Volume Change in Aquifer = Inflows into Aquifer – Outflows from Aquifer

These approaches are described in the following paragraphs.

The most commonly used approach for assessing sustainability prospects is the safe-yield analysis, which is similar to the method currently being used in GMD2 that was described in the previous section. This approach uses the water-balance equation with a defined recharge to calculate Q_{stable}. The challenge with this approach is that the level of uncertainty associated with recharge estimates is typically large because those estimates are heavily dependent on highly variable (in both space and time) and difficult-to-characterize conditions at the land surface and between the land surface and the water table. Moreover, for GMD2, the recharge estimate is only part of the sustainability budget picture. In many areas of the district, there is considerable interaction between the aquifer and the overlying surface water. Water drawn into the aquifer from surface water by pumping can be an important component of the water budget and must be considered in sustainability assessments. However, this component of the water budget is often overlooked in safe-yield analyses that are focused primarily on recharge-based calculations.

An increasingly common approach for assessing sustainability prospects is the distributed parameter groundwater flow model analysis (Anderson et al., 2015). In this approach, an aquifer is subdivided into a network of cells; the area represented by a single cell depends on the spatial resolution of the analysis (typically tens of thousands of square feet to a few square miles.) The water-balance equation is applied to each cell and the cells are linked to allow for the exchange of water across the network; Q_{stable} can then be estimated for each cell. The fundamental factor limiting the effectiveness of this approach is the data requirements. Model input requirements typically far exceed available data, so hydrologists use a procedure known as calibration to obtain estimates of recharge and other components of the water budget. Calibration involves adjusting these estimates until an acceptable level of agreement is obtained between existing water-level data and the model-calculated water levels. The technical sophistication of distributed parameter modeling can imbue the analysis with an aura of high reliability, but this approach is heavily dependent on the quality and quantity of available data. Although distributed parameter flow modeling analyses can consider the full range of aquifer inflows and outflow in the sustainability assessment, the level of uncertainty in sustainability assessments arising from these data limitations is typically large. In addition, the time and resources required to build these sophisticated models for sustainability assessments can be substantial.

The approach used in this study for assessing the sustainability of the HPA in GMD2 was recently developed at the Kansas Geological Survey to take advantage of conditions common to the HPA in Kansas (Butler et al., 2016). This data-based approach uses annually collected data on water levels and reported water use that can be readily processed to directly calculate Q_{stable}. The approach considers the complete picture of aquifer inflow and outflows at a scale of tens to thousands of square miles. The approach was specifically developed for seasonably pumped aquifers, i.e. aquifers for which irrigation is the main water use, that are in a mature stage of development. The approach lumps all components of the water budget contributing to Q_{stable} into one term to significantly reduce data requirements and considerably reduce the level of uncertainty relative to alternative approaches. In this study, the approach was applied at four spatial scales: that of the entire district, the portions of individual counties lying within the district, the portions of townships lying within the district, and areas defined by GMD2 staff. The calculations for and the results from these analyses are provided in the appendices that accompany this report. This approach is complementary to groundwater flow model simulations of an aquifer's response to various future scenarios, as the Q_{stable} estimates and the insights into aquifer behavior obtained from these analyses can be used to help reduce the uncertainty in the modeled future responses.

C. Report Outline

This report consists of the following three sections. The theoretical underpinnings of the approach, the data requirements, and the format of the spreadsheet with the results of the assessment calculations are described in Section II. The results and interpretations of the analysis at four spatial scales are then described in Section III. The presentation of the major conclusions, findings, and limitations of the study with accompanying discussion bring the report to a close in Section IV. The spreadsheet with the results of the assessment calculations, data plots for all analyses, and the underlying data are provided in electronic format in Appendices A, B, and C, respectively (http://www.kgs.ku.edu/Publications/OFR/2017/OFR17_3/index.html).

II. Sustainability Assessment—Theory, Data, and Methodology

This project used an approach that was recently developed at the Kansas Geological Survey for assessing the prospects for sustainability in the High Plains aquifer (HPA) in Kansas (Butler et al., 2016). The objective of the approach is to calculate Q_{stable}, the average annual pumping that would produce stable areally averaged water levels over a given area. Q_{stable} is a function of net inflow, which comprises recharge from the land surface, subsurface inflow from adjacent areas, water drawn into the aquifer from surface water sources by pumping, inflow from artificial recharge projects, and any additional pumping-induced inflows into the aquifer, **minus** discharge to streams, evapotranspiration, and subsurface outflow to adjacent areas. It is calculated using the average annual water-level change and annual reported water use for an area as described in the following section.

A. Theoretical Development

We begin by writing a simple water balance equation that holds for any area of an aquifer:

$$\text{Water Volume Change in Aquifer} = \text{Inflows into Aquifer} - \text{Outflows from Aquifer} \tag{1}$$

where all terms are given as annual volumes.

Equation (1) can be rewritten as follows:

$$\text{Water Volume Change in Aquifer} = \text{Net Inflow} - \text{Pumping} \tag{2}$$

where "Net Inflow" is all inflows into the aquifer minus all outflows from the aquifer except pumping. An aquifer's prospects for sustainability depend on the magnitude of the net inflow term relative to average annual pumping.

We can rewrite equation (2) using standard notation for groundwater studies:

$$\Delta WL \times Area \times S_Y = I - Q \tag{3}$$

where ΔWL is the annual average water-level change over an aquifer area, [L]; $Area$ is the size of the aquifer area under consideration, [L^2]; S_Y is the average specific yield for the aquifer area, [-]; I is the annual net inflow to the aquifer area, [L^3]; and Q is the annual total pumping in the aquifer area, [L^3].

We can rewrite equation (3) by dividing both sides by $Area \times S_Y$:

$$\Delta WL = \frac{I}{Area \times S_Y} - \frac{Q}{Area \times S_Y} \tag{4}$$

In the Kansas HPA, we have found that I and S_Y change little with time (Whittemore et al., 2016; Butler et al., 2016). Thus, we can simplify equation (4) to the following form:

$$\Delta WL \approx b - aQ \tag{5}$$

where a and b are constants (= $1/(Area \times S_Y)$ and $I/(Area \times S_Y)$, respectively).

Equation (5) demonstrates that a plot of ΔWL versus Q should be linear for conditions commonly found in the HPA in Kansas, when reliable water-level and water-use data are available. Moreover, the form of equation (5) reveals that it can be used to estimate S_Y and I from the slope (a) and intercept (b), respectively, of the best-fit line to that plot. Most importantly, equation (5) can be used to calculate Q_{stable}, the annual pumping that would lead to stable areally averaged water levels (ΔWL = 0) for an area:

$$Q_{stable} = \frac{b}{a} = I = I_{ua} * Area \quad (6)$$

where I_{ua} is the net inflow per unit aquifer area. An aquifer's prospects for sustainability depend on the magnitude of Q_{stable} relative to the average annual groundwater use.

In this work, equation (5) is fit to plots of ΔWL versus Q for each area under consideration to determine the slope (a) and intercept (b) parameters. Equation (6) is then used to estimate Q_{stable} from these parameters.

In some cases, the pumping reduction that would be required to reach stable water levels may be viewed as difficult to achieve. In that case, a goal for the acceptable annual water-level change (ΔWL_{goal}) can be set and the pumping that would produce that change (Q_{goal}) can be calculated:

$$Q_{goal} = \frac{b}{a} - \frac{\Delta WL_{goal}}{a} \quad (7)$$

Equation (7) is used here to calculate the average annual pumping that would be required to obtain a defined average annual water-level decline. The calculation is repeated at 0.1 ft increments in ΔWL_{goal} between the recorded average annual change for the period and ΔWL = 0 (stable water levels).

B. Data

This sustainability assessment requires data quantifying annual water-level changes and annual water use. These two data types are discussed in the following subsections.

1. Annual water-level changes

Estimates of annual water-level changes over the district from 1996 to 2014 were obtained from water-level measurements taken from wells in the state's Cooperative Water Level Program and in GMD2's own extensive water-level networks. The approach used here for the sustainability assessment requires that the measurements be taken during the winter period, typically from December to February, when irrigation water use is negligible. Ideally, the measurements are taken three to four months after cessation of irrigation pumping, as year-to-year variations in the timing of the irrigation season will have little impact on those measurements. Although the vast majority of wells were measured in the month of January, depth-to-water measurements ranging from December to early April were averaged for each year to establish a single winter value at each well site. This larger monthly range helps ensure use of a larger number of wells and smoothes out anomalous measurements affected by either late or earlier-than-normal pumping. Error can be introduced into the assessment in areas of significant amounts of municipal or industrial pumping where water is used throughout the year. To reduce the influence of such effects, measurements from monitoring wells within 330 feet (1/16 mile) of a vested or appropriated municipal groundwater right well were not used.

A number of the GMD2 monitoring well locations are nests of wells of different depths. For all but two nests, the water-level measurements from the deepest well of a nest were used to represent the nest. In two cases, the data for a shallower well in the nest that had a longer measurement history were used to represent that nest. Data from monitoring wells deemed non-representative by GMD2 staff (50 well sites) were not used. Figures II.B.1–3 display the distribution of all monitoring well sites with water-level measurements in the GMD2 region, wells with continuous water-level measurements for 1996–2015, and wells with continuous water-level measurements for 2005–2015, respectively.

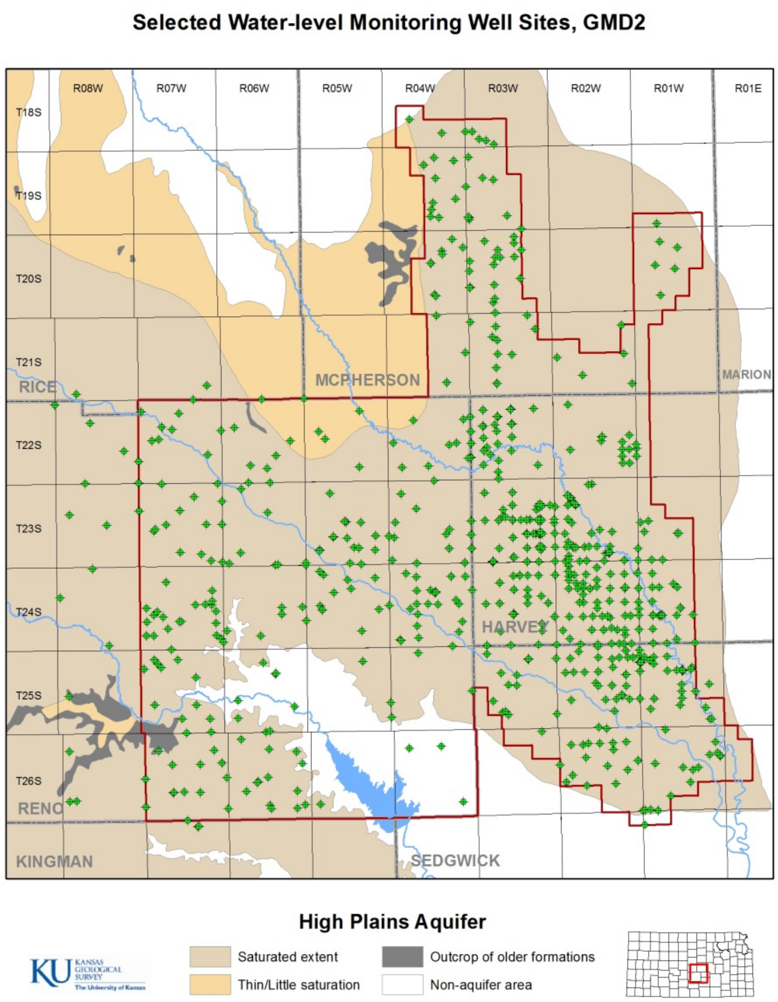

Figure II.B.1. Locations of water-level monitoring well sites in GMD2 and the western expansion area in Reno County. The bold red lines are boundaries of GMD2, the dashed black lines underlain by a wider gray line are county boundaries, and the solid black lines are township borders. The portions of the High Plains aquifer with significant saturated thickness are shaded in tan; thinly saturated parts of the aquifer and unsaturated materials that elsewhere comprise the aquifer are shaded in light orange.

Continuous Water-level Monitoring Well Sites, 1996 - 2015, GMD2

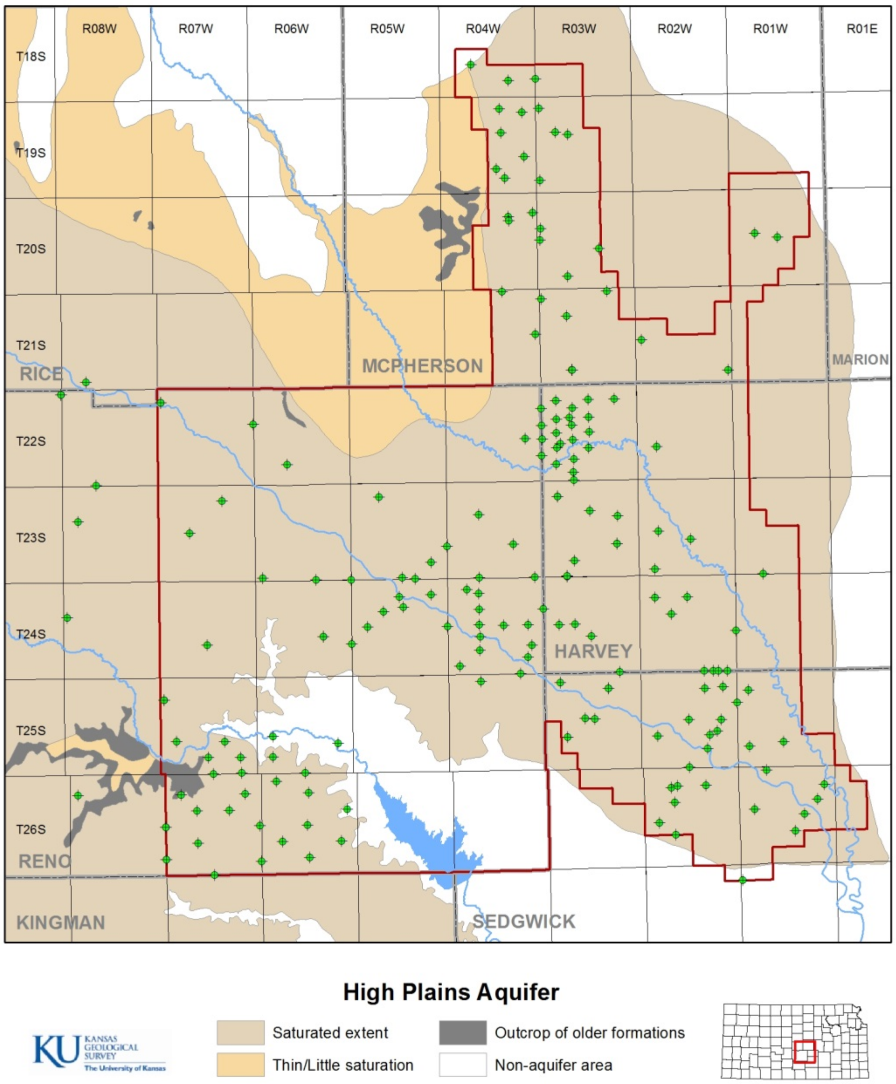

Figure II.B.2. Locations of monitoring well sites in GMD2 and the western expansion area in Reno County where water-level measurements were taken each winter from 1996 to 2015. See Figure II.B.1 for additional descriptions.

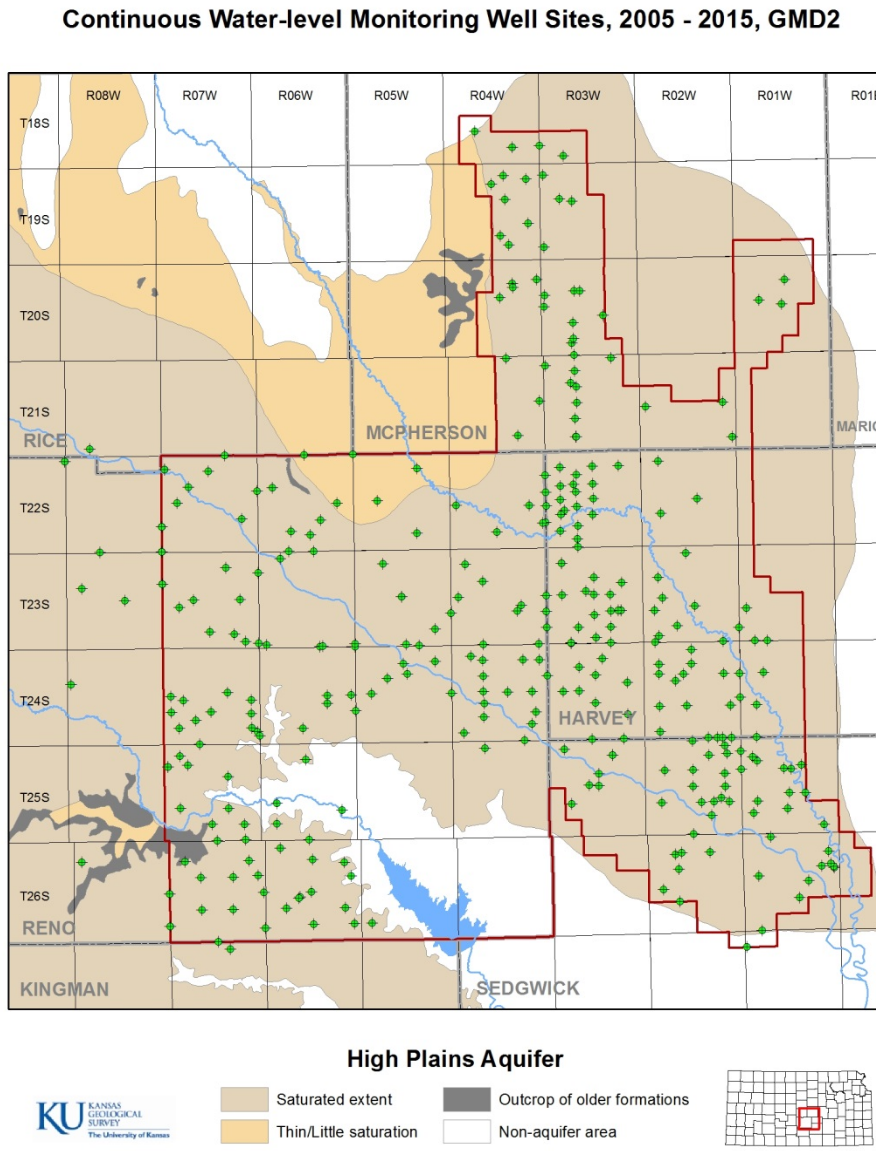

Figure II.B.3. Locations of monitoring well sites in GMD2 and the western expansion area in Reno County where water-level measurements were taken each winter from 2005 to 2015. See Figure II.B.1 for additional descriptions.

2. Annual water use

Reported annual groundwater use between 1996 and 2014 was obtained from the Division of Water Resources of the Kansas Department of Agriculture via the Water Information Management and Analysis System website (WIMAS: hercules.kgs.ku.edu/geohydro/wimas/index.cfm). Water use for all types of water rights (appropriated, vested, term, etc.) was summarized for each unique point of diversion.

At the start of the study period, fewer than half of the irrigation wells in GMD2 were metered. However, the percentage of irrigation wells with flowmeters significantly increased during the study period (fig. II.B.4). As of the 2013 irrigation season, 92.9% of the 1,597 active points of diversion reporting water use in GMD2 that year were metered (Lanning-Rush, 2016). Discussions with GMD2 staff indicate that the metering percentage is now nearing 100% (personal communication, Tim Boese, 2016). Figure II.B.5 displays the spatial distribution of points of diversion for groundwater-based water rights that submitted a water use report between 1996 and 2014.

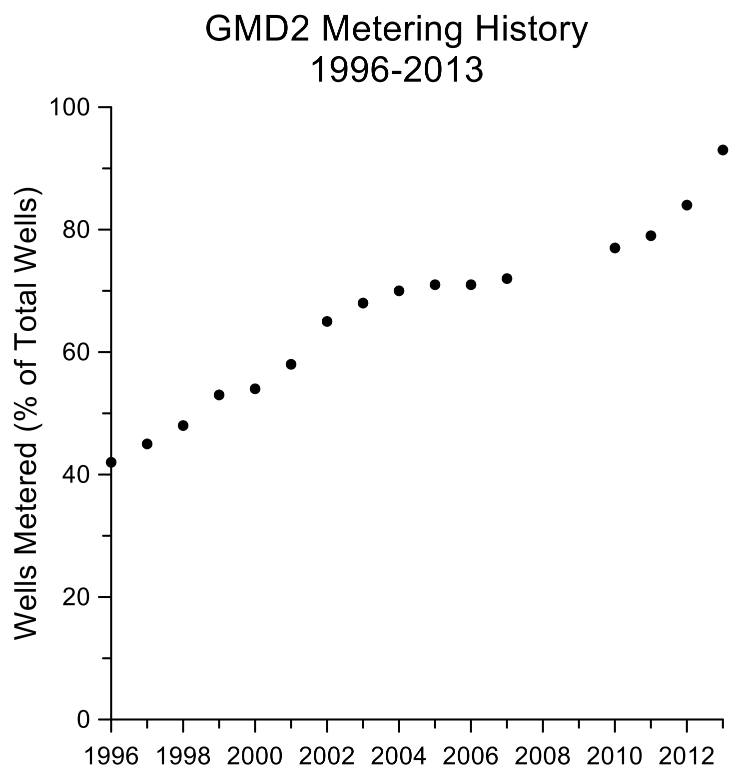

Figure II.B.4. Percentage of irrigation wells in GMD2 with flowmeters as a function of time (no data for 2008 and 2009).

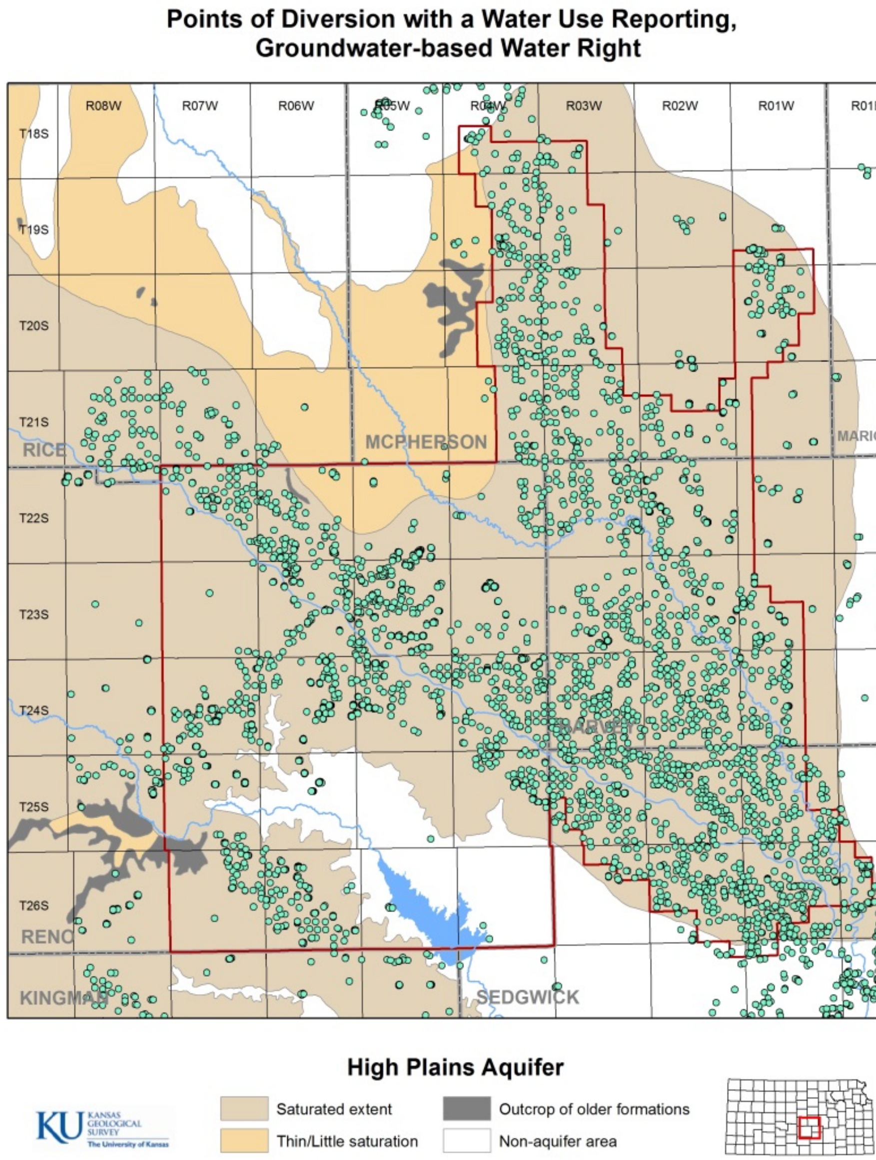

Figure II.B.5. Distribution of points of diversion for groundwater-based water rights that submitted an annual water use report between 1996 and 2014. See fig. II.B.1 for additional descriptions.

C. Methodology

The calculations for the sustainability assessment were performed for two time periods (1996–2014 and 2005–2014) at four spatial scales: that of the entire district, the portions of individual counties lying within the district, the portions of individual townships lying within the district, and areas defined by GMD2 staff (defined areas). The spreadsheet in Appendix A provides the calculations for and the results of the assessments performed at these four scales. The format of that spreadsheet is described here.

1. Spreadsheet format

The contents of individual columns are as follows:

Col. A.—Identifier consisting of GMD2, county name, or defined area number.

Col. B.—Name of wells used (GMD2 worksheet), township number, or defined area name. This column is blank in the county worksheet.

Col. C—Type of water-level data used in the analysis. The water-level data were divided into two categories of wells: Continuous—wells for which measurements were reported every year for the period of analysis; and Maximum—wells for which measurements were reported for at least one year of the analysis period. Results were also reported for averages of analyses performed over a certain time period, using a certain type of well data, and all analyses performed for a particular geographic area (GMD2, county, township, or defined area).

Col. D—Time period of analysis. Data were divided into two periods: 1996–2014 and 2005–2014.

Col. E—Area of GMD2, county, township, or defined area, depending on worksheet.

Col. F—Coefficient of determination (R^2) from linear regression of water-use and water-level data, see equation (5).

Col. G—Slope of best-fit line determined by linear regression, see equation (5) for definition.

Col. H—Intercept of best-fit line determined by linear regression, see equation (5) for definition.

Col. I—Q_{stable} calculated from equation (6).

Col. J—The average reported annual pumping for the period of the analysis.

Col. K—The pumping reduction (given as a positive number) or increase (given as a negative number) required to reach Q_{stable} given the average annual pumping.

Col. L—The net inflow expressed per unit aquifer area, see right-hand side of equation (6).

Col. M—The specific yield for the area calculated from the slope parameter in equation (5).

Cols. N and O—Indication of the general location of the Arkansas or Little Arkansas rivers if they cross the area (columns are blank in district worksheet).

Cols., P, S, V, Y, AB, AE, AH, AK, and AN—These columns are blank; the number of these blank columns shaded in gray between columns with values depends on the particular worksheet and the area.

Cols. Q, T, W, Z, AC, AF, AI, AL, and AP—Q_{goal} for water-level declines of 0.1 ft/yr, 0.2 ft/yr, 0.3 ft/yr, 0.4 ft/yr, 0.5 ft/yr, 0.6 ft/yr, 0.7 ft/yr, 0.8 ft/yr, and 0.9 ft/yr, respectively; see equation (7). The number of these columns with values depends on the area under consideration.

Cols. R, U, X, AA, AD, AG, AJ, AM, and AQ—The pumping reduction (given as a positive number) or increase (given as a negative number) required to reach Q_{goal}, given the average annual pumping, for water-level declines of 0.1 ft/yr, 0.2 ft/yr, 0.3 ft/yr, 0.4 ft/yr, 0.5 ft/yr, 0.6, ft/yr, 0.7 ft/yr, 0.8 ft/yr, and 0.9 ft/yr, respectively; see equation (7). The number of columns for which data are included depends on how many increments are required to bring Q_{goal} for all types of water-level data to near 1% or less of Q_{stable}.

Rows appended at the end of data for different areas

Col. A.—Legend color (in townships and defined areas worksheets)
Col. B.—Legend description (in townships and defined areas worksheets)
Col. C—Level of statistical significance.
Col. D—Time period of analysis.
Col. E—Lowest value of coefficient of determination for which given level of statistical significance applies.

III. Analysis and Interpretation

The sustainability assessment was applied at four spatial scales: that of the entire district, the portions of individual counties within the district, the portions of individual townships within the district, and the areas defined by GMD2 staff. The results and interpretation of the assessment are described in the following sections. The calculations used in the assessment and the results of those calculations can be found in a spreadsheet accompanying this report. That spreadsheet is provided in electronic form in Appendix A. Selected figures illustrating the results of the assessment are provided in the following sections; figures for all of the analyses for the areas examined in this study are provided in electronic form in Appendix B. If sufficient data were available, four analyses were performed on each of the areas. Two analyses were performed using wells measured every year during the analysis period (continuous data); one analysis was performed for the 1996–2014 period and the other for the 2005–2014 period. Two analyses were also performed using every well measured one or more times during those same two periods (maximum data). Results are reported for each of the analyses, as well as for the average of the two analyses (continuous and maximum data) performed for each time period and the average of all of the analyses performed for the area. All of the water-level and water-use data employed in the analyses are provided in a spreadsheet accompanying this report. That spreadsheet is provided in electronic form in Appendix C.

A. District Assessment

GMD2 covers 875,608 acres and includes parts of Harvey, McPherson, Reno, and Sedgwick counties. The average annual change in groundwater levels from 1996 to 2014 ranged from -3.55 ft in 2011 to 2.99 ft in 2013. The range in reported annual water use for the period was from 149,094 ac-ft/yr in 1996 to 247,790 ac-ft/yr in 2011.

The analysis of the relationship between average annual water-level change and annual reported water use (fig. III.A.1) for 1996–2014 continuous data yields a Q_{stable} value of 178,965 ac-ft/yr, 1.2% below the average reported annual water use. The R^2 value is 0.70 for the linear regression (best-fit line with $P<0.001$). The graph shows that the low water-use years of 1997, 2004, 2007, 2008, and 2013 had the greatest average annual water-level rises, whereas the high water-use years of 2006, 2011, and 2012 had the greatest declines. The water-level rises in 2007 and 2013 were substantially greater than predicted by the linear regression for the water use in those years. Both 2007 and 2013 were years of high precipitation immediately following drought years. The preceding droughts appear to have lowered water levels such that the aquifer could accept more net inflow than in a typical year.

Similar results were obtained using the 2005–2014 continuous data, as well as for both the 1996–2014 and 2005–2014 maximum data (Appendix A spreadsheet, *GMD2* worksheet—Q_{stable} ranges from 178,965 to 181,267 ac-ft/yr; average of all analyses is 180,308 ac-ft/yr, 1.5% below the average reported annual water use). The R^2 values are higher for the 2005–2014 data than the 1996–2014 data and for the maximum wells data than the continuously measured wells data; the highest R^2 is 0.77. The worksheet also lists information for the water-use and water-level change relationships based on the annual cooperative network well program operated by the KGS and the Division of Water Resources, Kansas Department of Agriculture (henceforth, annual cooperative network program). The R^2 values are a little lower for the network well data (0.65–0.73) than for the set of data for the wells used in this study, indicating that the data from the additional wells measured by GMD2 and other entities improved the significance of the water-level change and water-use relationships.

The green dashed lines on fig. III.A.1 graphically illustrate the determination of the amount of water use that would result in an annual water-level change of zero, which is the sustainable water use (Q_{stable}). The reduction in annual water use required to achieve Q_{stable} was less than 3% in all cases (average from all analyses is a reduction of 1.5%). Thus, based on the assessment of the entire district, annual water use appears to have been close to the sustainable level for the period of study. However, as analyses for county, township, and GMD2 defined areas described in the following sections show, the relative sustainability of the aquifer varies spatially.

As described earlier, Q_{stable} is equal to the net inflow into the district. Depending on the situation, net inflow can be less than or greater than the recharge from the land surface.

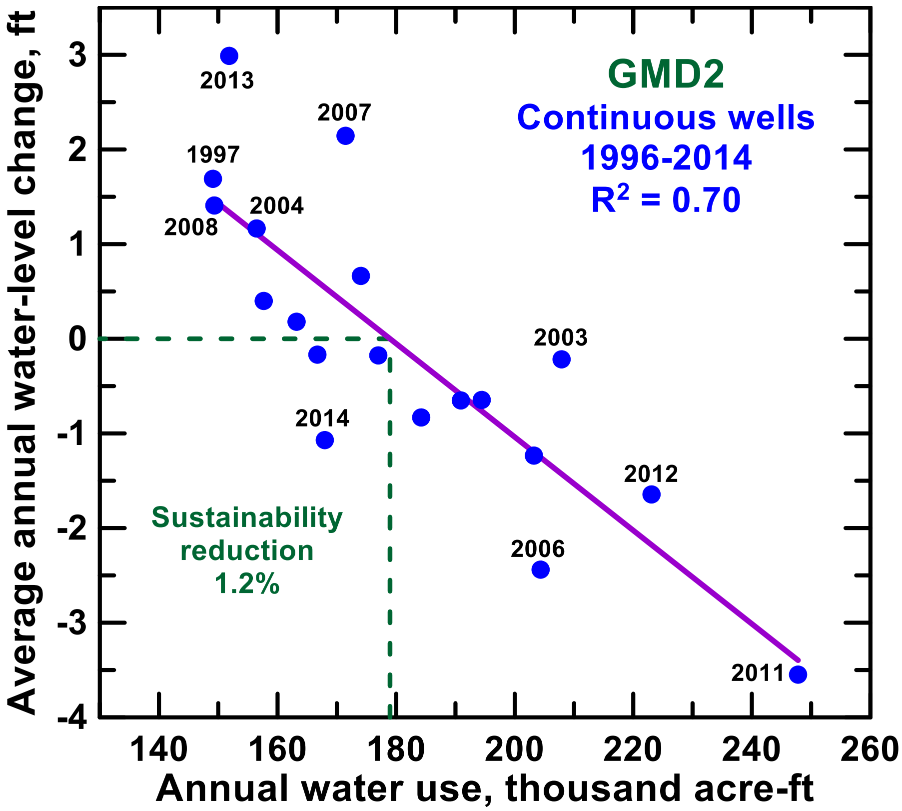

Figure III.A.1. Plot of annual water use versus average annual water-level change for GMD2. The analysis uses the 181 wells measured every year during 1996–2014 and the 3,415 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied from year to year). The linear regression (best-fit line) is in purple; the equation for the line is given in the spreadsheet in Appendix A. The labeled points are for years with extremes in the range of water use, as well as for years deviating substantially from the regression line. The green dashed lines graphically indicate the determination of Q_{stable}.

B. County Assessment

1. Harvey County

Approximately 167,821 acres of Harvey County lie within GMD2. Other than in the northeastern-most township completely in the county, numerous monitoring wells are distributed across the area, particularly when considering the number of monitoring wells measured at least once during the analysis period and those continuously measured since 2005 (fig. II.B.1–3).

However, even in that northeastern-most township, the monitoring wells are in the areas with concentrations of points of diversion with groundwater-based water rights (fig. II.B.5).

The results of the analyses for Harvey County vary little regardless of the type of data used in and the time period covered by the analysis. The Q_{stable} values range from 47,446 to 48,804 ac-ft/yr. In all cases, the average reported water use is within 2% of Q_{stable}. The R^2 values vary between 0.50 and 0.64. The R^2 values are significantly affected by three values that are distinctly different from the others.

Figure III.B.1 displays the plot for the analysis of the continuously measured wells since 2005 and is similar to the other analysis plots for Harvey County. In all cases, the 2007 and 2013 values lie well above the best-fit line and the 2014 value falls well below that line. The 2007 and 2013 values are for years of high precipitation that immediately followed a drought year. The drought appears to have lowered water levels such that the aquifer could accept more net inflow than in a typical year. The explanation for the 2014 value is less clear. One possibility is that more municipal pumping late in 2014 resulted in a water-level change that was more negative than would have been expected if the water use for that year had followed the typical temporal pumping pattern for the area. Although removal of 2007, 2013, and 2014 increases the R^2 to 0.86, the influence on Q_{stable} is quite modest; the calculated value (46,281 ac-ft for the 2005–2014 continuous well analysis) is 4% less than the average reported water use.

The conclusion of the assessment of the portions of Harvey County lying within GMD2 is that this part of the aquifer is developed for an average water use that is very close to the sustainable level. Considering the average of the results from all analyses, Q_{stable} is 48,060 ac-ft/yr, 0.2% below the average reported water use for the area. An analysis using only the nine wells measured every year from 1996 to 2014 as part of the annual cooperative network program yielded a Q_{stable} of 47,855 ac-ft/yr, indicating that the sustainability assessment can be performed using a relatively small number and consistent set of wells distributed across the county.

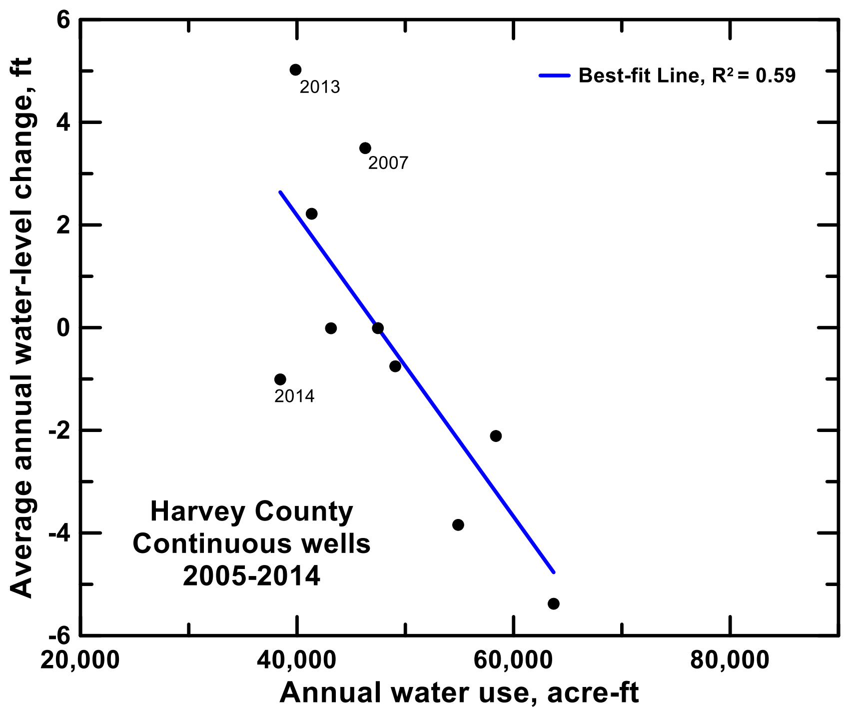

Figure III.B.1. Plot of annual water use versus average annual water-level change for the portions of Harvey County lying within GMD2. The analysis uses the 85 wells measured every year from 2005 to 2014 and the 796 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The labeled points are discussed in the text and the equation for the best-fit line is given in the spreadsheet in Appendix A.

2. McPherson County

Approximately 140,137 acres of McPherson County lie within GMD2. The density of monitoring wells is less than that of Harvey County. However, other than in the southwestern and southeastern townships, there are numerous monitoring wells distributed across the area (fig. II.B.1-3). Moreover, even in the areas with few monitoring wells, those wells are generally in the areas of concentration with points of diversion with groundwater-based water rights (fig. II.B.5).

The results of the analyses for McPherson County vary relatively little regardless of the type of data used in the analysis and the time period of the analysis. The Q_{stable} values range from 28,900 to 29,825 ac-ft/yr. The average reported water use exceeds Q_{stable} by 5.9-10.9%. The R^2 values are the largest for any of the county areas, ranging from 0.88 to 0.95.

Figure III.B.2 displays the plot for the analysis of the continuously measured wells since 2005 and is similar to all of the analysis plots for McPherson County. Unlike the Harvey County plot, all points lie close to the best-fit line. For this and the remaining county plots, the ranges for the x- and y-axes are the same as those used in fig. III.B.1 and the 2007, 2013, and 2014 points are labeled for comparative purposes.

The conclusion of the assessment of the portions of McPherson County lying within GMD2 is that this part of the aquifer is developed for an average water use that is above the sustainable level. Considering the average of the results from all analyses, Q_{stable} is 29,485 ac-ft/yr, 8.0% below the average reported water use for the study period. An analysis using only the 10 wells measured every year from 1996 to 2014 as part of the annual cooperative network program yielded a Q_{stable} of 29,816 ac-ft/yr, indicating that the sustainability assessment can be performed using a relatively small number and consistent set of wells distributed across the county.

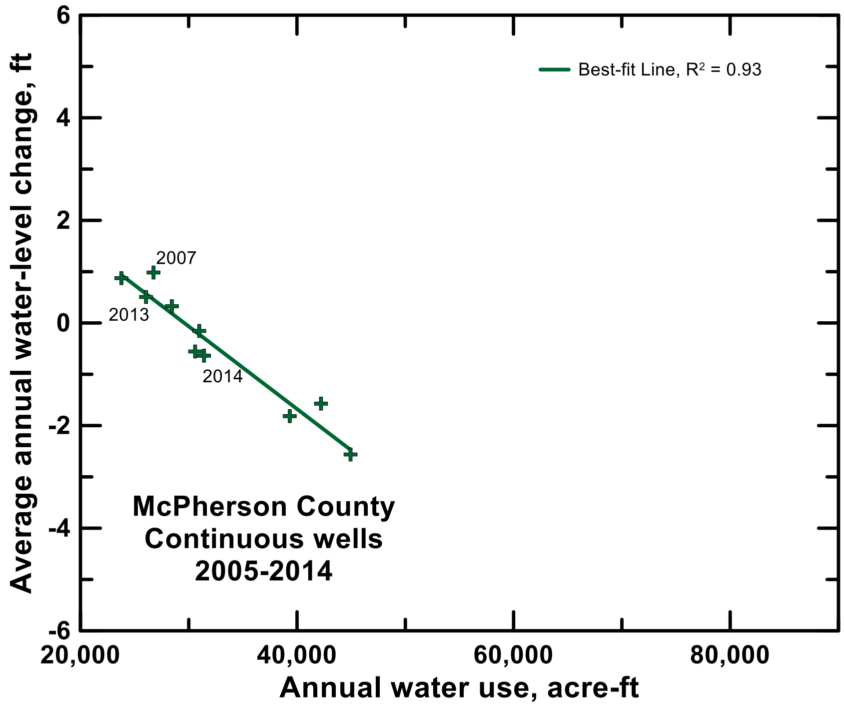

Figure III.B.2. Plot of annual water use versus average annual water-level change for the portions of McPherson County lying within GMD2. The analysis uses the 46 wells measured every year from 2005 to 2014 and the 469 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The equation for the best-fit line is given in the spreadsheet in Appendix A.

3. Reno County

Approximately 465,280 acres of Reno County lie within GMD2. In general, the distribution of monitoring wells is consistent with the distribution of points of diversion with groundwater-based water rights (figs. II.B.1–3,5). There are two areas of monitoring wells with few points of diversion with groundwater-based water rights; the wells in those areas comprise about 10% of the wells measured continuously from 2005–2014. One area is the township immediately to the west of Hutchinson and South Hutchinson; the groundwater in this area has salinity problems and is not used for irrigation. The additional monitoring wells in the area were installed to investigate the extent of the saline groundwater. The other area is all but the northeast quadrant of the southwestern-most township in the district; the aquifer in this area is very thin and thus not suitable for development for irrigation. The additional monitoring wells were installed for assessment of possible nitrate pollution in that area.

The results of the analyses for Reno County vary relatively little regardless of the type of data used in the analysis and the time period of the analysis. The Q_{stable} values range from 58,717 to 60,650 ac-ft/yr. The average reported water use exceeds Q_{stable} by 2.1–3.2%. The R^2 values vary between 0.58 and 0.64 and are significantly affected by two points that are distinctly different from the others.

Figure III.B.3 displays the plot for the analysis of the continuously measured wells from 2005 to 2014 and is similar to all of the analysis plots for Reno County. As with Harvey County, the 2007 and 2013 values, which were years of high precipitation immediately following a drought year, lie well above the best-fit line. The droughts preceding these years appear to have lowered water levels such that the aquifer could accept more net inflow than in a typical year. Removal of 2007 and 2013 values increases the R^2 to 0.73. The removal of these values influences Q_{stable} more than in the case of Harvey County. After the removal of the 2007 and 2013 values, the Q_{stable} is 55,282 ac-ft/yr, 12% less than the average reported annual water use.

The conclusion of the assessment of the portions of Reno County lying within GMD2 is that this part of the aquifer is developed for an average water use that is slightly above the sustainable level. Considering the average of the results from all analyses, Q_{stable} is 59,695 ac-ft/yr, 2.6% below the average reported annual water use for the area. However, the system appears to be heavily dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating further away (12% for the 2005–2014 continuous well analysis) from the sustainable level. An analysis using only the 16 wells measured every year from 1996 to 2014 as part of the annual cooperative network program yielded a Q_{stable} of 59,614 ac-ft/yr, indicating that the sustainability assessment can be performed using a relatively small number and consistent set of wells distributed across the county.

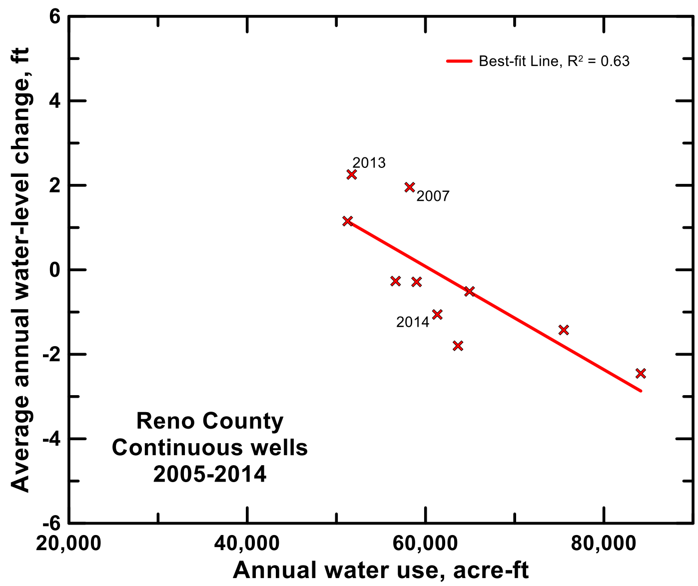

Figure III.B.3. Plot of annual water use versus average annual water-level change for the portions of Reno County lying within GMD2. The analysis uses the 136 wells measured every year from 2005 to 2014 and the 1,419 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The equation for the best-fit line is given in the spreadsheet in Appendix A.

4. Sedgwick County

Approximately 111,229 acres of Sedgwick County lie within GMD2. Other than in the southwestern part of the county within GMD2, the monitoring wells are in the areas with concentrations of points of diversion with groundwater-based water rights (fig. II.B.1–3,5).

The results of the analyses for Sedgwick County vary little regardless of the type of data used in the analysis and the time period of the analysis. The Q_{stable} values range from 40,958 to 41,745 ac-ft/yr. In all cases, the average reported water use is within 2% of Q_{stable}. The R^2 values vary between 0.67 and 0.79.

Figure III.B.4 displays the plot for the analysis of the continuously measured wells since 2005 and is similar to all of the analysis plots for Sedgwick County. Three of the four wettest years during this period (2005, 2007, and 2013) clearly lie above the best-fit line. Removal of those points increases R^2 to 0.91 and lowers Q_{stable} to 38,084 ac-ft/yr, 8.8% below the average reported annual water use.

The conclusion of the assessment of the portions of Sedgwick County lying within GMD2 is that this part of the aquifer is developed for an average water use that is very close to the sustainable level. Considering the average of the results from all analyses, Q_{stable} is 41,343 ac-ft/yr, 0.5% below the average reported water use for the area. However, the system is clearly dependent on the inflows produced by the years of high precipitation. In the absence of those high inflow years, the system is operating further away (8.8% for the 2005–2014 continuous well analysis) from the sustainable level. An analysis using only the nine wells measured every year from 1996 to 2014 as part of the annual cooperative network program yielded a Q_{stable} of 41,505 ac-ft/yr, indicating that the sustainability assessment can be performed using a relatively small number and consistent set of wells distributed across the county.

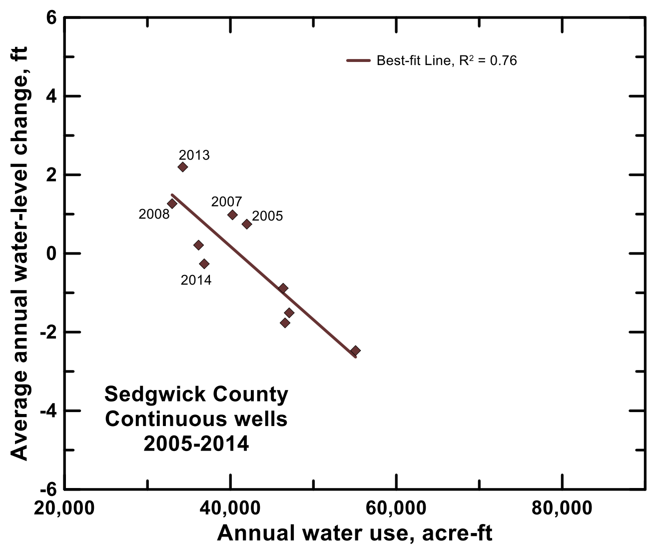

Figure III.B.4. Plot of annual water use versus average annual water-level change for the portions of Sedgwick County lying within GMD2. The analysis uses the 54 wells measured every year from 2005 to 2014 and the 731 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The equation for the best-fit line is given in the spreadsheet in Appendix A.

5. Summary of county results

Figures III.B.5 and III.B.6 summarize the results of the sustainability assessment at the scale of the portions of individual counties lying within GMD2. The plotted results are the averages of all the analyses performed for each county.

The conclusions of the county-level assessment are the following:

a) The aquifer in the portions of Harvey County lying within GMD2 has an average annual water use that is very close to the sustainable level. However, the aquifer appears to be somewhat dependent on inflows produced by years of high precipitation following drought years.

b) The aquifer in the portions of McPherson County lying within GMD2 has an average annual water use that is above the sustainable level.

c) The aquifer in the portions of Reno County lying within GMD2 has an average annual water use that is slightly above the sustainable level. However, the aquifer appears to be heavily dependent on inflows produced by years of high precipitation following drought years.

d) The aquifer in the portions of Sedgwick County lying within GMD2 has an average annual water use that is very close to the sustainable level. However, the aquifer appears to be somewhat dependent on inflows produced by years of high precipitation.

In all counties, the sustainable annual water use volume is 8% or less below the average reported annual water use (fig. III.B.6). However, outside of McPherson County, the difference is much less (0.2–2.6%). Although the sum of the Q_{stable} values from the counties is within 1% of the value from the district-wide analysis, McPherson County clearly stands out as being farther from sustainability than the other counties in GMD2. The three other counties appear to have an average annual water use that is only slightly above the sustainable level under current climatic conditions.

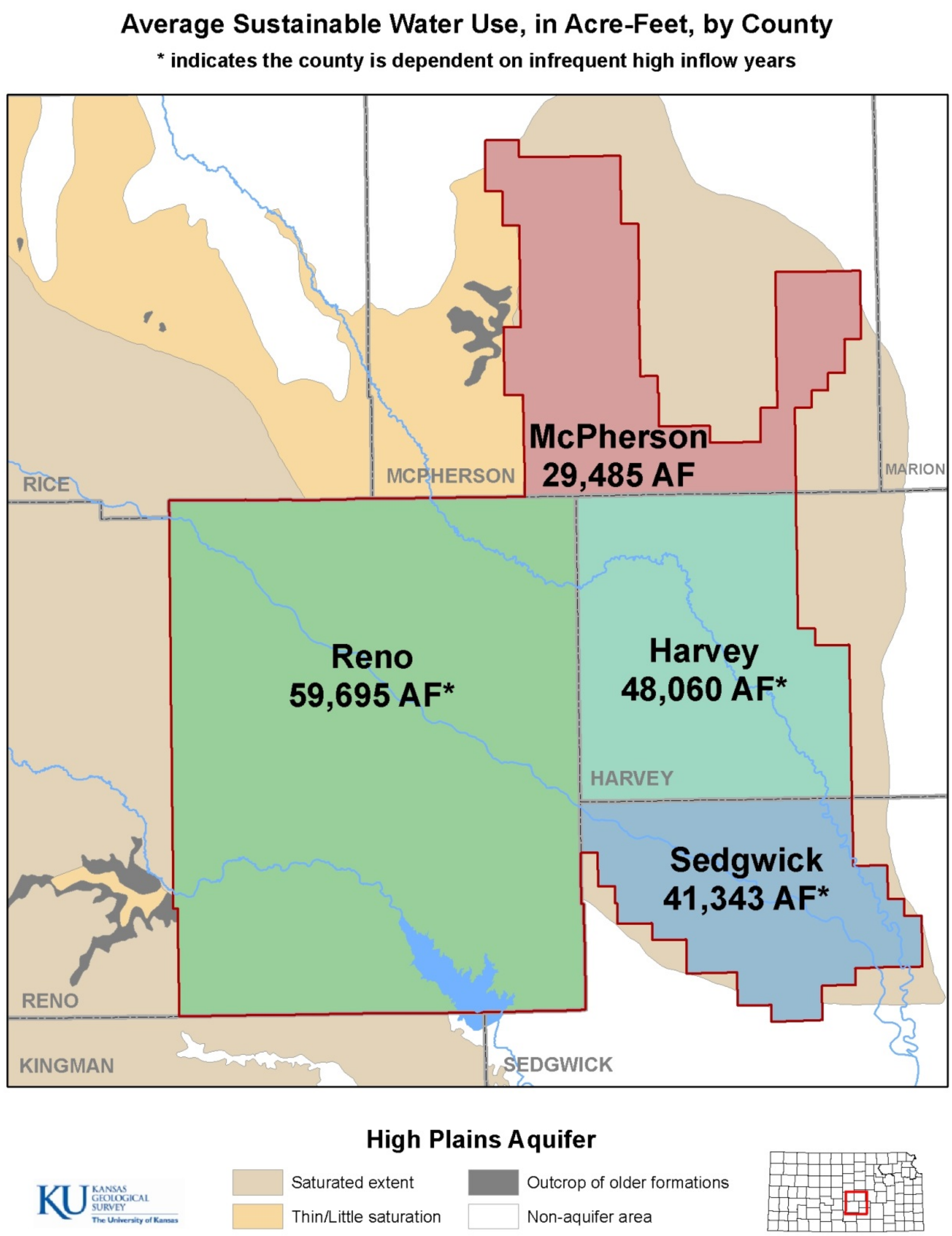

Figure III.B.5a. Results of the sustainability assessment at the scale of individual counties within GMD2. Plotted amounts are the sustainable average annual water-use volumes (Q_{stable}) for each county.

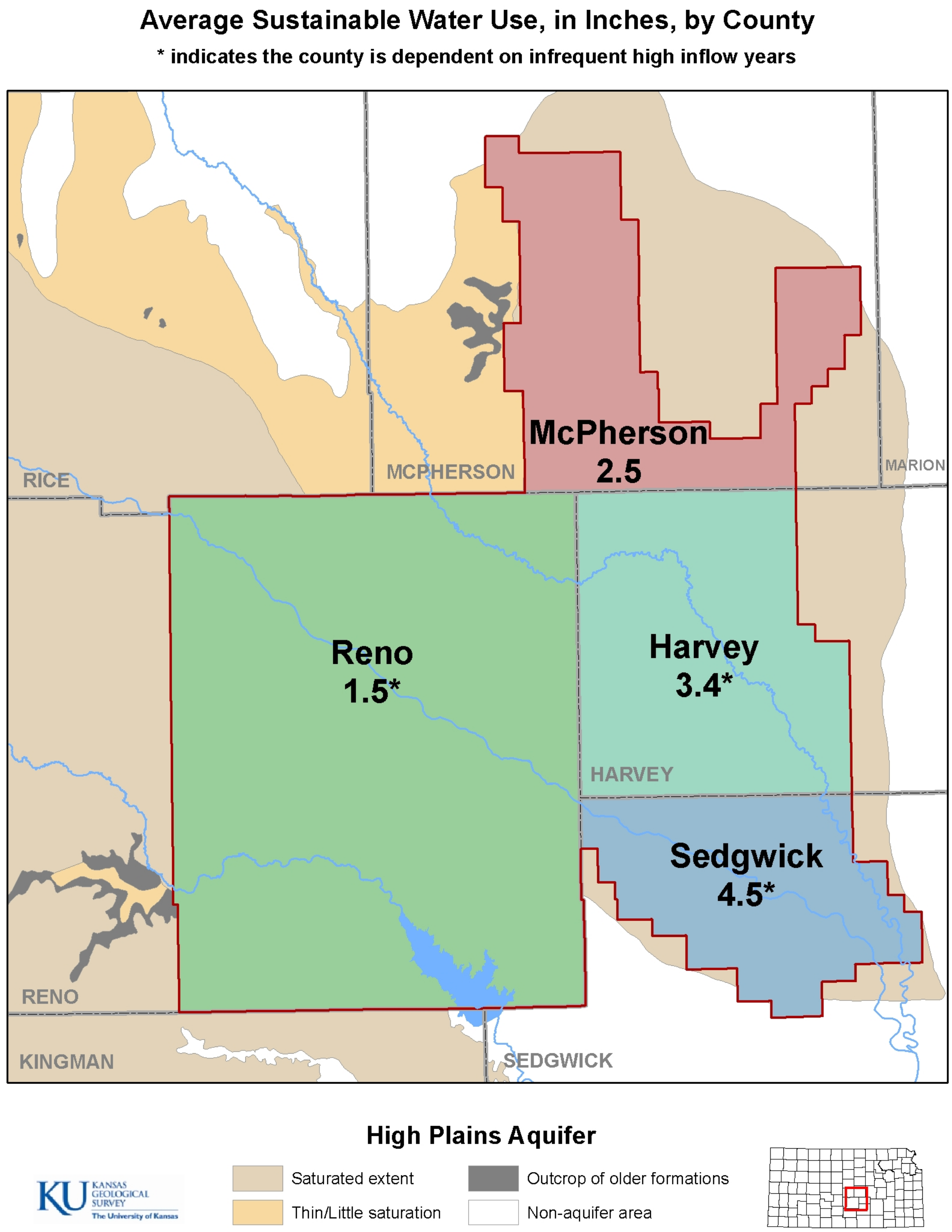

Figure III.B.5b. Results of the sustainability assessment at the scale of individual counties within GMD2. Plotted amounts are the sustainable average annual water use (Q_{stable}) for each county divided by the area of that county, expressed as inches (acre-inches/acre).

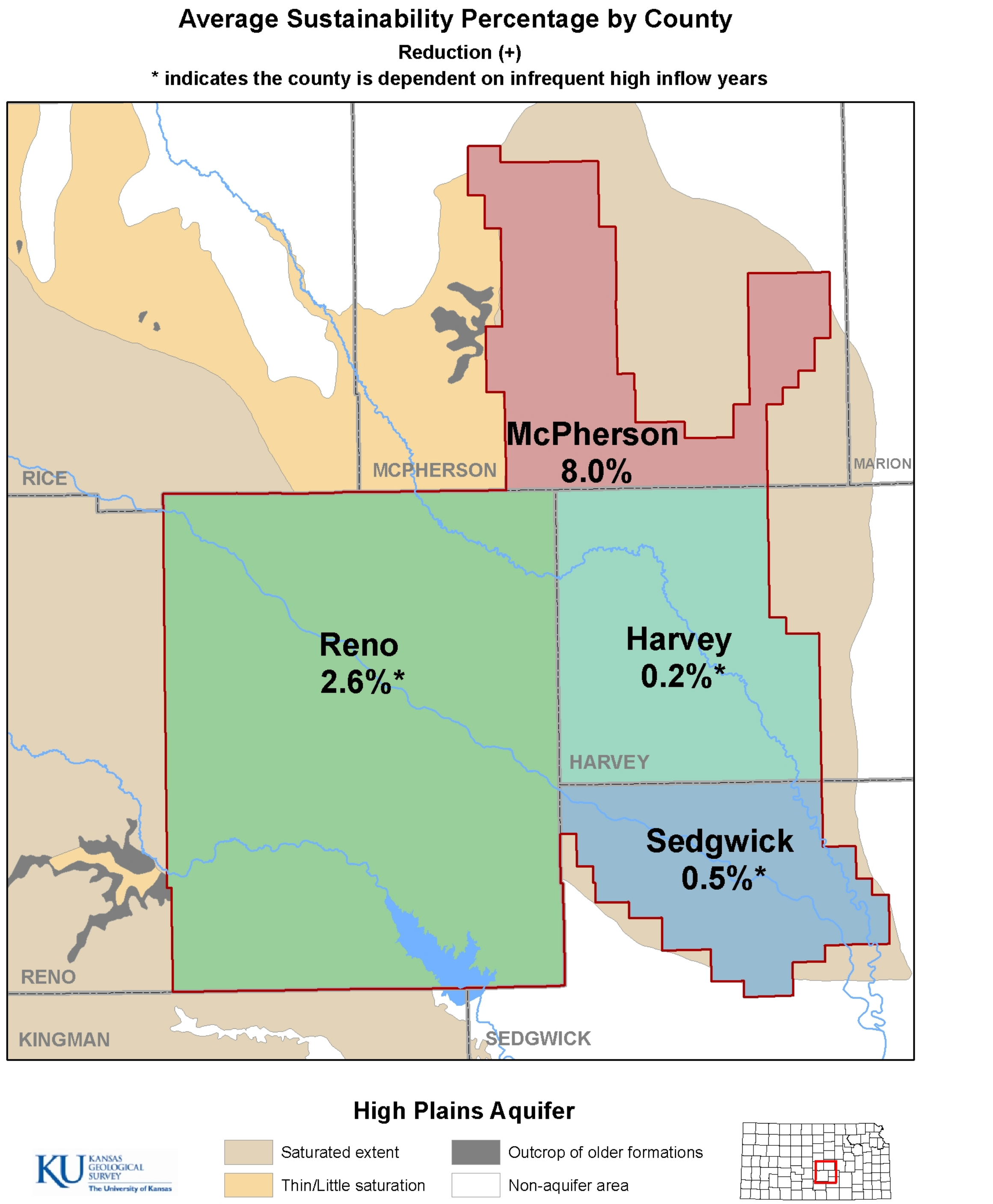

Figure III.B.6. Results of the sustainability assessment at the scale of individual counties within GMD2. Plotted values are the percent reductions (given as positive numbers) in average annual water use that would be needed to reach the sustainable average annual water use volume (Q_{stable}) for each county.

C. Township Assessment

The results of the township assessment will be presented on a county-by-county basis to enable ready comparison with the county-level assessment. Each of the subsections for a particular county discuss the analyses of the township-range units for a particular township. The three values labeled on the county-level plots will also be labeled on the township plots for comparative purposes. However, the x- and y-axes ranges will vary among plots.

1. Harvey County

a. Township 22S

There are three township-range units for this tier of townships in Harvey County. The 22S-01W unit has no reported water use, so it is not analyzed here. The 22S-02W unit has only a few monitoring wells, particularly before 2005, so the emphasis will be on the analyses for the 2005–2014 period. The 22S-03W unit has a reasonable coverage of monitoring wells for all periods.

22S-02W: The results of the analyses vary somewhat between the continuous and maximum well analyses for the 2005–2014 period. The average Q_{stable} value for the period is 2,933 ac-ft/yr, 13.9% below the average reported annual water use for 2005 to 2014; the average R^2 value is 0.53 and is significantly affected by one value (2006) that is distinctly different from the others.

22S-03W: The results of the analyses varied relatively little regardless of the type of data used in the analysis and the time period of the analysis. The overall average Q_{stable} value is 5,563 ac-ft/yr, 3.1% below the average reported annual water use; the average R^2 value is 0.65 and is significantly affected by two values (2007 and 2013) that are distinctly different from the others.

Figure III.C.1 displays the plots for the analyses of the maximum wells from 2005 to 2014 for the 22S-02W and 22S-03W units. For the 22S-02W unit, the 2006 value lies well below the best-fit line, possibly as a result of late-season pumping and the few monitoring wells available for the analysis. Removal of the 2006 value increases the R^2 to 0.71 and the Q_{stable} to 3,100 ac-ft/yr (9% less than the average reported water use). For the 22S-03W unit, the 2007 and 2013 values, which were years of high precipitation immediately following a drought year, lie well above the best-fit line. As with the county-level assessment for Harvey County, the drought appears to have lowered water levels such that the aquifer could accept more net inflow in those years than in a typical year. Removal of the 2007 and 2013 values increases the R^2 to 0.86 and significantly influences Q_{stable}. After the removal of the 2007 and 2013 values, the Q_{stable} is 4,929 ac-ft/yr, 17% less than the average reported water use.

The conclusions of the assessment of the two analyzed township-range units in township 22S in Harvey County vary between the two units. For the 22S-02W unit, this part of the aquifer appears to be developed for an average water use that is above the sustainable level. For the 22S-03W unit, this part of the aquifer appears to be developed for an average water use that is somewhat above the sustainable level. However, the system appears to be heavily dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is much further away (17% for the 2005–2014 maximum well analysis) from the sustainable level.

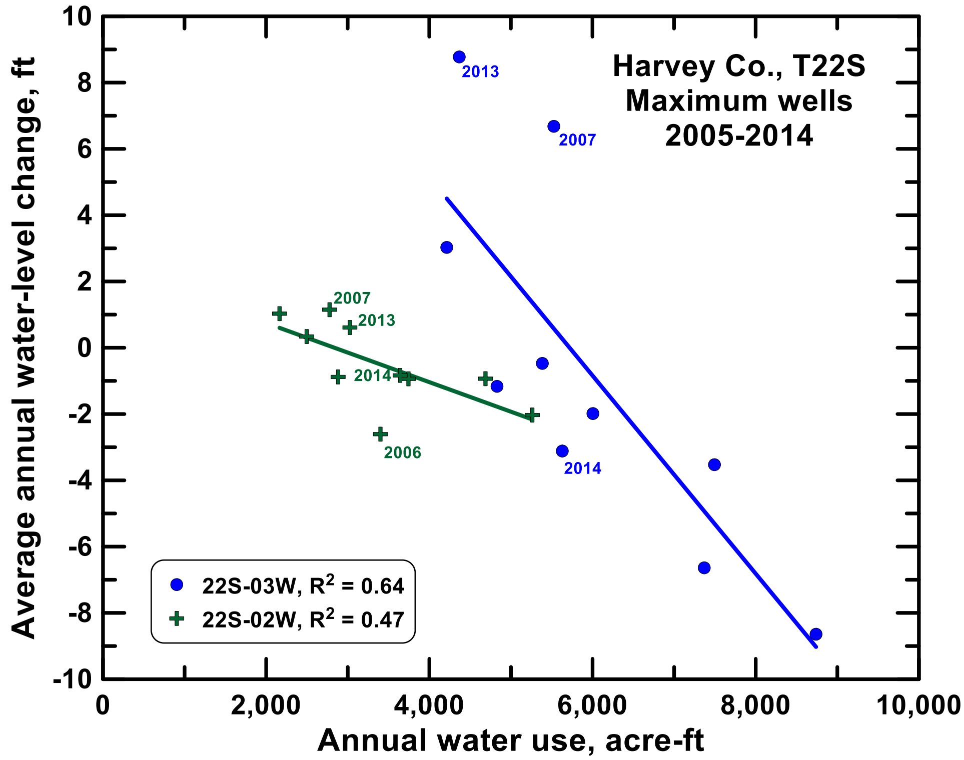

Figure III.C.1. Plots of annual water use versus average annual water-level change for the township-range units in Harvey County in GMD2 lying within T22S. The analyses for 22S-02W and -03W use the 93 and 94 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

b. Township 23S

There are three township-range units for this tier of townships in Harvey County. The 23S-01W unit has only two continuous monitoring wells for the 2005–2014 period, so the analysis was performed using the maximum number of wells for the 2005–2014 period. Use of the maximum number of wells for the 2005–2014 period for the other township-range units resulted in the monitoring wells being well distributed in the areas of concentration of points of diversion with groundwater-based water rights.

23S-01W: Only the results of the 2005–2014 maximum well analysis are considered because few wells were available for the other analyses. The Q_{stable} value is 2,001 ac-ft/yr, 0.3% below the average reported water use for 2005 to 2014; the R^2 value is 0.70. The continuous well analysis (based on two wells) produced similar values.

23S-02W: The results of the analyses vary depending on the type of data used in the analysis and the time period of the analysis; the R^2 values are low (0.40 or less) because of the considerable degree of noise in the data. In an effort to reduce the impact of the noise, the maximum well 2005–2014 analysis was performed using a two-year average of the data. The resulting Q_{stable} value is 6,730 ac-ft/yr, 1.7% below the average reported water use for 2005 to 2014; the R^2 value is 0.70. Clearly, averaging helped damp the noise, which was likely introduced by wells cutting on and off near the time of the annual water-level measurements.

23S-03W: The results of the analyses vary relatively little regardless of the type of data used in the analysis and the time period of the analysis. The overall average from all the analyses is a Q_{stable} value of 2,970 ac-ft/yr, 1.4% below the average reported annual water use. The average R^2 value is 0.66 and is significantly affected by two values (2007 and 2013) that are distinctly different from the others.

Figure III.C.2 displays the plots for the analyses of the maximum wells from 2005 to 2014 for the 23S-01W, -02W, and -03W units. The points on the plot for the 23S-01W unit lie reasonably close to the best-fit line; the scatter is likely a result of the few wells available for the analysis. For the 23S-02W unit, both the yearly data and the two-year averages are plotted. For the 23S-03W unit, the 2007 and 2013 values, which were years of high precipitation immediately following a drought year, lie well above the best-fit line. As with the county-level assessment for Harvey County, the drought appears to have lowered water levels such that the aquifer could accept more net inflow in those years than in a typical year. Removal of the 2007 and 2013 values increases the R^2 to 0.86 and significantly influences Q_{stable}. After the removal of the 2007 and 2013 values, Q_{stable} is 2,576 ac-ft/yr, 16% less than the average reported water use.

The conclusions of the assessment of the three township-range units in township 23S in Harvey County vary among the three units. For the 23S-01W unit, this part of the aquifer appears to be developed for an average water use that is close to the sustainable level (Q_{stable} is 0.3% below the average reported water use for the area). For the 23S-02W unit, this part of the aquifer appears to be developed for an average water use that is slightly above the sustainable level. Q_{stable} from the maximum well two-year average analysis is 1.7% below the average reported water use for the area; the noise in the annual data makes it difficult to have confidence in the Q_{stable} estimates obtained without averaging. For the 23S-03W unit, this part of the aquifer appears to be developed for an average water use that is slightly above the sustainable level (Q_{stable} is 1.4% below the average reported water use for the area). However, the system appears to be heavily dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating much further away (16% for the 2005–2014 maximum well analysis) from the sustainable level.

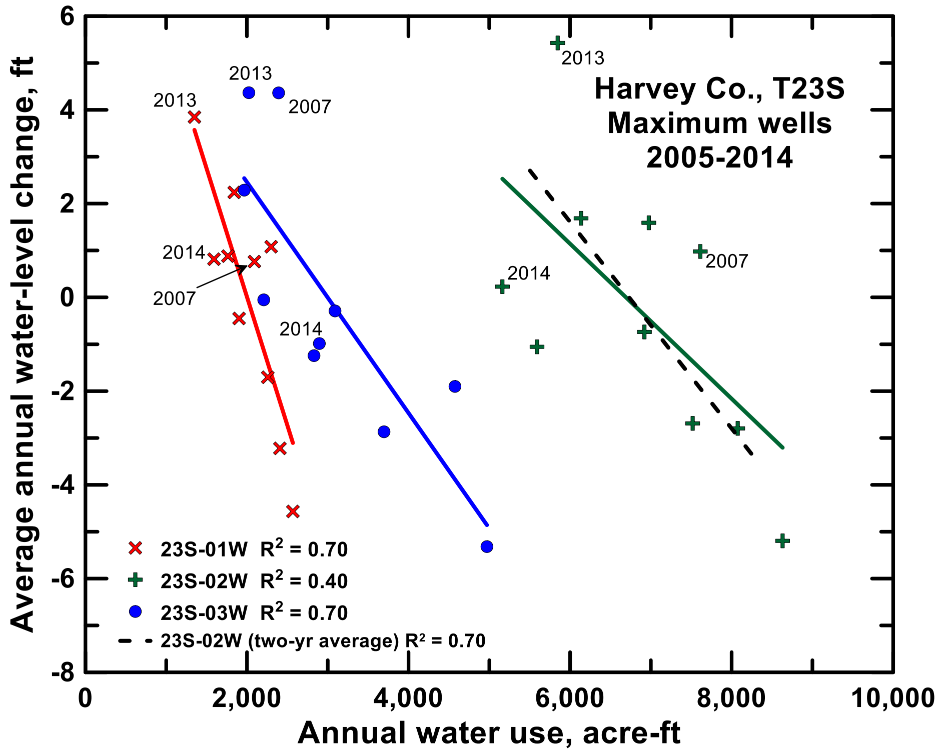

Figure III.C.2. Plots of annual water use versus average annual water-level change for the portions of the township-range units in Harvey County in GMD2 lying within T23S. The analyses for 23S-01W, -02W, and -03W use the 50, 104, and 74 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

c. Township 24S

There are three township-range units for this tier of townships in Harvey County. The 24S-01W unit has only two continuous monitoring wells for the 2005–2014 period, so the analyses were performed using the maximum number of wells for the 2005–2014 period. Use of the maximum number of wells for the 2005–2014 period for the other township-range units resulted in the monitoring wells being well distributed in the areas of concentration of points of diversion with groundwater-based water rights.

24S-01W: Only the results of the 2005–2014 maximum well analysis are considered because few wells were available for the other analyses. The Q_{stable} value is 3,664 ac-ft/yr, 0.1% below the average reported water use for 2005 to 2014; the R^2 value is 0.52 as a result of the 2013 value falling far above the best-fit line. The 2005–2014 continuous well analysis (based on two wells) produced similar values.

24S-02W: The results of the analyses vary depending on the type of data used in the analysis and the time period of the analysis; the R^2 values are all low (0.44 or less) because the 2014 point falls far to the left of the others. To reduce the impact of that single anomalous point, which was possibly produced by a change in municipal pumping practices, the maximum well

2005–2014 analysis was repeated for the 2005–2013 period. The resulting Q_{stable} value is 14,354 ac-ft/yr, 1.1% above the average reported water use for 2005 to 2013; the R^2 value is 0.85.

24S-03W: The results of the analyses vary depending on the type of data used in the analysis and the time period of the analysis; the R^2 values are relatively low (0.57 or less) because of the considerable degree of noise in the data. In an effort to reduce the impact of the noise, the maximum well 2005–2014 analysis was repeated using a two-yr average of the data. The resulting Q_{stable} value is 9,834 ac-ft/yr, 0.9% above the average reported water use for 2005 to 2014; the R^2 value is 0.77. Although the averaging helped damp the noise, which was likely introduced by municipal pumps cutting on and off near the time of the annual water-level measurements, there was virtually no change from the Q_{stable} estimate for the 2005–2014 period without averaging.

Figure III.C.3 displays the plots for the analyses of the maximum number of wells for 2005–2014 for the 24S-01W, -02W, and -03W units. For the 24S-01W unit, the 2013 value, which was a year of high precipitation immediately following a drought year, is well above the best-fit line. As with the county-level assessment for Harvey County, the drought appears to have lowered water levels such that the aquifer could accept more net inflow in that year than in a typical year. Removal of the 2013 value reduces Q_{stable} to 3,368 ac-ft/yr (8% less than the average reported water use) and increases R^2 to 0.80. For the 24S-02W unit, the removal of the anomalous 2014 value had a large impact on the R^2 value but a relatively small influence on the Q_{stable} estimate (14,198 ac-ft vs 14,354 ac-ft) because the two best-fit lines intersect close to the zero average annual water-level change value. For the 24S-03W unit, the points on the plot are scattered about the best-fit line; that scatter is likely a result of municipal wells cutting on and off near the time of the annual measurement. Although averaging significantly reduces the scatter, it has essentially no influence on the Q_{stable} estimate as shown by the near coincidence of the two best-fit lines.

The conclusions of the assessment of the three township-range units in township 24S in Harvey County vary among the units. For the 24S-01W unit, this part of the aquifer appears to be developed for an average water use that is essentially at the sustainable level. However, the system appears to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average water use that is above (8% for the 2005–2014 maximum well analysis) the sustainable level. For the 24S-02W unit, this part of the aquifer appears to be developed for an average water use that is very slightly below the sustainable level (Q_{stable} is 1.1% greater than the average water use for 2005–2013). For the 24S-03W unit, this part of the aquifer also appears to be developed for an average water use that is very slightly below the sustainable level (Q_{stable} is 0.9% greater than the average water use for 2005–2014).

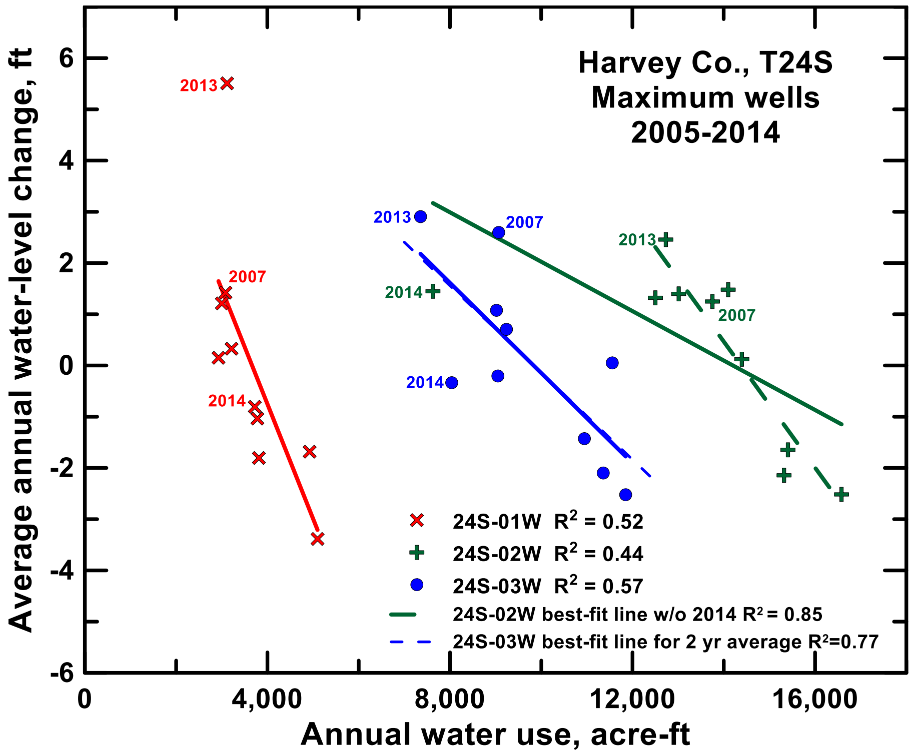

Figure III.C.3. Plots of annual water use versus average annual water-level change for the portions of the township-range units in Harvey County in GMD2 lying within T24S. The analyses for 24S-01W, -02W and -03W use the 82, 141, and 157 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

2. *McPherson County*

a. Township 18S

There are portions of two township-range units for this tier of townships in McPherson County. Both units only have a few monitoring wells but they are in the areas of concentrated groundwater use.

18S-03W: Other than the continuous well analysis for the 1996–2014 period, for which only one well was available, the results of the analyses for the 18S-03W unit are consistent. The average Q_{stable} value for the 2005–2014 analyses is 513 ac-ft/yr, 3.5% below the average reported water use for 2005 to 2014; the R^2 value is 0.87.

18S-04W: The R^2 values are low (0.47 or less) because of the considerable degree of noise in the data, which was likely introduced by the small number of monitoring wells. Despite the noise, the results of all the analyses are consistent. The overall average from all the analyses is a Q_{stable} of 1,213 ac-ft/yr, 16.3% below the average reported water use. In an effort to reduce the impact of the noise, the continuous well 2005–2014 analysis was repeated using a two-year average of the data. The resulting Q_{stable} value is 1,148 ac-ft/yr, 4.1% less than the value obtained for that time interval without averaging and 21.0% below the average reported water use for 2005 to 2014; the R^2 value increases to 0.64. Given that the results of the analyses using the annual data are similar for all data types and time periods, the average of those analyses is used as the best estimate of the sustainable water use for this unit.

Figure III.C.4 displays the plots for the analyses of the continuous wells since 2005 for the 18S-03W and 18S-04W units. The points for the 18S-03W unit lie close to the best-fit line, but there is considerable scatter for the 18S-04W unit. Although the 2007 and 2013 values, which were years of high precipitation immediately following a drought year, lie well above the best-fit line for 18S-04W, there is considerable scatter in the remaining points, so removal of 2007 and 2013 did not improve the fit to the data. A two-year average reduced the scatter and improved the quality of the fit.

The conclusions of the assessment of the two township-range units in township 18S in McPherson County vary between the units. For the small portion of the 18S-03W unit lying within GMD2, the aquifer appears to be developed for an average water use that is somewhat above the sustainable level (Q_{stable} is 3.5% below the average reported water use for the area). For the larger portion of 18S-04W unit lying within GMD2, this part of the aquifer appears to be developed for an average water use that is above the sustainable level (Q_{stable} is 16.3% below the average reported water use for the area).

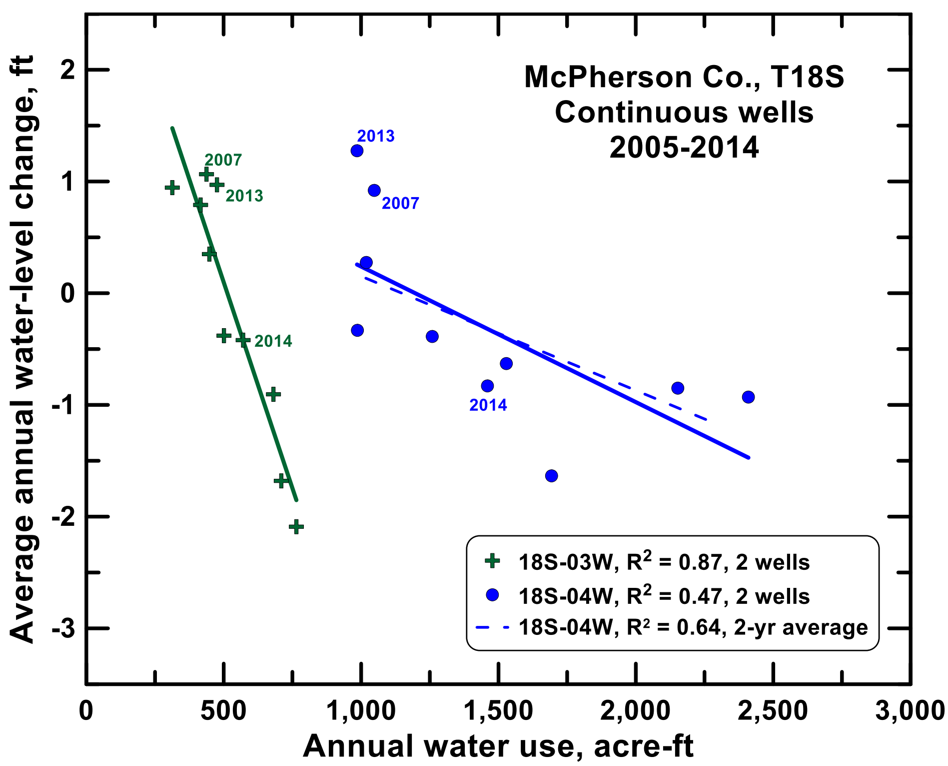

Figure III.C.4. Plot of annual water use versus average annual water-level change for the portions of township-range units in McPherson County in GMD2 lying within T18S. The analyses for the 18S-03W and -04W units use the 16 and 22 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

b. Township 19S

There are portions of three township-range units for this tier of townships in McPherson County. In general, the monitoring wells appear to be located in the areas of concentrated groundwater use.

19S-01W: No wells were measured every year for either period of analysis. Only the maximum well analysis for the 2005–2014 period produced statistically significant results, so the results of that analysis are reported here. The Q_{stable} value is 232 ac-ft/yr, 5.6% below the average reported water use for 2005 to 2014; the R^2 value is 0.51.

19S-03W: The results of the analyses for the 19S-03W unit vary relatively little between the type of data used in the analysis and the time period of the analysis. The overall average from all the analyses is a Q_{stable} of 3,048 ac-ft/yr, 7.4% below the average reported water use. The overall average R^2 value is 0.79.

19S-04W: The focus of the analysis was on the 2005–2014 analysis as there is considerably more noise in the 1996–2014 data. The overall average from the continuous and maximum well analyses for the 2005–2014 period is a Q_{stable} of 2,271 ac-ft/yr, 13.9% below the average reported water use. The overall average R^2 value is 0.80.

Figure III.C.5 displays the plots for the analyses of the maximum wells in the 2005 to 2014 time period for the 19S-01W, -03W, and -04W units. All the plotted points lie relatively close to the best-fit lines.

The conclusions of the assessment of the three township-range units in township 19S in McPherson County vary somewhat among the units. For the portions of the 19S-01W and -03W units lying within GMD2, the aquifer appears to be developed for an average water use that is above the sustainable level (Q_{stable} estimates are 5.6% and 7.4% below the average reported water use, respectively). For the portion of 19S-04W unit lying within GMD2, the aquifer appears to be developed for an average water use that is further above the sustainable level (Q_{stable} estimate is 13.9% below the average reported water use) than the other township-range units.

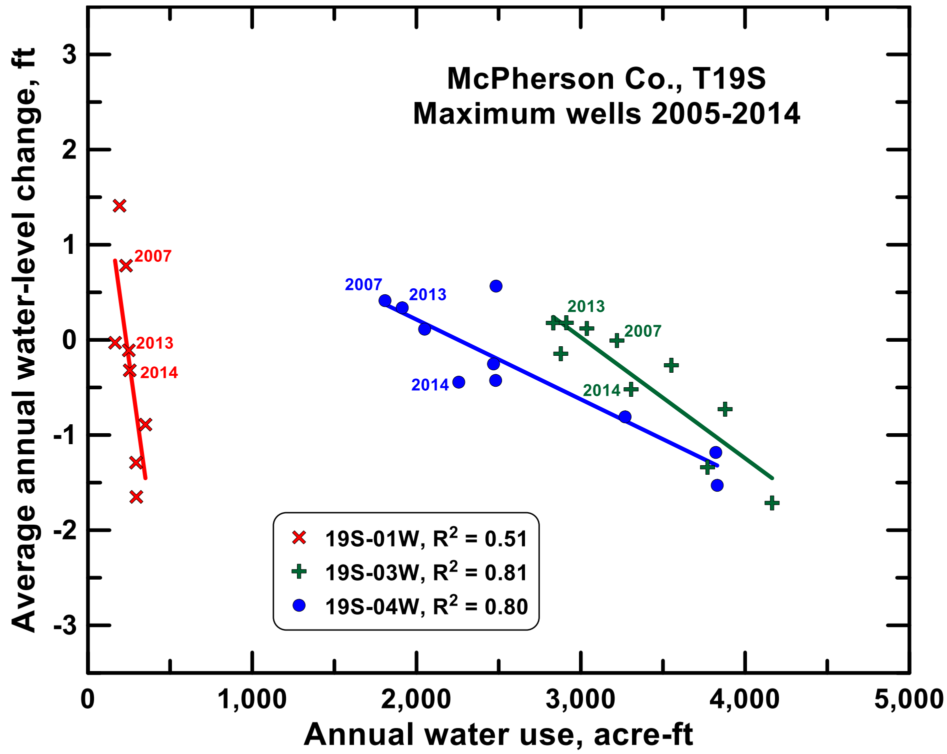

Figure III.C.5. Plot of annual water use versus average annual water-level change for the portions of township-range units in McPherson County in GMD2 lying within T19S. The analyses for the 19S-01W, -03W, and -04W units use the 14, 25, and 48 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

c. Township 20S

There are portions of three township-range units for this tier of townships in McPherson County. The data from the 20S-03W unit are noisy prior to 2005. As a result, the analyses were performed using the continuous and maximum well data sets for the 2005–2014 period. Use of these data sets resulted in the monitoring wells being reasonably well distributed in the areas of concentration of points of diversion with groundwater-based water rights for all three units.

20S-01W: The Q_{stable} value, which is the same for the continuous and maximum well analyses for the 2005–2014 period, is 1,442 ac-ft/yr, 3.7% below the average reported water use for 2005 to 2014; the R^2 value is 0.70 and is significantly affected by one value (2007) that is distinctly different from the others.

20S-03W: The Q_{stable} value varies somewhat between the continuous and maximum well analyses for 2005–2014. The average Q_{stable} from these analyses is 5,785 ac-ft/yr, 15.4% below the average reported water use for 2005 to 2014; the average R^2 value is 0.76.

20S-04W: The Q_{stable} value varies somewhat between the continuous and maximum well analyses for 2005–2014. The average Q_{stable} from these analyses is 3,851 ac-ft/yr, 19.8% below the average reported water use for 2005 to 2014; the average R^2 value is 0.76.

Figure III.C.6 displays the plots for the analyses of the continuous wells for the 2005–2014 period for the 20S-01W, -03W, and -04W units. The 2007 point lies well above the plotted line for the 20S-01W data. Removal of that point results in a R^2 of 0.84 and a Q_{stable} of 1,337 ac-ft/yr, 8.9% below the average reported water use. Other than the 2009 value in the 20S-03W plot, which has a small impact on the Q_{stable} value, the points for the other plots lie relatively close to the best-fit lines.

The conclusions of the assessment of the three township-range units in township 20S in McPherson County vary somewhat among the units. For the portions of the 20S-01W unit lying within GMD2, the aquifer appears to be developed for an average annual water use that is somewhat above the sustainable level (Q_{stable} estimate is 3.7% below the average reported water use). However, the system appears to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average water use that is further above (8.9% for the 2005–2014 continuous well analysis) the sustainable level. The influence of high precipitation years is probably more pronounced for this unit within McPherson County than for the others due to the shallower water table coupled with the presence of West Emma Creek and its tributaries. For the portions of 20S-03 and -04W units lying within GMD2, the aquifer appears to be developed for an average annual water use that is further below the sustainable level (Q_{stable} estimates are 15.4% and 19.8% below the average reported water use for the 20S-03 and -04 units, respectively) than the 20S-01W unit.

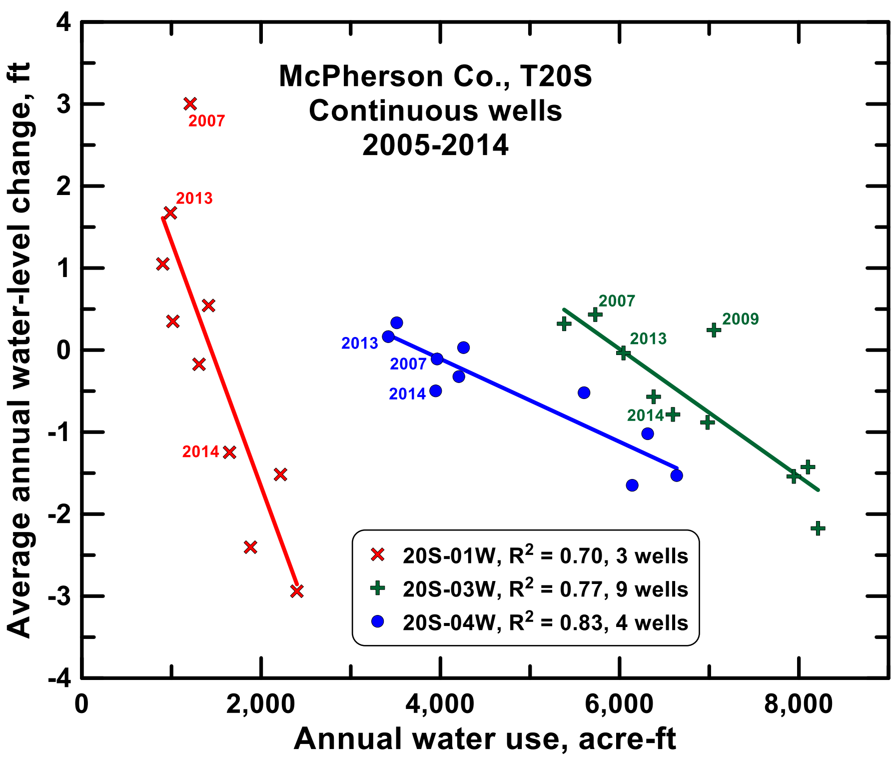

Figure III.C.6. Plots of annual water use versus average annual water-level change for the portions of township-range units in McPherson County in GMD2 lying within T20S. The analyses for the 20S-01W, -03W, and -04W units use the 55, 53, and 49 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

d. Township 21S

There are portions of four township-range units for this tier of townships in McPherson County. T21S-01W has no reported water use, so it will not be analyzed here. Only two wells were measured continuously across the 1996–2014 period for the -02W and -04W units, so the analyses were performed using the data from the 2005–2014 period. In general, the monitoring wells appear to be located in the areas of concentrated groundwater use.

21S-02W: The results for the analyses of different time periods and data types vary little. The overall average Q_{stable} value is 1,816 ac-ft/yr, 8.0% below the average reported water use; the R^2 value is 0.78.

21S-03W: The results for the analyses of different time periods and data types vary little. The overall average Q_{stable} value is 5,977 ac-ft/yr, 7.3% below the average reported water use; the average R^2 value is 0.82.

21S-04W: The results for the analyses of different time periods and data types vary little. The overall average Q_{stable} value is 2,273 ac-ft/yr, 5.7% below the average reported water use; the R^2 value is 0.85.

Figure III.C.7 displays the plots for the analyses of the maximum wells for the 2005–2014 period for the 21S-02W, -03W, and -04W units. In all cases, the points lie relatively close to the best-fit lines; there is little indication of the high inflow years as seen in many of the Harvey County township units.

The conclusions of the assessment of the three analyzed township-range units in township 21S in McPherson County vary little among the units. For the portions of the 21S-02W and -03W units lying within GMD2, the aquifer appears to be developed for an average water use that is above the sustainable level (Q_{stable} estimates are 8.0% and 7.3%, respectively, below the average reported water use). For the portion of the 21S-04W unit lying within GMD2, the aquifer appears to be developed for an average water use that is somewhat closer to the sustainable level (Q_{stable} estimate is 5.7% below the average reported water use).

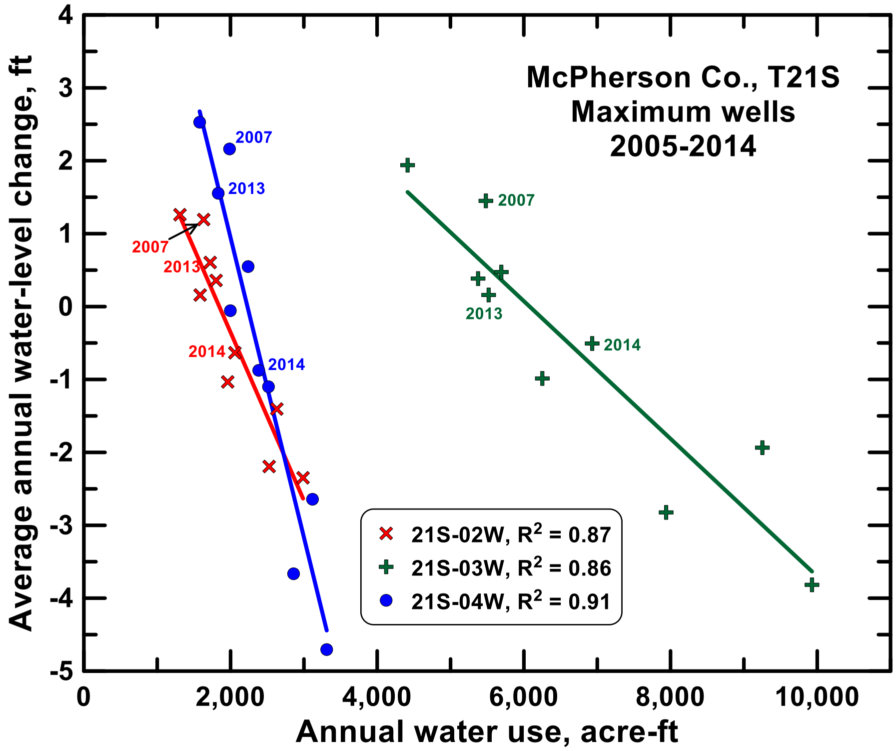

Figure III.C.7. Plots of annual water use versus average annual water-level change for the portions of the analyzed township-range units in McPherson County in GMD2 lying within T21S. The analyses for the 21S-02W, -03W, and -04W units use the 68, 78, and 41 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

3. *Reno County*

a. Township 22S

There are four township-range units for this tier of townships in Reno County. Outside of the areas of little pumping in 22S-04W and -05W and in the southwestern half of 22S-07W, most of the monitoring wells are in the areas of concentrated groundwater use. Relatively few wells were measured over the 1996–2014 period, so the primary focus of the analyses was on the 2005–2014 period.

22S-04W: The average Q_{stable} value for the 2005–2014 period is 2,104 ac-ft/yr, 3.8% below the average reported water use for 2005–2014. The average R^2 value is 0.60 and is significantly affected by two values (2007 and 2013) that are distinctly different from the others.

22S-05W: There was very little pumping in this township-range unit (reported annual water use was only 5–13% of that for the other units in this township). The average Q_{stable} value for the 2005–2014 period is 261 ac-ft/yr, 7.8% below the reported water use for 2005–2014. The average R^2 value is 0.46 and is significantly affected by two values (2007 and 2013) that are distinctly different from the others.

22S-06W: The average Q_{stable} value for the 2005–2014 period is 5,289 ac-ft/yr, 0.9% below the average reported water use for 2005–2014. The average R^2 value is 0.58 and is significantly affected by two values (2007 and 2013) that are distinctly different from the others.

22S-07W: The average Q_{stable} value for the 2005–2014 period is 2,931 ac-ft/yr, 4.3% below the average reported water use for 2005–2014. The average R^2 value is 0.35 and is significantly affected by two values (2007 and 2013) that are distinctly different from the others; the result was that the relationship was just below statistical significance at the 0.05 level.

Figure III.C.8 displays the plots for the analyses of the continuously measured wells for 2005–2014 for the 22S-04W, -05W, -06W, and -07W units. For all units, the 2007 and 2013 values, which were years of high precipitation immediately following drought years, are well above the best-fit line. As with the county-level assessment for Reno County, the drought appears to have lowered water levels such that the aquifer could accept more net inflow in those years than in a typical year. For unit 22S-04W, removal of the 2007 and 2013 values reduces Q_{stable} to 1,740 ac-ft/yr (20% less than the average reported water use) and increases R^2 to 0.80. For the 22S-05W unit, the removal of the 2007 and 2013 values reduces Q_{stable} to 192 ac-ft/yr (32% less than the average reported water use) and increases R^2 to 0.63. For unit 22S-06W, removal of the 2007 and 2013 values reduces Q_{stable} to 4,961 ac-ft/yr (7% less than the average reported water use) and increases R^2 to 0.73. For the 22S-07W unit, the removal of the 2007 and 2013 values reduces Q_{stable} to 1,899 ac-ft/yr (38% less than the average reported water use) and increases R^2 to 0.60. The relationship is now significant at the 0.01 level.

The conclusions of the assessment of the four township-range units in township 22S in Reno County vary among the units. For the 22S-04W unit, this part of the aquifer appears to be developed for an average water use that is somewhat above the sustainable level. However, the system appears to be heavily dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average water use that is much further above (20% for the 2005–2014 continuous well analysis) the sustainable level. For the 22S-05W unit, this part of the aquifer appears to be developed for an average water use that is above the sustainable level. However, the system appears to be heavily dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average water use that is much further above (32% for the 2005–2014 continuous well analysis) the sustainable level. The small amount of pumping in this unit undoubtedly introduces greater uncertainty into the Q_{stable} estimate than for the other units in this township. For the 22S-06W unit, this part of the aquifer appears to be developed for an average water use that is very slightly above the sustainable level. However, the system appears to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average water use that is further above (7% for the 2005–2014 continuous well analysis) the sustainable level. For the 22S-07W unit, this part of the aquifer appears to be developed for an average water use that is somewhat above the sustainable level. However, the system appears to be heavily dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average water use that is much further above (38% for the 2005–2014 continuous well analysis) the sustainable level. In all cases, the units in township 22S in Reno County appear to be heavily dependent on infrequent high inflow years to maintain this portion of the aquifer at near-sustainable levels.

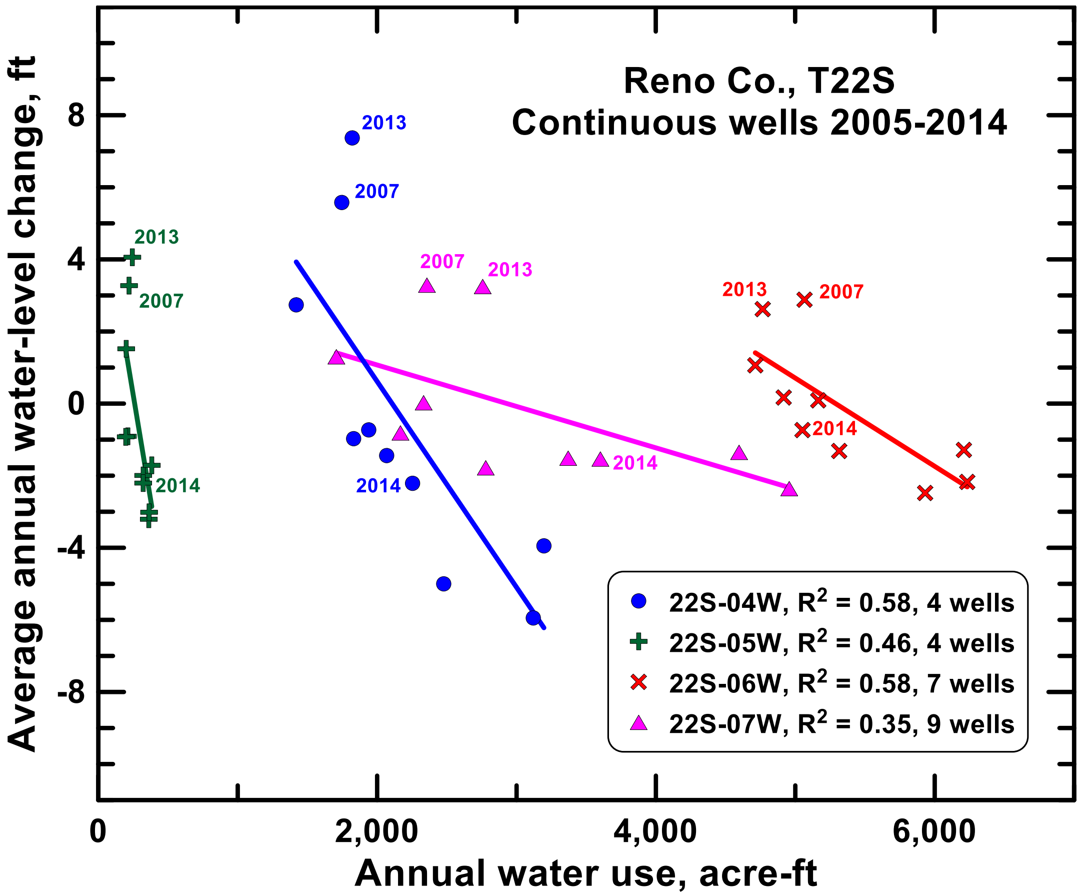

Figure III.C.8. Plots of annual water use versus average annual water-level change for the township-range units in Reno County in GMD2 lying within T22S. The analyses for the 22S-04W, -05W, -06W, and -07W units use the 36, 62, 95, and 75 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

b. Township 23S

There are four township-range units for this tier of townships in Reno County. Outside of 23S-07W, where there has been little pumping, most of the monitoring wells are in the areas of concentrated groundwater use. Relatively few wells were measured over the 1996–2014 period, so the primary focus of the analyses was on the 2005–2014 period.

23S-04W: The average Q_{stable} value for the 2005–2014 period is 1,040 ac-ft/yr, 5.6% below the average reported water use for 2005–2014. The average R^2 value is 0.58 and is affected by two values (2007 and 2013) that are somewhat different from the others.

23S-05W: We were unable to obtain statistically significant relationships for either data type or time period; results are far from statistical significance at the 0.05 level for all time periods and data types. Applying a two-year average of the measurements also did not produce statistically significant relationships. The failure to obtain statistically significant relationships is likely related to the large amount of non-irrigation pumping in the area (average irrigation pumping only 10.7% of total average pumping for 2005–2014). Even if the analysis is restricted to irrigation pumping, the correlation is very low because the number of pumping wells appears to be increasing with time. We will examine this area further in our analysis of the Arkansas River Hutchinson defined area.

23S-06W: We were unable to obtain statistically significant relationships for any data type or time period; results are far from statistical significance at the 0.05 level for all time periods and data types. Removal of the anomalous 2014 point also did not produce statistically significant relationships. The failure to obtain statistically significant relationships is likely related to the large amount of non-irrigation pumping in the area (average irrigation pumping only 9.3% of total average pumping for 2005–2014). If the analysis is restricted to irrigation pumping, a reasonable relationship (R^2=0.55) is obtained. If the 2007 and 2013 values, which are distinctly different from the others, are removed, R^2 increases to 0.92, an indication that the area is heavily dependent on infrequent high inflow years. However, given the low percentage of irrigation pumping, it is difficult to draw conclusions about the appropriate Q_{stable} for this area. We will examine this area further in our analysis of the Arkansas River Hutchinson defined area.

23S-07W: The average Q_{stable} value for the 2005–2014 period is 195 ac-ft/yr (only 2–19% of the reported use in the other units in this township), 7.5% below the average reported water use for 2005–2014. The average R^2 value is 0.43 and is affected by two values (2007 and 2013) that are somewhat different from the others.

Figure III.C.9 displays the plots for the analyses of the continuously measured wells for 2005–2014 for the 23S-04W, -05W, -06W, and -07W units. For unit 23S-04W, the 2007 and 2013 values, which were years of high precipitation immediately following drought years, are somewhat above the best-fit line. As with the county-level assessment for Reno County, the drought appears to have lowered water levels such that the aquifer could accept more net inflow in those years than in a typical year. Removal of the 2007 and 2013 values reduces Q_{stable} to 858 ac-ft/yr (22% less than the average reported water use) and increases R^2 to 0.66. For the 23S-07W unit, the 2007 and 2013 values are somewhat above the best-fit line. Removal of the 2007 and 2013 values reduces Q_{stable} to 146 ac-ft/yr (31% less than the average reported water use) and increases R^2 to 0.60.

The conclusions of the assessment of the four township-range units in township 23S in Reno County vary among the units. For the 23S-04W unit, this part of the aquifer appears to be developed for an average annual water use that is somewhat above the sustainable level. However, the system appears to be heavily dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average annual water use that is much further above (22% for the 2005–2014 continuous well analysis) the sustainable level. We could not obtain defensible conclusions for the 23S-05W and -06W units beyond that 23S-06W does appear to be heavily dependent on high inflow years; we will address these areas further in the analysis of the Arkansas River Hutchinson defined area. For the 22S-07W unit, this part of the aquifer appears to be developed for an average annual water use that is above the sustainable level. However, the system appears to be heavily dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average water use that is much further above (31% for the 2005–2014 continuous well analysis) the sustainable level. The small amount of pumping in this unit undoubtedly introduces greater uncertainty into the Q_{stable} estimate than for the other units in this township. As with the units in township 22S in Reno County, the units in township 23S in Reno County appear to be dependent on infrequent high inflow years to maintain this portion of the aquifer at near-sustainable levels.

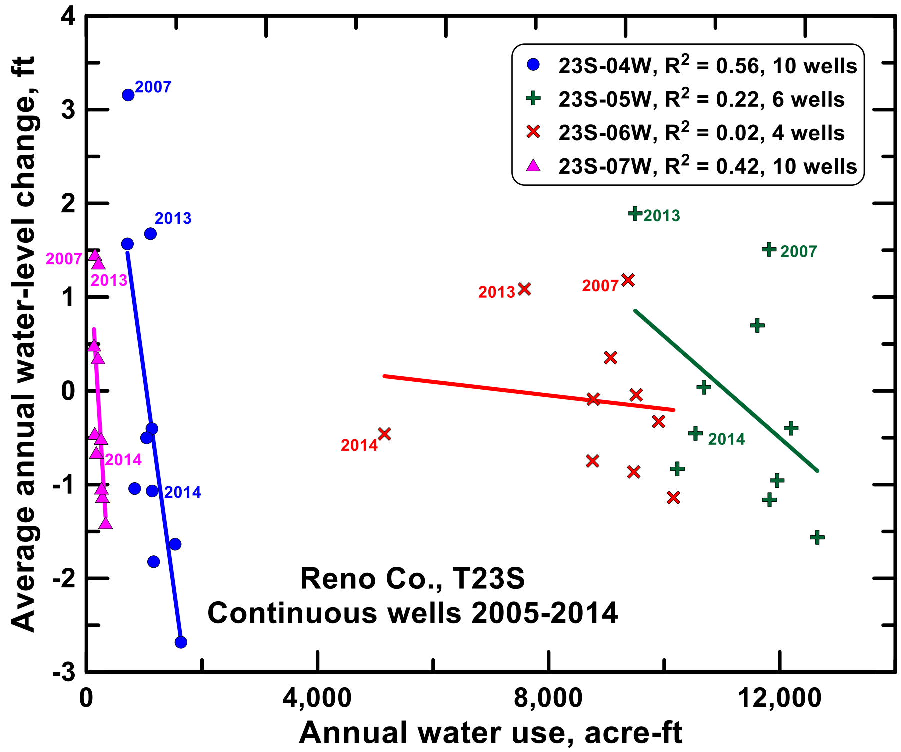

Figure III.C.9. Plots of annual water use versus average annual water-level change for the township-range units in Reno County in GMD2 lying within T23S. The analyses for the 23S-04W, -05W, -06W, and -07W units use the 48, 197, 104, and 6 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

c. Township 24S

There are four township-range units for this tier of townships in Reno County. In general, the monitoring wells appear to be located in the areas of concentrated groundwater use. Few wells were measured over the 1996–2014 period in the two westernmost units, so the primary focus of the analyses was on the 2005–2014 period.

24S-04W: The average Q_{stable} value for the 2005–2014 period is 6,277 ac-ft/yr, 5.0% below the average reported water use for 2005–2014. The average R^2 value is 0.62 and is affected by two values (2007 and 2013) that are distinctly different from the others.

24S-05W: The average Q_{stable} value for the 2005–2014 period is 3,625 ac-ft/yr, 7.3% below the average reported water use for 2005–2014. The average R^2 value is 0.60 and is affected by two values (2007 and 2013) that are distinctly different from the others.

24S-06W: The average Q_{stable} value for the 2005–2014 period is 3,404 ac-ft/yr, 3.3% below the average reported water use for 2005–2014. The average R^2 value is 0.72; the relationships for this unit appear less sensitive to the 2007 and 2013 high precipitation years than the other Reno County units in this township.

24S-07W: The average Q_{stable} value for the 2005–2014 period is 3,752 ac-ft/yr, 6.0% below the average reported water use for 2005–2014. The average R^2 value is 0.77 and is affected by two values (2007 and 2013) that are distinctly different from the others.

Figure III.C.10 displays the plots for the analyses of the continuously measured wells for 2005–2014 for the 24S-04W, -05W, -06W, and -07W units. For unit 24S-04W, the 2007 and 2013 values, which were years of high precipitation immediately following drought years, are well above the best-fit line. As with the county-level assessment for Reno County, the drought appears to have lowered water levels such that the aquifer could accept more net inflow in those years than in a typical year. Removal of the 2007 and 2013 values reduces Q_{stable} to 5,184 ac-ft/yr (22% less than the average reported water use) and increases R^2 to 0.69. For unit 24S-05W, the 2007 and 2013 values are also well above the best-fit line. Removal of the 2007 and 2013 values reduces Q_{stable} to 3,023 ac-ft/yr (23% less than the average reported water use) and increases R^2 to 0.89. For the 24S-07W unit, the 2007 and 2013 values are again well above the best-fit line. Removal of the 2007 and 2013 values reduces Q_{stable} to 3,434 ac-ft/yr (14% less than the average reported water use) and increases R^2 to 0.88.

The conclusions of the assessment of the four township-range units in township 24S in Reno County vary somewhat among the units. For the 24S-04W and -05W units, this part of the aquifer appears to be developed for an average annual water use that is above the sustainable level. However, the system appears to be heavily dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average water use that is much further above (22–23% for the 2005–2014 continuous well analysis) the sustainable level. For the 24S-06W unit, this part of the aquifer appears to be operating at an average annual water use that is somewhat above the sustainable level. For the 24S-07W unit, this part of the aquifer also appears to be developed for an average annual water use that is somewhat above the sustainable level. However, the system appears to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average annual water use that is further above (14% for the 2005–2014 continuous well analysis) the sustainable level. As with the units in townships 22S and 23S in Reno County, most of the units in township 24S in Reno County appear to be heavily dependent on infrequent high inflow years to maintain this portion of the aquifer at near sustainable levels.

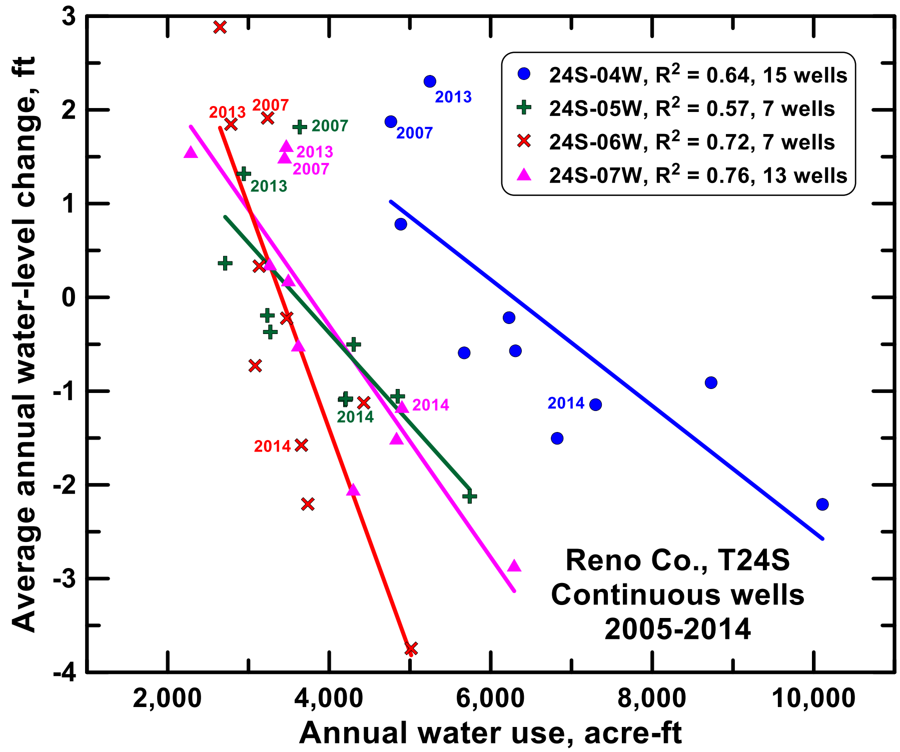

Figure III.C.10. Plots of annual water use versus average annual water-level change for the township-range units in Reno County in GMD2 lying within T24S. The analyses for the 24S-04W, -05W, -06W, and -07W units use the 162, 115, 104, and 111 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

d. Township 25S

There are four township-range units for this tier of townships in Reno County. Other than in the northeast portion of 25S-04W and the northern half of 25S-07W, there was little pumping in these four units. There was only one year of reported water use in the 25S-05W unit from 2005–2014 and no continuously measured wells, so we did not analyze conditions in that unit. In general, there was less noise in the 2005–2014 data, so the primary focus of the analyses was on the 2005–2014 period.

25S-04W: The results for the analyses of different time periods and data types varied little. The overall average Q_{stable} value is 2,041 ac-ft/yr, 4.6% below the average reported water use. The average R^2 value is 0.44 and is affected by four values (2005, 2006, 2007, and 2013) that are distinctly different from the others.

25S-06W: Statistically significant relationships could not be obtained at the 0.05 level for the 1996–2014 period. The average Q_{stable} value for the 2005–2014 period is 266 ac-ft/yr (12–20% of the reported use for 25S-04W and -07W), 3.7% below the average reported water use for 2005–2014. The average R^2 value is 0.56 and is affected by two values (2007 and 2013) that are somewhat different from the others.

25S-07W: There is considerably less noise in the 2005–2014 data, so the primary focus of the analyses is on the 2005–2014 period. The average Q_{stable} value for the 2005–2014 period is 1,356 ac-ft/yr, 4.3% below the average reported water use for 2005–2014. The average R^2 value is 0.56 and is affected by three values (2006, 2007, and 2013) that are somewhat different from the others.

Figure III.C.11 displays the plots for the analyses of the continuously measured wells for 2005–2014 for the 25S-04W, -06W, and -07W units. For unit 24S-04W, the 2007 and 2013 values, which were years of high precipitation immediately following drought years, are well above the best-fit line, while the 2005 and 2006 values, which were possibly the result of late-season pumping, are well below the best-fit line. Removal of these four values reduces Q_{stable} slightly to 2,039 ac-ft/yr (7.3% less than the average reported water use for 2005–2014) and increases R^2 to 0.90. For unit 25S-06W, the 2007 and 2013 values are also somewhat above the best-fit line. Removal of the 2007 and 2013 values reduces Q_{stable} to 229 ac-ft/yr (17% less than the average reported water use) and increases R^2 to 0.62. For the 24S-07W unit, the 2007 and 2013 values are again well above the best-fit line, while the 2006 value, which is possibly the result of late-season pumping, falls well below the best-fit line. Removal of these three values reduces Q_{stable} to 1,274 ac-ft/yr (10% less than the average reported water use) and increases R^2 to 0.90.

The conclusions of the assessment of the three analyzed township-range units in township 25S in Reno County vary little among the units. For the 25S-04W unit, this part of the aquifer appears to be developed for an average annual water use that is somewhat above the sustainable level. However, the system appears to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average annual water use that is further above (7.3% for the 2005–2014 continuous well analysis) the sustainable level. For the 25S-06W unit, this part of the aquifer appears to be operating at an average annual water use that is somewhat above the sustainable level. However, the system appears to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average annual water use that is much further above (17% for the 2005–2014 continuous well analysis) the sustainable level. The small amount of pumping in this unit undoubtedly introduces greater uncertainty into the Q_{stable} estimate than for the other units in this township. For the 25S-07W unit, this part of the aquifer appears to be developed for an average annual water use that is again somewhat above the sustainable level. However, the system appears to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average annual water use that is further above (10% for the 2005–2014 continuous well analysis) the sustainable level. As with the units in townships 22S-24S in Reno County, most of the units in township 25S in Reno County appear to be dependent on infrequent high inflow years to maintain this portion of the aquifer at near-sustainable levels.

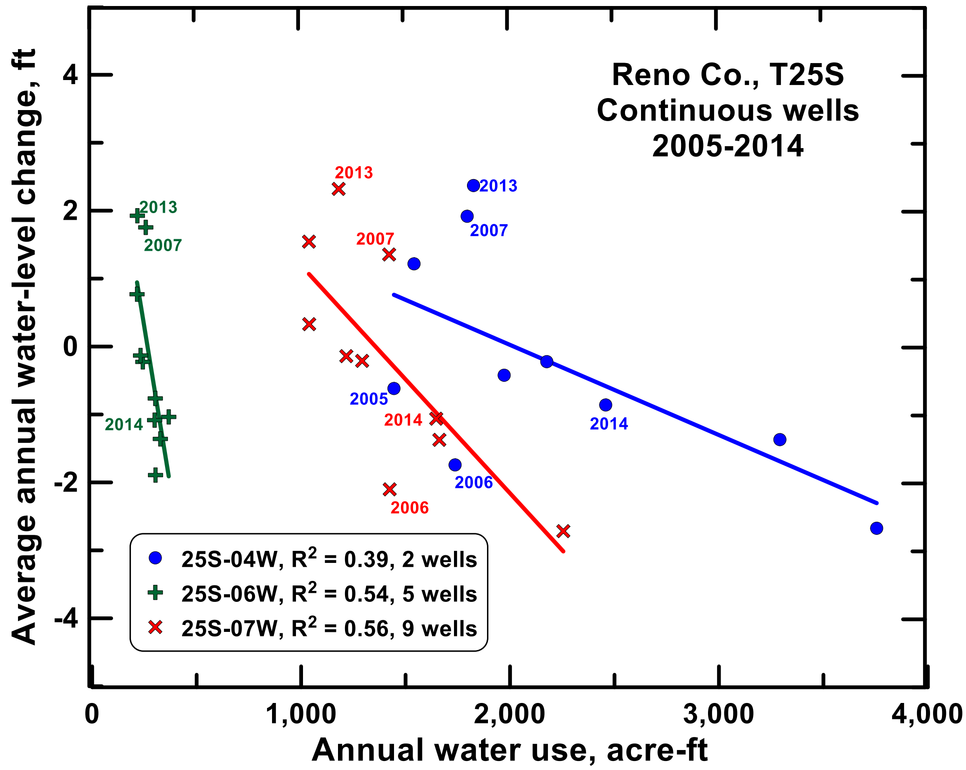

Figure III.C.11. Plots of annual water use versus average annual water-level change for the township-range units in Reno County in GMD2 lying within T25S. The analyses for the 25S-04W, -06W, and -07W units use the 63, 30, and 50 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

e. Township 26S

There are four township-range units for this tier of townships in Reno County. Other than in 26S-06W and the northeastern portion of 26S-07W, there was little pumping in these four units. There was little reported water use in the 26S-04W unit (maximum value was 4.95 ac-ft in 1999) and there were no continuously measured wells, so we did not analyze conditions in this unit. There was no reported water use in the 26S-05W unit, which includes Cheney Reservoir, so we did not analyze conditions in that unit.

26S-06W: There was considerably less noise in the 2005–2014 data, so the primary focus of the analyses was on the 2005–2014 period. The average Q_{stable} value for the 2005–2014 period is 4,907 ac-ft/yr, 7.5% below the average reported water use for 2005–2014. The average R^2 value is 0.65 and was affected by the apparent noise in the water-level data. A two-year average of the data had a very small impact on Q_{stable} and the R^2 value.

26S-07W: The results for the analyses of different time periods and data types vary little. The overall average Q_{stable} value is 3,074 ac-ft/yr, 2.2% below the average reported water use. The average R^2 value is 0.69.

Figure III.C.12 displays the plots for the analyses of the continuously measured wells for 2005–2014 for the 26S-06W and -07W units. For unit 26S-06W, the 2007 and 2013 values, which were years of high precipitation immediately following drought years, are above the best-fit line. However, they appear to fall within the noise band of the data. For the 26S-07W unit, the 2007 and 2013 values fall close to the best-fit line.

The conclusions of the assessment of the two analyzed township-range units in township 26S in Reno County vary somewhat between the units. For the 26S-06W unit, this part of the aquifer appears to be developed for an average annual water use that is above the sustainable level. For the 26S-07W unit, this part of the aquifer appears to be operating at an average annual water use that is slightly above the sustainable level. Unlike most of the units in townships 22S-25S in Reno County, the units in township 26S in Reno County do not appear to be heavily dependent on infrequent high inflow years to maintain this portion of the aquifer at near-sustainable levels.

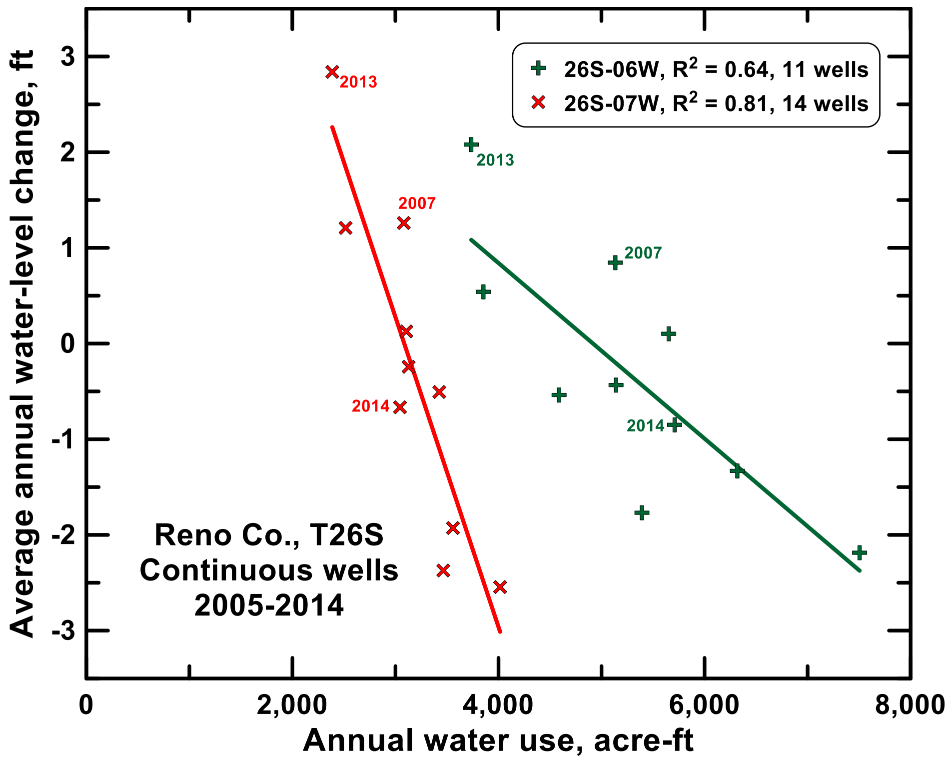

Figure III.C.12. Plots of annual water use versus average annual water-level change for the township-range units in Reno County in GMD2 lying within T26S. The analyses for the 26S-06W and -07W units use the 115 and 41 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

4. Sedgwick County

a. Township 25S

There are portions of three township-range units for this tier of townships in Sedgwick County. In general, the monitoring wells for the 2005–2014 period are relatively well distributed in the areas of groundwater use.

25S-01W: The average Q_{stable} value for the 2005–2014 period is 7,783 ac-ft/yr, 2.1% below the average reported water use for the period. The average R^2 value is 0.59 and is affected by the apparent noise in the water-level data. A two-year average of the data had a large impact on the

R^2 value (0.89) but a very small impact on Q_{stable} (7,791 ac-ft/yr, 2.0% below the average reported water use for 2005–2014).

25S-02W: The average Q_{stable} value for the 2005–2014 period is 11,915 ac-ft/yr, 0.6% below the average reported water use for the period. The average R^2 value is 0.69 and is affected by the apparent noise in the water-level data. A two-year average of the data had a large impact on the R^2 value (0.91) but a very small impact on Q_{stable} (11,920 ac-ft/yr, 0.6% below the average reported water use for 2005–2014).

25S-03W: The difference in the number of wells between the 1996–2014 and 2005–2014 analyses was small; six wells were measured continuously for 1996–2014 and seven for 2005–2014. The results of the analyses vary relatively little regardless of the type of data used in the analysis and the time period of the analysis. The Q_{stable} value for the average of all the analyses is 5,993 ac-ft/yr, 2.8% below the average reported water use. The average R^2 value is 0.64 and is affected by one value (2013) that is distinctly different from the others.

Figure III.C.13 displays the plots for the analyses of the continuously measured wells for 2005–2014 for the 25S-01W, -02W, and -03W units. For unit 25S-03W, the 2013 value, which was a year of high precipitation following a drought year, falls well above the best-fit line. Removal of the 2013 value reduces Q_{stable} to 5,389 ac-ft/yr (13% less than the average reported water use) and increases R^2 to 0.74.

The conclusions for the assessments of the three analyzed township-range units in township 25S in Sedgwick County vary little among the units. All three units generally appear to be developed for an average annual water use that is slightly above the sustainable level. Similar to many of the units in townships in Reno and Harvey counties, the units appear to be somewhat dependent on infrequent high inflow years to maintain the aquifer at near-sustainable levels. The three wettest years during 1996–2014 for Sedgwick County within GMD2 were 2005, 2008, and 2013 (fig. I.A.2). The greatest change from the previous year's precipitation occurred from 2012 to 2013; 2013 was the year with the most anomalously high water-level change, relative to the linear regression, for the most western of the units (-03W). However, 2005 was the most anomalous year (above the linear regression) for the two eastern units.

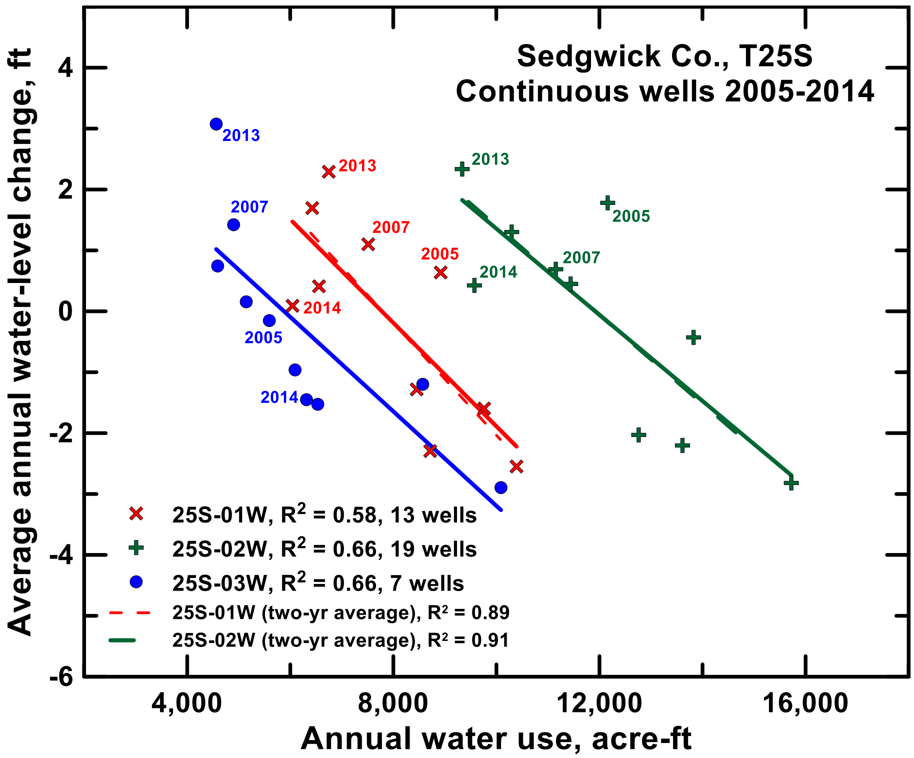

Figure III.C.13. Plots of annual water use versus average annual water-level change for the township-range units in Sedgwick County in GMD2 lying within T25S. The analyses for the 25S-01W, -02W, and -03W units use the 108, 158, and 126 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

b. Township 26S

There are portions of four township-range units for this tier of townships in Sedgwick County. Although there are 26 points of diversion with groundwater-based water rights in the 26S-01E unit, there are no monitoring wells. Thus, that area cannot be analyzed. In general, there were relatively few monitoring wells measured continuously in these township-range units, so the analysis was performed using the maximum wells for the 2005–2014 period.

26S-01W: The data from this township-range unit are very noisy, so we were unable to obtain statistically significant relationships working with the annual data or a two-year average. The failure to obtain statistically significant relationships is likely related to the large amount of non-irrigation pumping in the area (average annual irrigation pumping is 44% of total average annual pumping). An analysis of only the irrigation pumping shed little insight. We will examine this area further in our analysis of the Arkansas River Wichita and Maize defined areas.

26S-02W: The data from this township-range unit are noisy, but we were able to obtain statistically significant relationships. The average Q_{stable} value for the 2005–2014 period is 7,676 ac-ft/yr, 5.9% below the average reported water use for 2005–2014. The average R^2 value is 0.44 and is affected by the apparent noise in the water-level data. A two-year average of the data did not produce a statistically significant relationship. The likely reason for the low R^2 value is that the area has a large amount of non-irrigation pumping (average annual irrigation pumping is 54% of total average annual pumping). If the analysis is restricted to irrigation pumping, a reasonable relationship (R^2=0.72) is obtained. However, it is difficult to draw general conclusions. We will examine a portion of this area further in our analysis of the Maize defined area.

26S-03W: The average Q_{stable} value for the maximum wells measured in the 1996–2014 and the 2005–2014 periods is 1,114 ac-ft/yr, 2.8% below the average reported water use for 1996–2014. The average R^2 value is 0.61 and is affected by the apparent noise in the water-level data.

Figure III.C.14 displays the plots for the analyses of the maximum wells for 2005–2014 for the 26S-01W, -02W, and -03W units. Although the points for 2007 and 2013 fall well above the best-fit line for the -01W units, their removal did not produce a statistically significant relationship.

The conclusions for the assessments of the two analyzed township-range units with statistically significant relationships in township 26S in Sedgwick County vary somewhat between the units. For the 26S-02W unit, this part of the aquifer appears to be developed for an average water use that is somewhat above the sustainable level. For the 26S-03W unit, this part of the aquifer appears to be operating at an average annual water use that is slightly above the sustainable level. In both cases, the data are quite noisy.

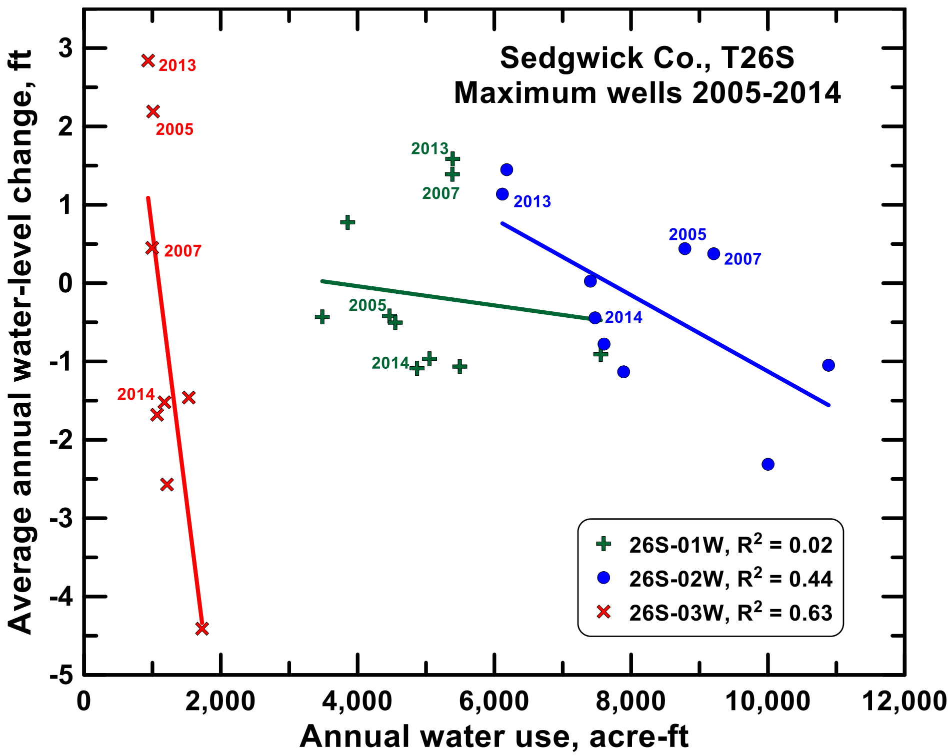

Figure III.C.14. Plots of annual water use versus average annual water-level change for the township-range units in Sedgwick County in GMD2 lying within T26S. The analyses for the 26S-01W, -02W, and -03W units use the 149, 131, and 20 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

c. Township 27S

There are small portions of two township-range units for this tier of townships in Sedgwick County in GMD2. There are no continuously measured wells in 27S-01W, but there are wells that are sporadically measured across the study period. There is no reported water use and there are no monitoring well measurements in 27S-02W, so we did not analyze conditions in that unit.

27S-01W: The data from this township-range unit are very noisy, and we were unable to obtain statistically significant relationships working with the annual data (relationship was close to being significant at the 0.05 level). We were able to increase the R^2 value by working with a two-year average of the 2005–2014 data, but the significance was lower than using the annual data as a result of the decrease in the number of points. The Q_{stable} values for the 2005–2014 maximum-well analysis are nearly the same for the annual and two-year average data sets so the value for the annual data set, which is closer to statistical significance ($R^2 = 0.35$, an R^2 of 0.40 is significant at the 0.05 level), is used (58.4 ac-ft/yr, 14.3% below the average reported water use for 2005–2014).

Figure III.C.15 displays the plots for the analyses of the maximum wells for 2005–2014 for the 27S-01W unit. The best-fit line resulting from the analysis of the two-year average of the data is essentially indistinguishable from that resulting from the analysis of the annual data. Note that all of the high precipitation years in 2005–2014 (2005, 2007, 2008, and 2013) fall above the best-fit line.

The conclusion for the assessment of the portions of the 27S-01W unit in Sedgwick County in GMD2 is that this part of the aquifer appears to be developed for an average annual water use that is above the sustainable level. However, the water use is relatively small and the correlation low. Thus, the analysis has more uncertainty than other townships in GMD2 with higher water use and R^2 values.

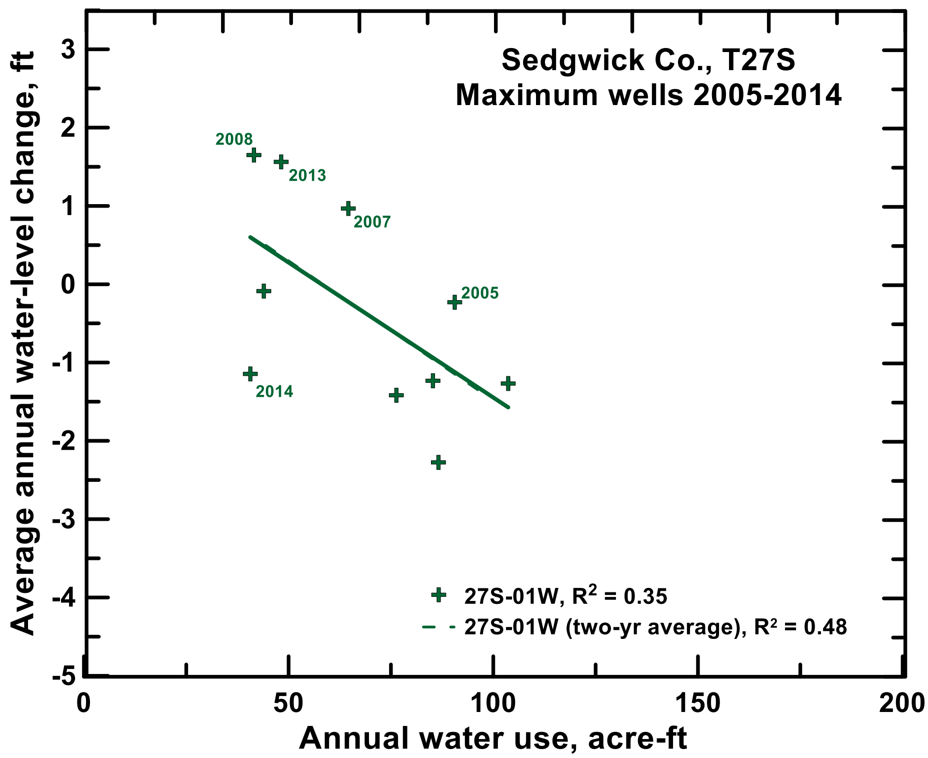

Figure III.C.15. Plots of annual water use versus average annual water-level change for the portions of the T27S-01W unit in Sedgwick County in GMD2. The analysis uses the 11 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit lines are given in the spreadsheet in Appendix A.

5. Summary of township results

Figures III.C.16a–c present the results of the sustainability assessment at the scale of the portions of individual townships lying within GMD2. The plotted results are the average sustainable annual water-use volumes deemed to be most appropriate for each township-range unit (fig. III.C.16a), the average sustainable annual water-use volumes deemed to be most appropriate for each township-range unit expressed in units of inches (acre-inches/acre) (fig. III.C.16b), and the percent reduction or increase in average annual water use that would be required to reach the sustainable level (fig. III.C.16c).

There are portions of 50 township-range units within GMD2. Six of the 50 units (T21S-01W, T22S-01W, T25S-05W, T26S-04W and -05W, and T27S-02W) had essentially no reported water-use data. One of the 50 units (T26S-01E) had reported water use (average annual use of 1,054 ac-ft for 1996–2014) but no monitoring well data. Three of the 50 units (T23S-05W, T23S-06W, and T26S-01W) did not have statistically significant relationships; we will examine those three areas in more detail as part of the assessment of the Arkansas River Hutchinson, Arkansas River Wichita, and Maize defined areas. Seventeen of the 50 units are heavily dependent on infrequent high inflow years to remain close to sustainable aquifer conditions. Figure III.C.17 shows the percent reductions in average water use that would be required to reach the sustainable level if those infrequent high inflow years are removed from the analysis.

The conclusions of the township-level assessment are the following:

a) Harvey County—Portions of nine township-range units lie within GMD2, eight of which had sufficient data for analysis. Other than T22S-02W, the aquifer in these units has an average annual water use that is somewhat above to very slightly below the sustainable level. However, three of the nine township-range units appear to be dependent on inflows produced by years of high precipitation following drought years (designated with asterisks on fig. III.C.16a). In the absence of those high inflow years, the average annual water use will be considerably above the sustainable level in those units (fig. III.C.17); the Little Arkansas River crosses two of those township-range units. The average annual water use in T22S-02W is considerably above (14%) the sustainable use, which may be reflective of poorer aquifer conditions in that unit. Only T24S-02W and -03W had average annual water use below the sustainable amount (indicated by the negative values in fig. III.C.16c). These units are within the area of the greatest past declines in groundwater levels in the Equus Beds (Hansen, 2007) but the water levels are now recovering primarily as a product of decreases in municipal pumping resulting from use of Cheney Reservoir for a portion of Wichita's water supply, as well as some effect of the Wichita Aquifer Storage and Recovery project. This recovery is likely the explanation for the higher sustainable than reported water use, i.e. the net inflow has not completely adjusted to the lower level of annual pumping. Statistically significant relationships were obtained for all of the analyzed units in Harvey County. The summation of the Q_{stable} values from the township-range units within Harvey County is within 0.03% of the Q_{stable} value calculated from the county-level assessment.

b) McPherson County—Portions of 12 township-range units lie within GMD2, 11 of which had sufficient data for analysis. In general, the aquifer in these units has an average annual water use that is much further above the sustainable level than in the other counties in GMD2. In terms of percentage of the average reported annual use, the distance above the sustainable level ranges from 3.5% in T18S-03W to 19.8% in T20S-04W. This is undoubtedly a reflection of lower natural recharge largely attributable to generally greater thicknesses of low permeability material between the land surface and the water table than in the other counties (see geologic cross sections in Williams and Lohman, 1949) and of the lack of significant stream-aquifer interactions in this portion of GMD2. One of the township-range units (T20S-01W designated by an asterisk on fig. III.C.16a) appears to be dependent on inflows produced by years of high precipitation following drought years; this is probably related to the shallower water table and smaller saturated thickness in this unit compared to most of the other portions of the HPA within GMD2. Statistically significant relationships were obtained for all of the analyzed units in McPherson County. The summation of the Q_{stable} values from the township-range units within McPherson County is within 4% of the Q_{stable} value calculated from the county-level assessment.

c) Reno County—Twenty township-range units lie within GMD2, 17 of which had sufficient data for analysis. In general, the aquifer in these units has an average annual water use that is very slightly to somewhat above the sustainable level. In terms of percentage of the average reported annual use, the maximum distance above the sustainable level was 7.8% in T22S-05W. As with Harvey County, a sizable number

(12—designated by asterisks on fig. III.C.16a) of the township-range units appear to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the average annual water use will be considerably above the sustainable level in those units (fig. III.C.17). The Arkansas or Little Arkansas rivers cross the majority of those units. Statistically significant relationships were obtained for all but two of the analyzed units in Reno County. A summation of the Q_{stable} values from the township-range units within Reno County cannot be compared with the Q_{stable} value calculated from the county-level assessment because the two unanalyzed township-range units had large amounts of annual reported water use.

d) Sedgwick County—Portions of nine township-range units lie within GMD2, seven of which had sufficient data for analysis. Other than the small portion of T27S-01W lying within GMD2, the aquifer in these units has an average annual water use that is very slightly to somewhat above the sustainable level. One of the township-range units (designated by an asterisk on fig. III.C.16a and crossed by the Arkansas River) appears to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the average annual use will be considerably above the sustainable level in that unit (fig. III.C.17). The average reported annual water use in T27S-01W is considerably above (14%) the sustainable use. However, the total annual reported use is quite small (average of 65 ac-ft/yr for 1996–2014) and has not increased over time. Statistically significant relationships were obtained for all but one of the analyzed units in Sedgwick County. A summation of the Q_{stable} values from the township-range units within Sedgwick County cannot be compared with the Q_{stable} value calculated from the county-level assessment because that unanalyzed township-range unit has a large amount of annual reported water use.

The overall conclusion is that, as with the county-level assessment, the aquifer in the portions of Harvey, Reno, and Sedgwick counties in GMD2 has an average annual water use that appears to be slightly above the sustainable level under current climatic conditions. The aquifer in the portion of McPherson County in GMD2 has an average water use that is further above the sustainable level.

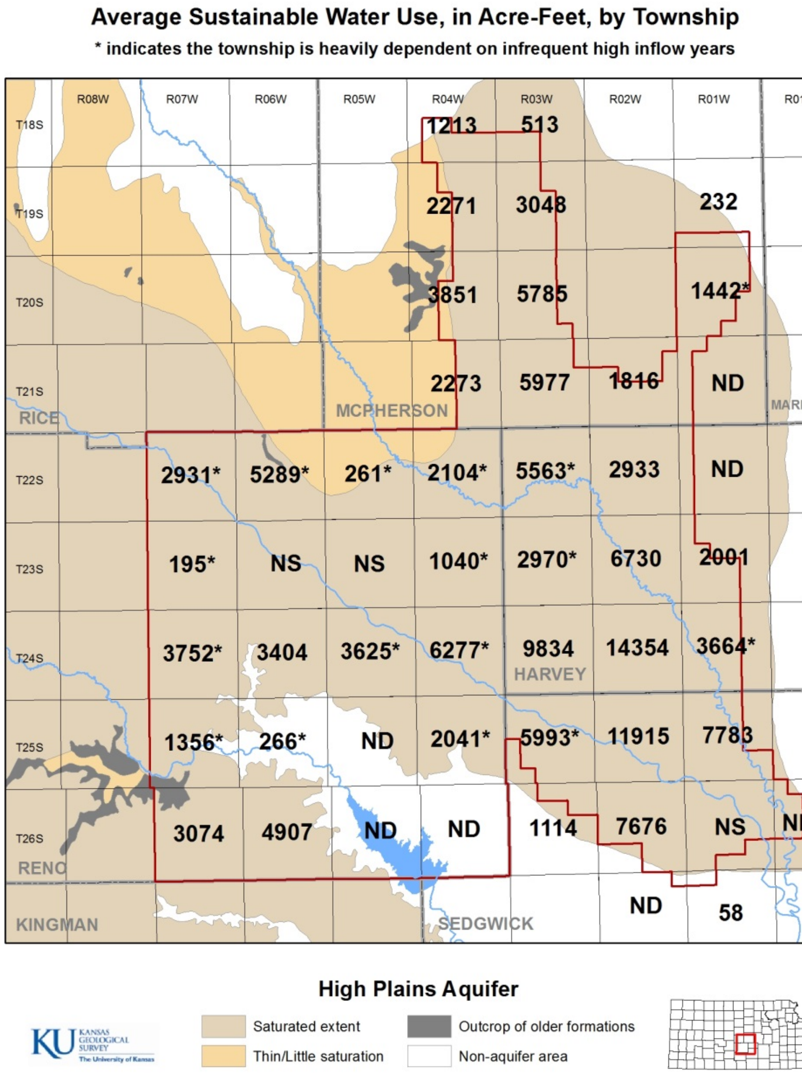

Figure III.C.16a. Results of the sustainability assessment at the scale of individual township-range units within GMD2. Plotted amounts are the sustainable average annual water-use volumes for each township-range unit. ND in a township indicates that the sustainability analysis could not be performed because of insufficient water-level or water-use data. NS in a township indicates that the analysis was so far below statistical significance that no valid result could be reported.

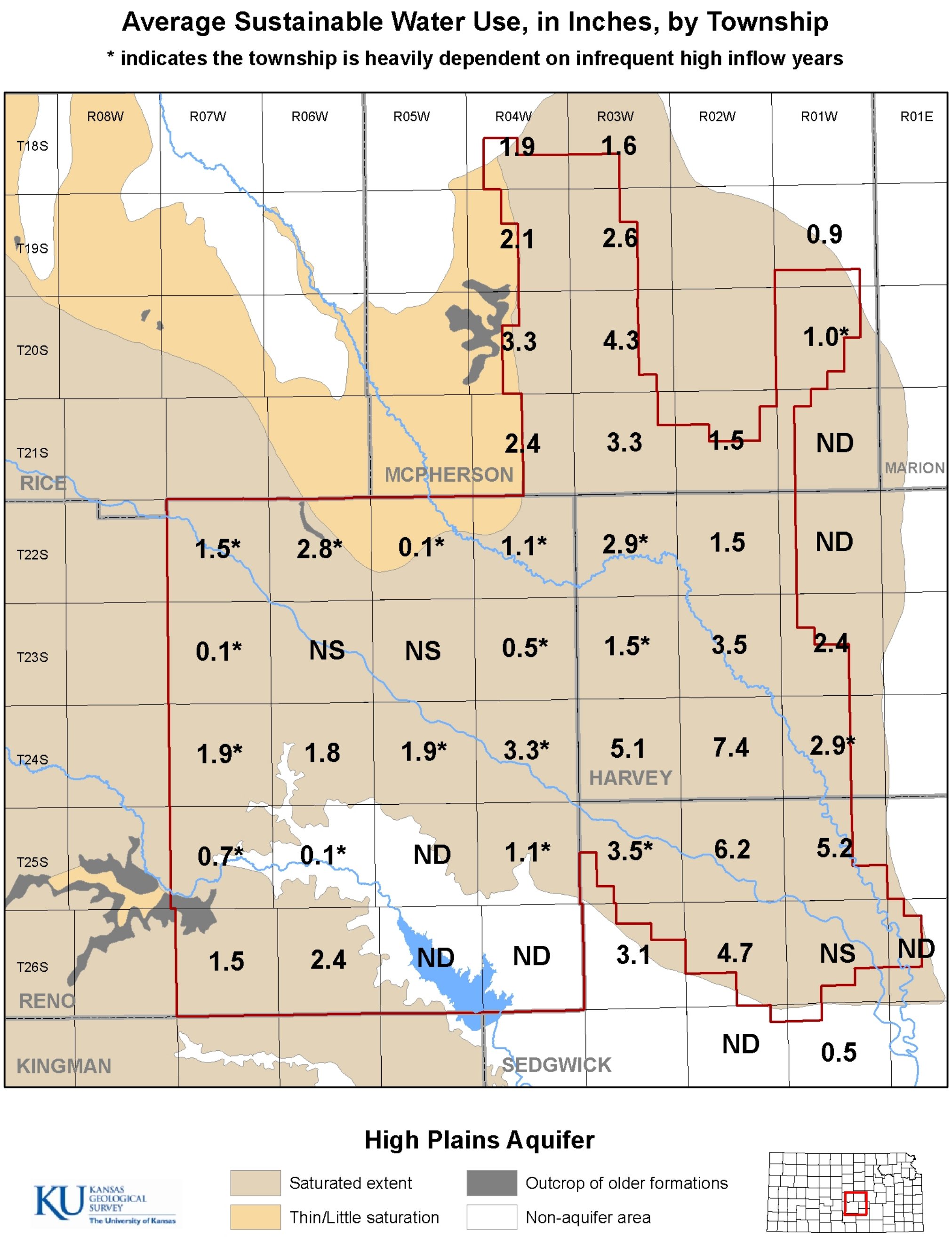

Figure III.C.16b. Results of the sustainability assessment at the scale of individual township-range units within GMD2. Plotted amounts are the sustainable average annual water-use volumes for each township-range unit expressed in units of inches (acre-inches/acre). ND in a township indicates that the sustainability analysis could not be performed because of insufficient water-level or water-use data. NS in a township indicates that the analysis was so far below statistical significance that no valid result could be reported.

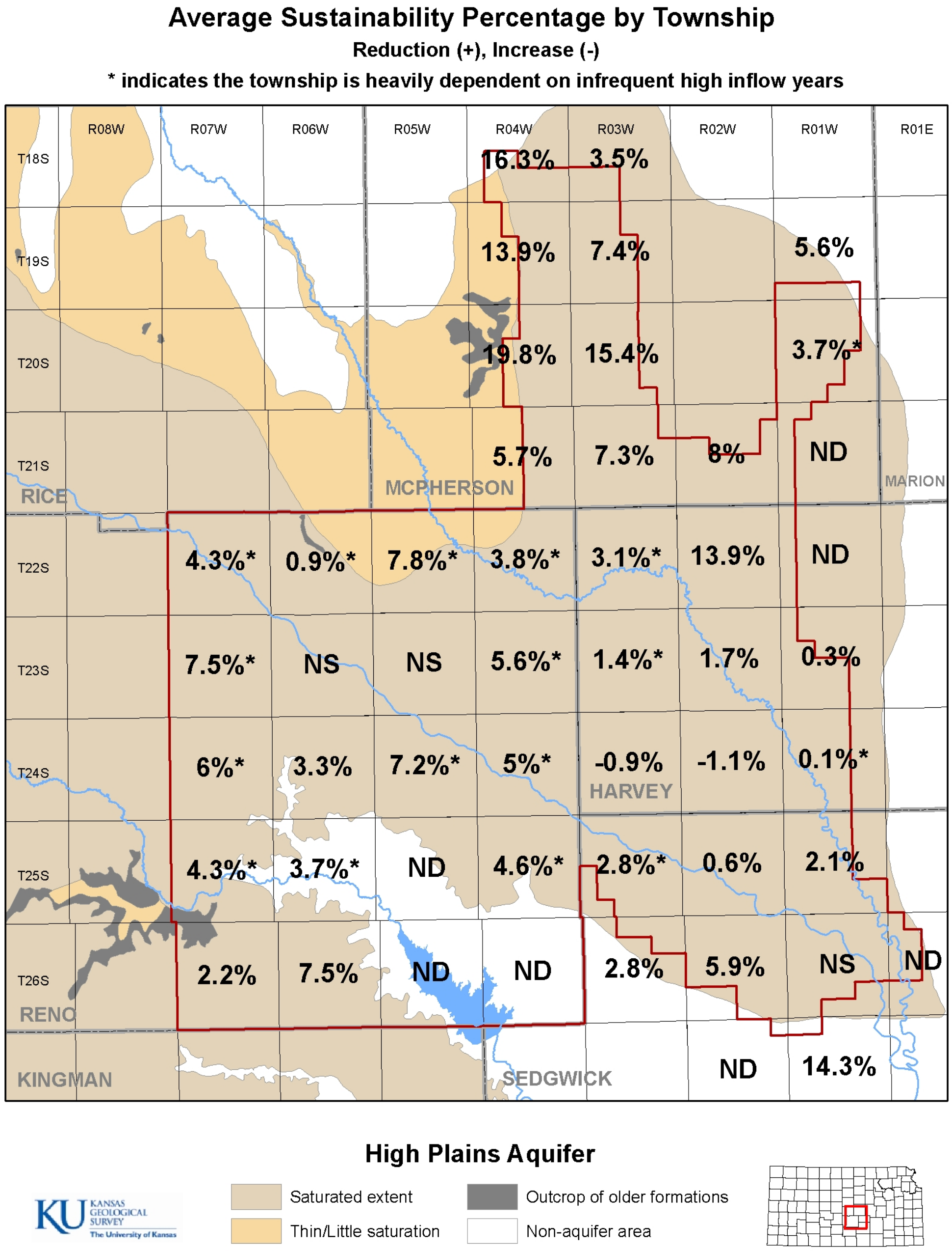

Figure III.C.16c. Results of the sustainability assessment at the scale of individual township-range units within GMD2. Plotted values are the percent reductions (given as positive numbers) or increases (given as negative numbers) in average annual water use that would be needed to reach the sustainable average annual water use for each township-range unit. ND indicates that the sustainability analysis could not be performed for that township because of insufficient water-level or water-use data. NS indicates that the analysis was so far below statistical significance that no valid result could be reported for that township.

Average Sustainability Percentage, without High Inflows, by Township

Reduction (+), Increase (-)

*** indicates the township is heavily dependent on infrequent high inflow years**

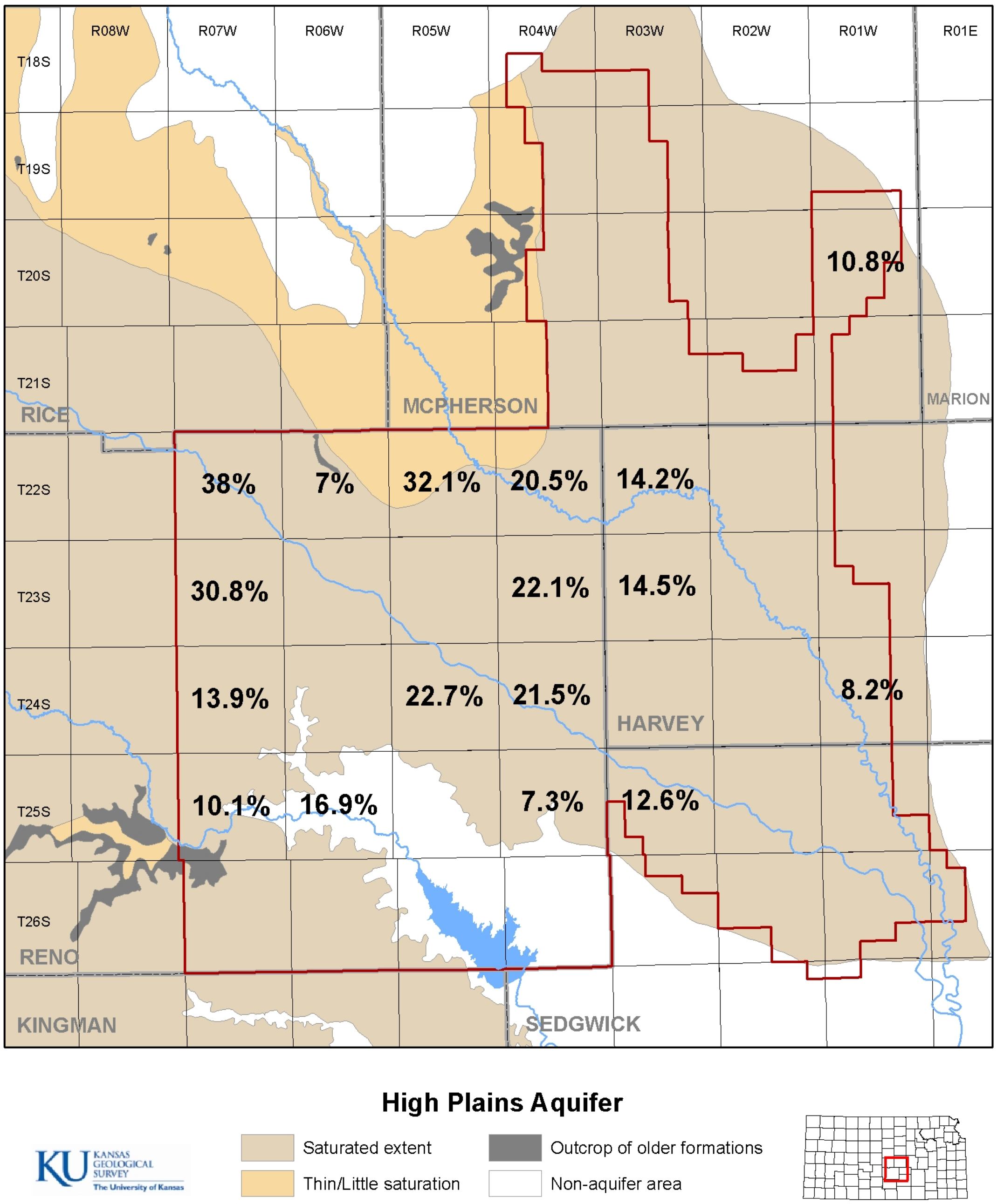

Figure III.C.17. Percent reductions (given as positive numbers) in average annual water use that would be needed to reach the sustainable average annual water use if the infrequent high inflow years are removed from the analysis.

6. Western expansion area in Reno County

GMD2 has petitioned to expand the boundaries of the district in four areas: the western side of the district in Reno County between GMD5 and GMD2, the gap in the two prongs of the district in McPherson County, the gap between the eastern boundary of Reno County and the district area in Sedgwick County, and an area on the eastern side of the district in Sedgwick County. Except for the western expansion area in Reno County, there are very few water-level monitoring wells within the expansion areas. Thus, only the western area was assessed for sustainability on the township level. The sustainability assessments for the other expansion areas, as well as the western side of GMD2, were examined as part of the defined areas assessments.

The western expansion area in Reno County comprises a column of five townships (22S to 26S) in R08W (although township 22S-08W in the expansion area only includes sections 5–36 that are in Reno County; sections 1–4 in that township are in Rice County). Sustainability assessments could only be completed for three of the five townships because two of the townships (23S-08W and 26S-08W) had no reported water use during 1996–2011. Water use in 22S-08W was zero in 1996 and only 1.0 ac-ft in 1997; the water use then increased in 1998 to 181 ac-ft and then to a range of 200–738 ac-ft for 1999–2014. The water use in 24S-08W ranged between 24.4 ac-ft and 46.5 ac-ft during 1996–2006, then increased to 110–118 ac-ft in 2007–2008, followed by a further increase to 251–439 ac-ft during 2009–2014.

The number of water-level monitoring wells appropriate for the sustainability analysis is relatively small in the three townships with adequate water-use data. To increase the number of wells used in the assessment, data for wells that are located just outside the township boundaries were used along with data for those wells within the townships. Thus, data from some wells were used for two different townships.

22S-08W: Given the trend in water use discussed above, the analysis was performed using the 2005–2014 data. The average Q_{stable} value for 2005–2014 is 462 ac-ft/yr, 3.7% below the average reported water use for 2005–2014. The average R^2 value is 0.60 and is significantly affected by two values (2007 and 2013) that are distinctly different from the others.

24S-08W: Given the trend in water use discussed above, none of the correlations between water-level change and reported water use are statistically significant. As a result of the large change in annual water use in 2007 and again in 2009, the analysis was repeated for the 2007–2014 and 2009–2014 maximum well data sets. The average Q_{stable} value for 2007–2014 is 282 ac-ft/yr, within 0.1% of the average reported water use for 2007–2014. The R^2 value is 0.53 (statistically significant at the 0.05 level) and is heavily affected by data noise, which was likely produced by the trend in water use and the small number of monitoring wells. A statistically significant relationship could not be produced using the 2009–2014 dataset.

25S-08W: The data for the 1996–2014 period were relatively noisy, so the focus was on the 2005–2014 period. The average Q_{stable} value for 2005–2014 is 1,486 ac-ft/yr, 2.8% below the average reported water use for 2005–2014. The average R^2 value is 0.62 and is substantially affected by three values (2006, 2007, and 2013) that are distinctly different from the others.

Figure III.C.18 displays the plots for the maximum-well analysis for 2005–2014 for the 22S-08W, 24S-08W, and 25S-08W units. For unit 22S-08W, the 2007 and 2013 values, which were years of high precipitation immediately following drought years, are well above the best-fit line. Removal of these two values reduces Q_{stable} to 380 ac-ft/yr (21% less than the average reported water use for 2005–2014) and increases R^2 to 0.96. For the 25S-08W unit, the 2007 and 2013 values are again well above the best-fit line, while the 2006 value, which is possibly the result of late-season pumping, falls well below the best-fit line. Removal of these three values reduces Q_{stable} to 1,434 ac-ft/yr (6.2% less than the average reported water use) and increases R^2 to 0.95.

The conclusions of the assessment of the three analyzed township-range units in R08W in the western expansion area in Reno County vary among the units. For the 22S-08W unit, this part of the aquifer appears to be currently developed for an average annual water use that is somewhat above the sustainable level. However, the system appears to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average annual water use that is much further above (21% for the 2005–2014 maximum well analysis) the sustainable level. For the 24S-08W unit, this part of the aquifer appears to be operating at an average annual water use that is close to the sustainable level. However, the trend in water use and data noise make it difficult to reach a conclusive assessment of conditions in this township-range unit. For the 25S-08W unit, this part of the aquifer appears to be developed for an average annual water use that is again somewhat above the sustainable level. However, the system appears to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the system is operating at an average annual water use that is further above (6.2% for the 2005–2014 maximum well analysis) the sustainable level. Expanding the monitoring well network in these township-range units is recommended to obtain more confidence in the assessment of conditions in these areas.

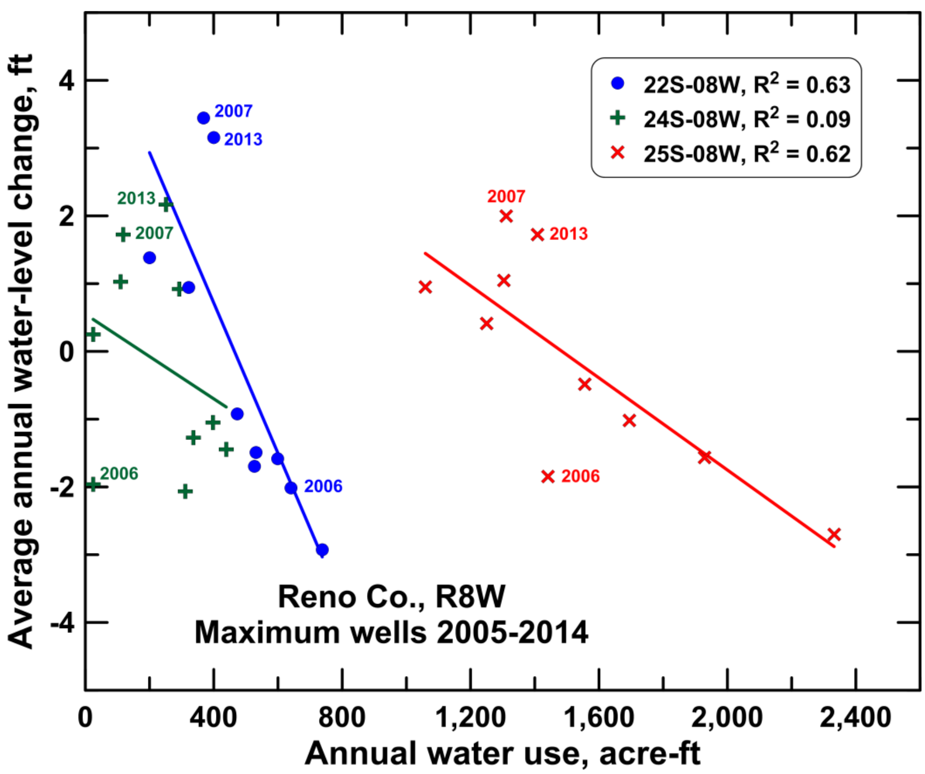

Figure III.C.18. Plots of annual water use versus average annual water-level change for the township-range units in Reno County in the proposed western expansion area lying within R8W. The analyses for the 22S-08W, 24S-08W, and 25S-08W units use the 22, 29, and 42 points of diversion with groundwater-based water rights, respectively, that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit line are given in the spreadsheet in Appendix A.

7. Comparison with authorized quantities

Figure III.C.19 presents a comparison of the sustainability assessment results with the authorized quantities for each of the townships in GMD2 and those in the western expansion area in Reno County. In all but three townships (T22S-06W, T22S-08W, and T26S-07W), the average annual water use is less than 70% of the authorized annual quantity. In no case is the annual average water use within 15% of the authorized quantity. Q_{stable} is less than the authorized quantity in every township in which a sustainability assessment could be performed.

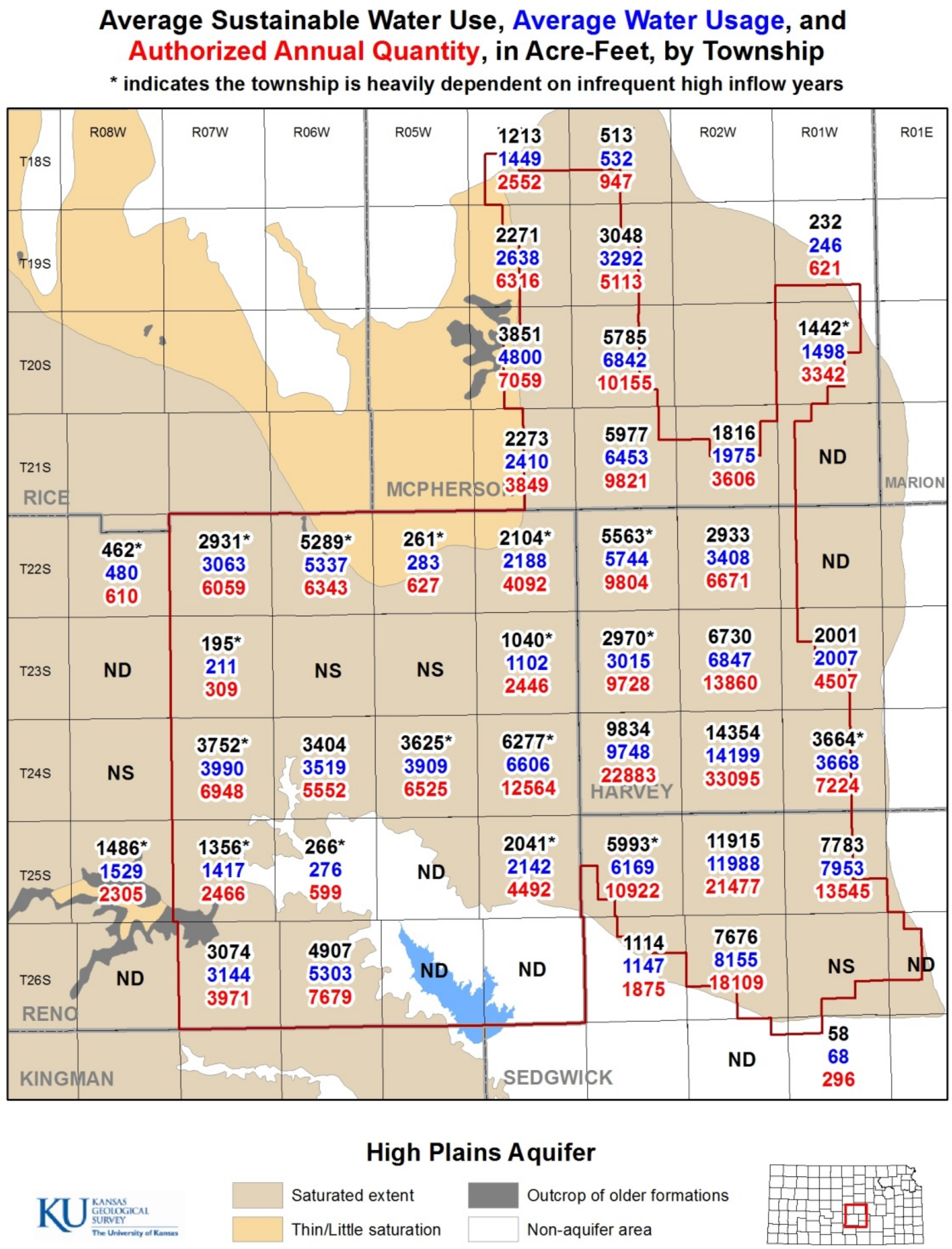

Figure III.C.19. Comparison of the average sustainable water use (black numbers), the average annual water use (blue), and the authorized annual quantity (red) at the scale of individual township-range units within GMD2 and the western expansion area in Reno County. ND in a township indicates that the sustainability analysis could not be performed because of insufficient water-level or water-use data. NS in a township indicates that the analysis was so far below statistical significance that no valid result could be reported.

D. Defined Area Assessment

Figure III.D.1a is a map of the 45 areas defined by GMD2 staff (henceforth, defined areas). The results of the defined area assessment are presented in Appendices A (spreadsheet) and B (plots). The defined areas include the four areas that GMD2 has proposed in its petition to expand the boundaries of the district. In general, the results for the defined areas are consistent with the results for the townships in which they are located. The focus here will be on the three areas for which statistically significant results could not be obtained at the township level and on the six areas along the eastern boundary of GMD2 (highlighted areas on Figure III.D.1b). These areas will be discussed in alphabetical order in the following section. The three values labeled on the county- and township-level plots will also be labeled on the defined area plots for comparative purposes, but the x- and y-axes ranges will vary.

GMD2 Defined Areas

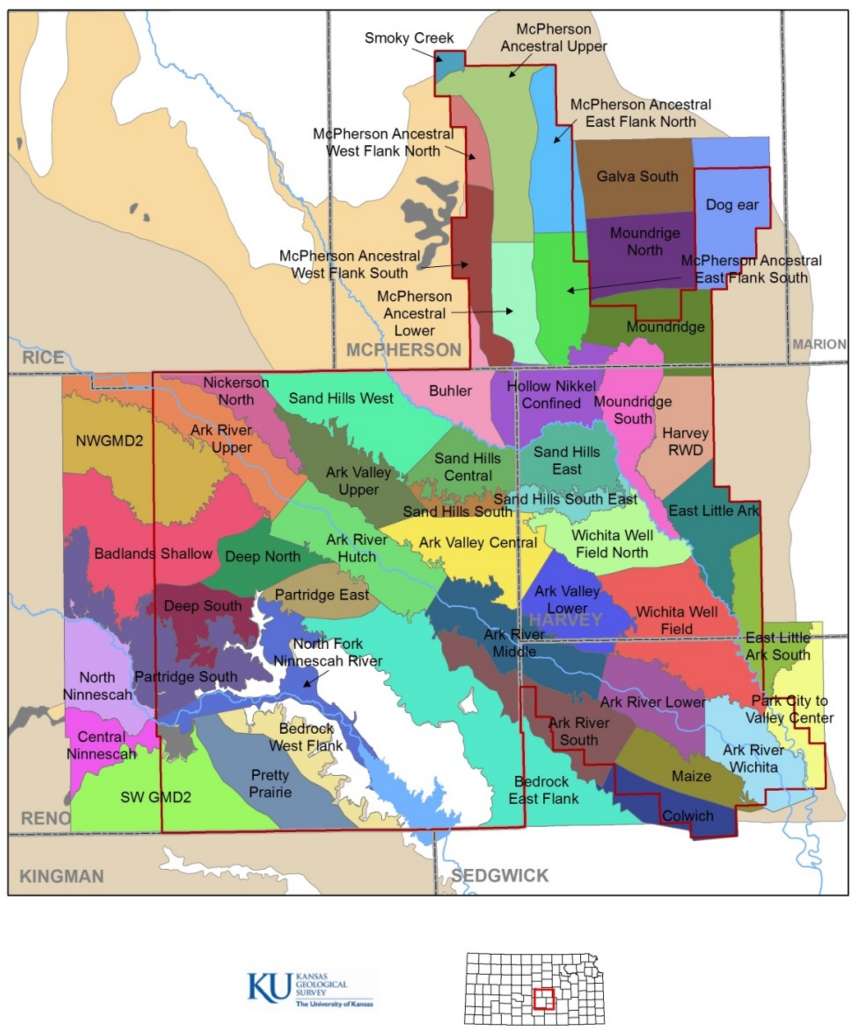

Figure III.D.1a. Map of the GMD2 defined areas.

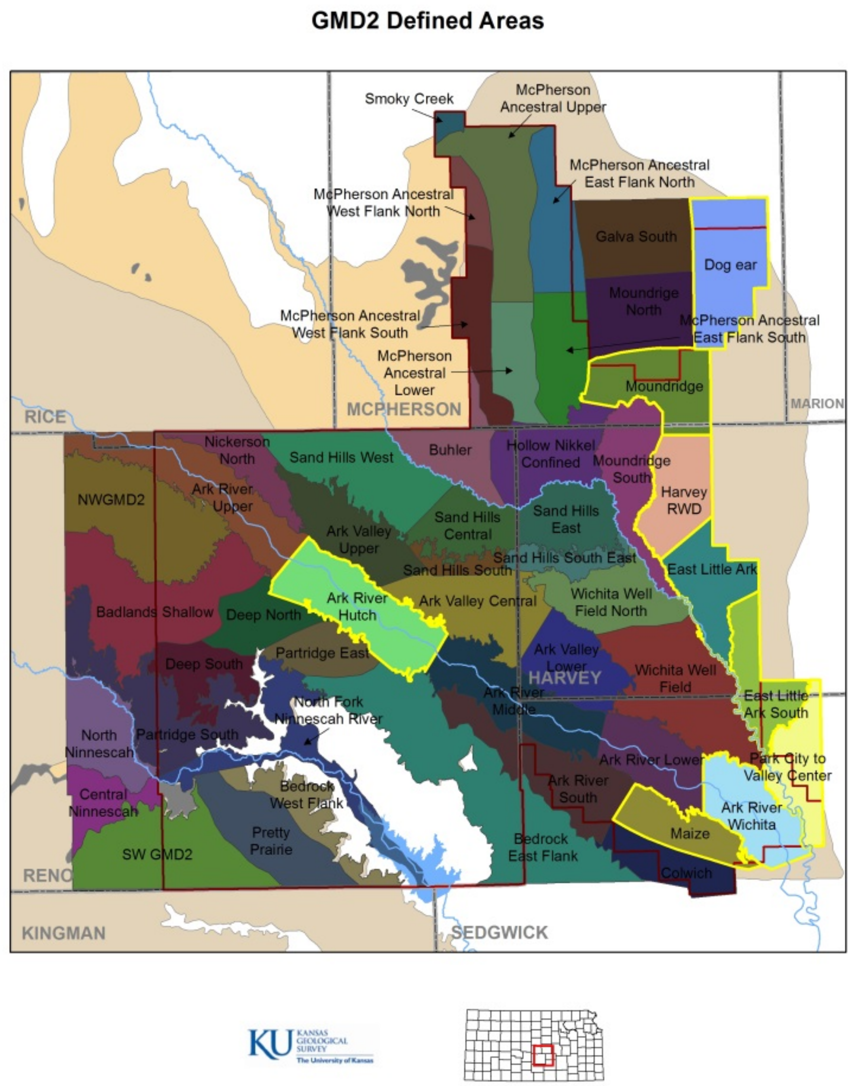

Figure III.D.1b. Map of the GMD2 defined areas with areas discussed in the report highlighted.

1. Analysis of defined areas

This section discusses the nine defined areas highlighted on fig. III.D.1b. These areas are either those for which statistically significant results could not be obtained from the township analysis (Arkansas River Hutchinson, Arkansas River Wichita, and Maize) or those along the eastern boundary of GMD2 (Dog Ear, Moundridge, Harvey RWD, East Little Arkansas, East Little Arkansas South, and Park City to Valley Center).

a) Arkansas River Hutchinson: None of the datasets produced statistically significant results for this area (fig. III.D.2a). Industrial use was the major water use from 1996 to 2014 (industrial use varied from 5,203 to 13,088 ac-ft/yr, irrigation use varied from 1,533 to 5,322 ac-ft/yr, municipal use varied from 54 to 196 ac-ft/yr), but the monitoring wells appear to be primarily located in the area of irrigation pumping. Thus, there is little correlation between annual industrial water use and the average water-level change (fig. III.D.2b) and the slope of the regression is positive rather than negative as expected for the water-level change versus water use relationship. A much stronger relationship, albeit still not statistically significant, is observed for the maximum well 2005–2014 analysis with the annual irrigation use (fig. III.D.2c). The Q_{stable} value is 3,181 ac-ft/yr, 8.1% below the average irrigation use for that period; the R^2 value is 0.31 and is heavily affected by two values (2007 and 2013) that are distinctly different from the others. Removal of the 2007 and 2013 points results in a Q_{stable} value of 2,123 ac-ft/yr, 40% below the average irrigation use for that period; the R^2 value increases to 0.89. Those two years, 2007 and 2013, were years of high precipitation immediately following drought years. As with many of the previous assessments, the drought appears to have lowered water levels such that the aquifer could accept more net inflow in those years than in a typical year.

The conclusion for the assessment of the Arkansas River Hutchinson defined area is that the part of the area that is dominated by irrigation pumping appears to be developed for an average annual water use that is above the sustainable level. However, this portion of the defined area appears to be heavily dependent on infrequent high inflow years to maintain the aquifer reasonably close to sustainable levels. The lack of monitoring wells in the portion of the defined area dominated by industrial pumping prevents estimation of Q_{stable} for that portion of the area.

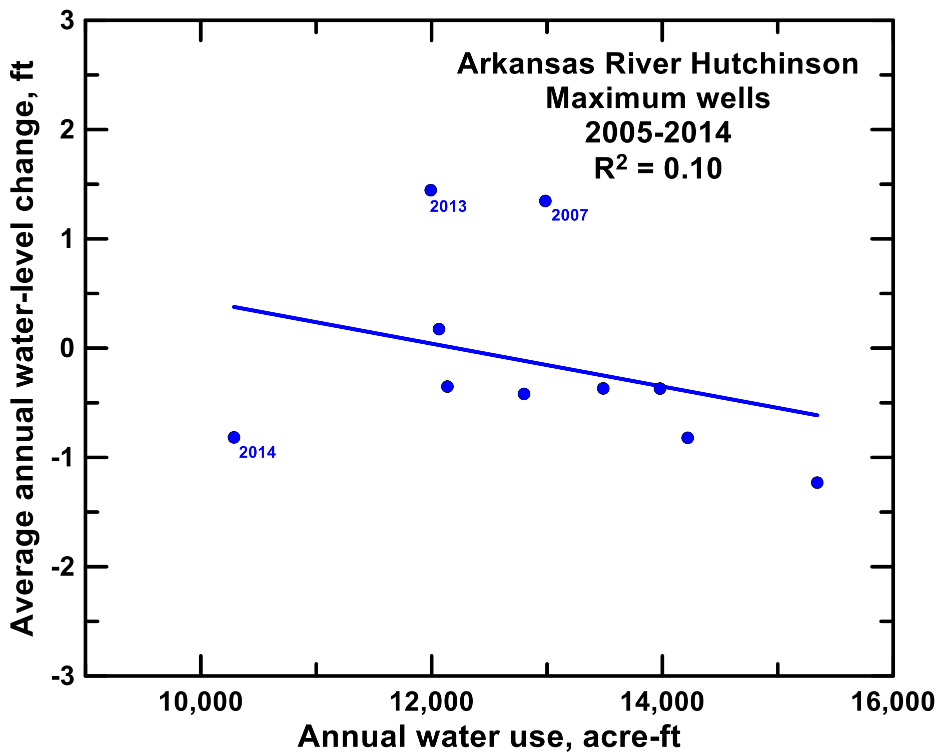

Figure III.D.2a. Plot of annual water use versus average annual water-level change for the Arkansas River Hutchinson defined area. The analysis uses the 185 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year).

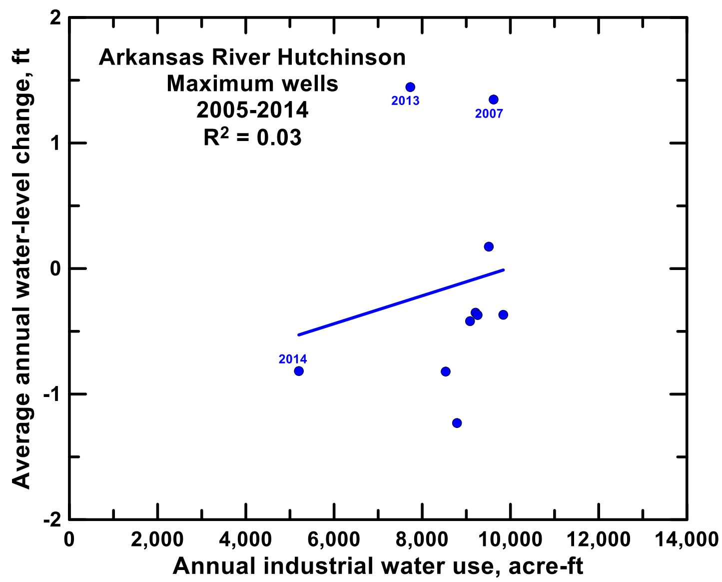

Figure III.D.2b. Plot of annual industrial water use versus average annual water-level change for the Arkansas River Hutchinson defined area.

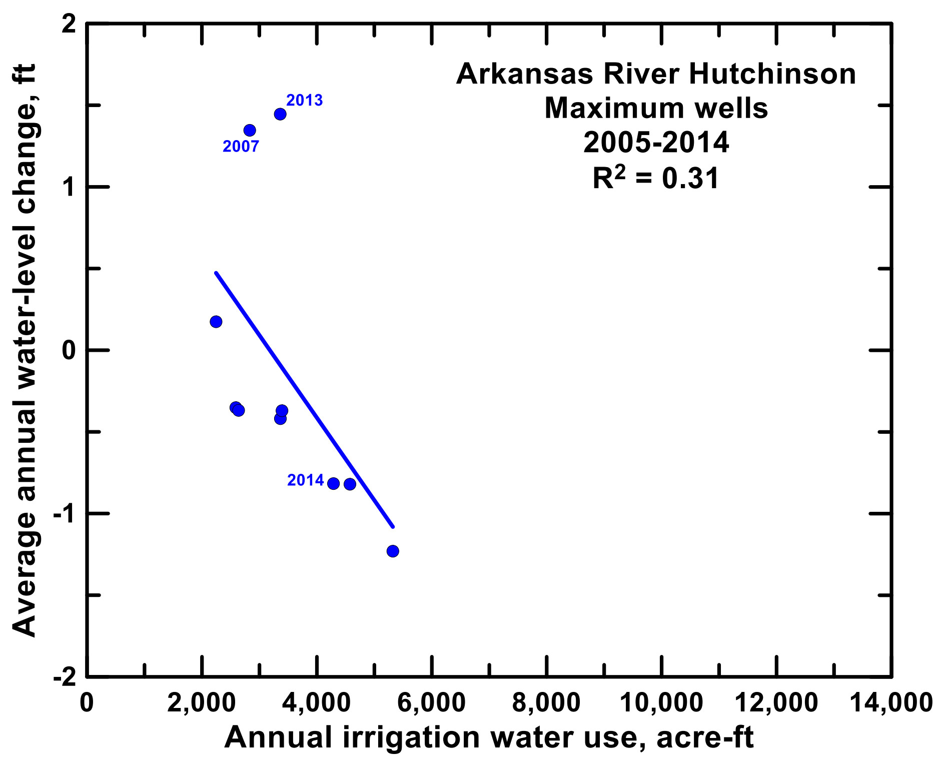

Figure III.D.2c. Plot of annual irrigation water use versus average annual water-level change for the Arkansas River Hutchinson defined area. The equation for the best-fit line is given in the spreadsheet in Appendix A.

b) Arkansas River Wichita: The datasets produced results that were either slightly above (1996–2014) or slightly below (2005–2014) statistical significance at the 0.05 level. In all cases, the R^2 values are low (fig. III.D.3a). Irrigation was the major water use for all but one year (2010) from 1996 to 2014 (irrigation use varied from 2,117 to 4,553 ac-ft/yr); the other major use was the "other" category, which refers to dewatering and other non-municipal and non-industrial uses (excluding 2010, all other water use categories varied from 142 to 3,099 ac-ft/yr for 1996 to 2014; the total spiked to 5,017 ac-ft/yr in 2010). The low R^2 values likely are a result of the lack of sensitivity of the measured water-level changes to non-irrigation water use, as there is little correlation between annual non-irrigation water use and the annual average water-level change (fig. III.D.3b); removal of 2010 has little effect on the relationship. The water-level changes display a much greater sensitivity to irrigation pumping as shown in fig. III.D.3c for the maximum well analysis for 2005–2014. The Q_{stable} value is 2,979 ac-ft/yr, 4.5% below the average irrigation use for that period; the R^2 value is 0.67 and is affected by two values (2007 and 2013) that are distinctly different from the others. Removal of the 2007 and 2013 points results in a Q_{stable} value of 2,624 ac-ft/yr, 16% below the average irrigation use for that period; the R^2 value increases to 0.78. Those two years, 2007 and 2013, were years of high precipitation immediately following drought years. As with many of the previous assessments, the drought appears to have lowered water levels such that the aquifer could accept more net inflow in those years than in a typical year.

The conclusion for the assessment of the Arkansas River Wichita defined area is that the part of the area that is dominated by irrigation pumping appears to be developed for an average annual water use that is somewhat above the sustainable level. However, this portion of the defined area appears to be dependent on infrequent high inflow years to maintain the aquifer at near-sustainable levels. The lack of monitoring wells in the portion of the defined area dominated by non-irrigation water use prevents estimation of Q_{stable} for that portion of the area.

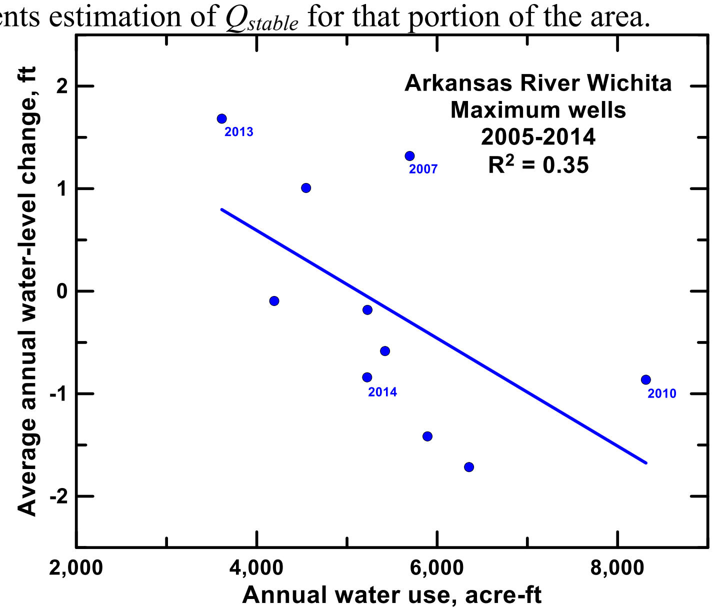

Figure III.D.3a. Plot of annual water use versus average annual water-level change for the Arkansas River Wichita defined area. The analysis uses the 108 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The equation for the best-fit line is given in the spreadsheet in Appendix A.

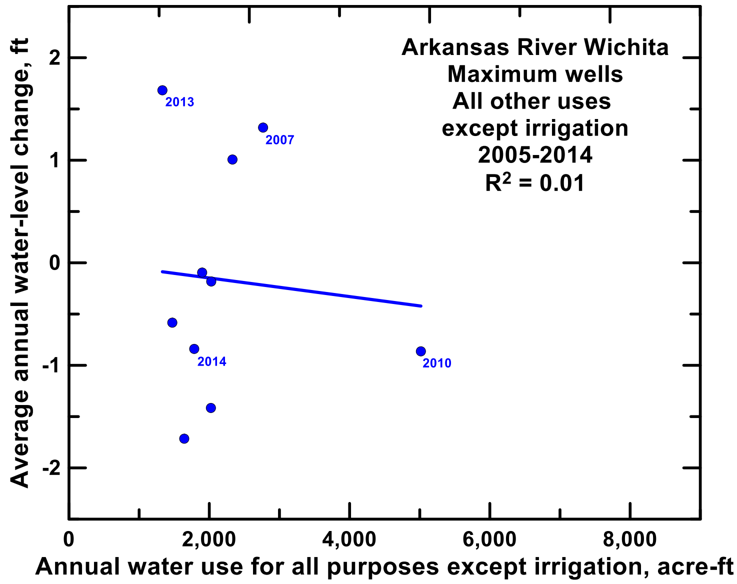

Figure III.D.3b. Plot of annual water use for all purposes except irrigation versus average annual water-level change for the Arkansas River Wichita defined area.

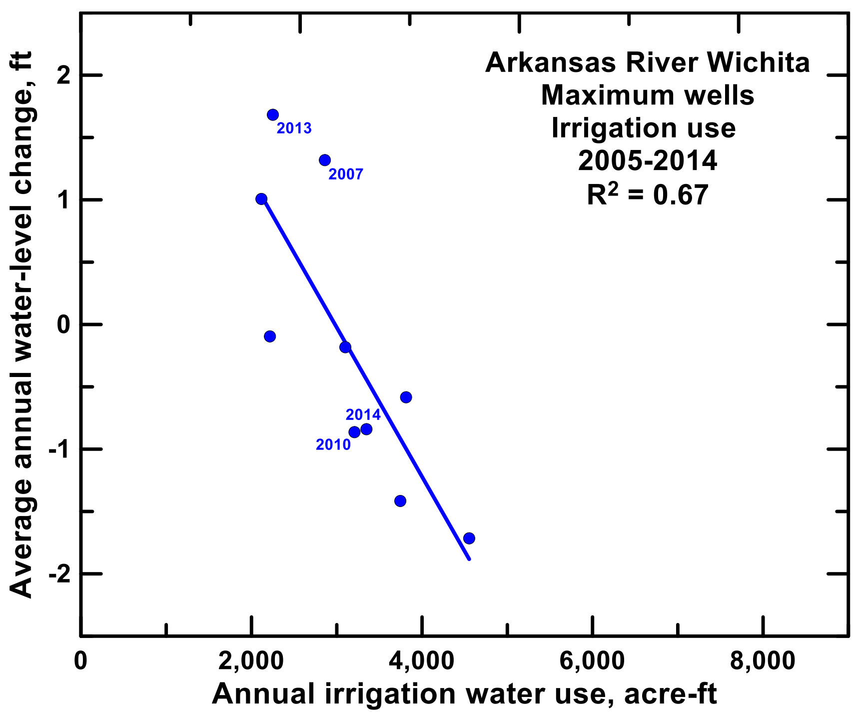

Figure III.D.3c. Plot of annual irrigation water use versus average annual water-level change for the Arkansas River Wichita defined area. The equation for the best-fit line is given in the spreadsheet in Appendix A.

c) Dog Ear: There were few wells measured continuously in this area; two wells from 1996 to 2014 and three wells from 2005 to 2014. More wells were measured sporadically during both periods, so the focus here was on the 2005–2014 maximum well analysis. The monitoring wells for the maximum well analysis appear to be located in the areas of concentrated groundwater use. The Q_{stable} value for the 2005–2014 period is 1,682 ac-ft/yr, 4.1% below the average reported water use for the period; the R^2 value is 0.73 and is affected by one value (2007) that is distinctly different from the other points. Similar results were obtained using the maximum well dataset for the 1996–2014 period.

Figure III.D.4 displays the plot for the analysis of the maximum wells for 2005–2014 for this area. The 2007 value, which was a year of high precipitation following a drought year, is well above the best-fit line. As with many of the previous assessments, the drought appears to have lowered water levels such that the aquifer could accept more net inflow that year than in a typical year. Removal of the 2007 value reduces Q_{stable} to 1,579 ac-ft/yr (10% less than the average reported water use) and increases R^2 to 0.86.

The conclusion of the assessment of the Dog Ear defined area is that this part of the aquifer appears to be developed for an average annual water use that is somewhat above the sustainable level. However, this area appears to be dependent on infrequent high inflow years to maintain the aquifer at near-sustainable levels.

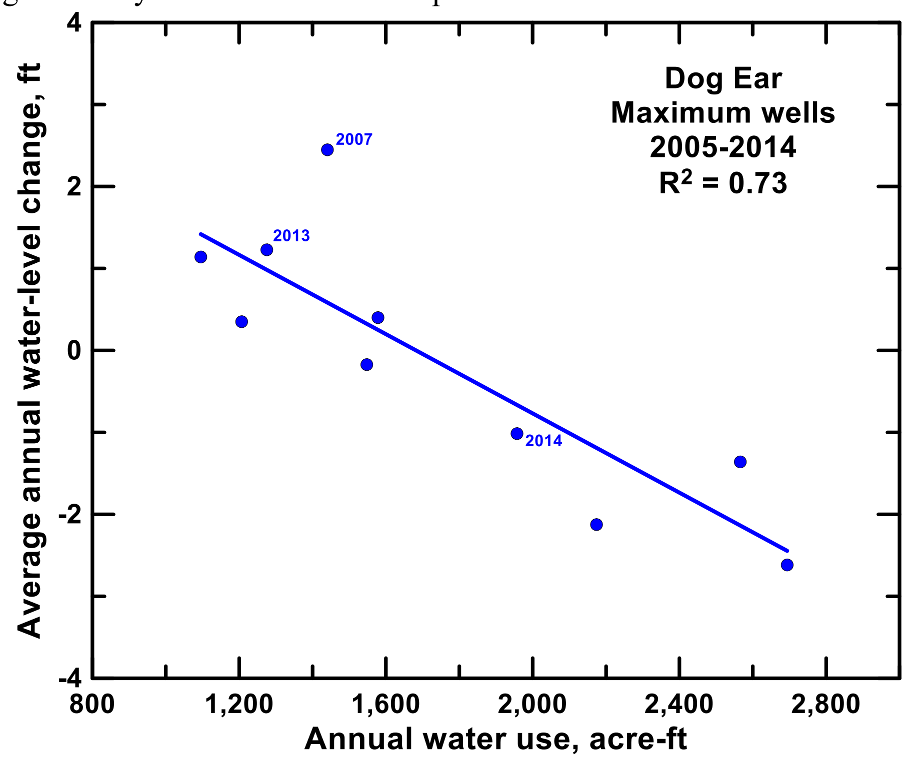

Figure III.D.4. Plot of annual water use versus average annual water-level change for the Dog Ear defined area. The analysis uses the 91 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The equation for the best-fit line is given in the spreadsheet in Appendix A.

d) East Little Arkansas River: There was only one continuously monitored well from 1996 to 2014, so the 2005–2014 dataset was used. The average Q_{stable} value for the 2005–2014 period is 3,842 ac-ft/yr, 0.4% below the average reported water use for 2005–2014. The average R^2 value is 0.68 and is affected by noise in the water-level data.

Figure III.D.5 displays the plot for the analysis of the continuous wells for 2005–2014 for the East Little Arkansas River defined area. Note that all of the high precipitation years in 2005–2014 (2005, 2007, 2008, and 2013) fall above the best-fit line.

The conclusion for the assessment of the East Little Arkansas River defined area is that this part of the aquifer appears to be developed for an average annual water use that is close to the sustainable level.

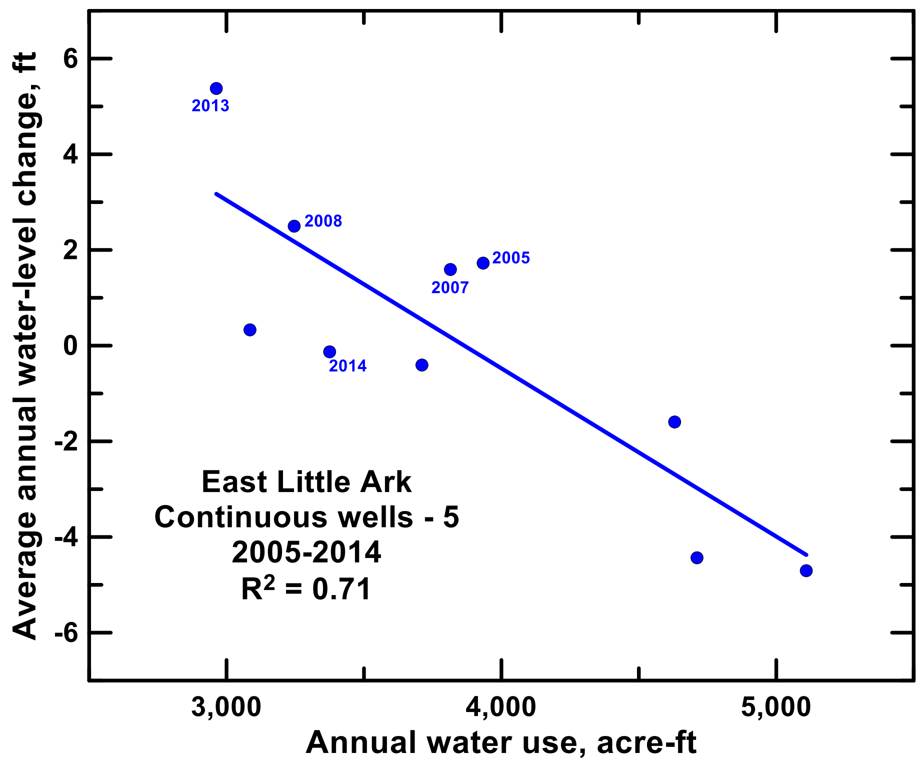

Figure III.D.5. Plot of annual water use versus average annual water-level change for the East Little Arkansas River defined area. The analysis uses the 92 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The equation for the best-fit line is given in the spreadsheet in Appendix A.

e) East Little Arkansas River South: No wells were measured continuously from 1996 to 2014 and only three wells from 2005 to 2014. More wells were measured sporadically in the 2005–2014 period, so the analysis was applied to the 2005–2014 maximum well dataset. The Q_{stable} value for the 2005–2014 period is 1,744 ac-ft/yr, 4.5% below the average reported water use for the period. The relationship, however, is not significant at the 0.05 level (R^2=0.30) because of one data point (2013) that is distinctly different from the others. Municipal water use, which was 33% of the average total water use for the area, may also be introducing noise into the relationship.

Figure III.D.6 displays the plot for the analysis of the maximum wells for 2005–2014 for the East Little Arkansas River South defined area. The 2013 point falls far above the best-fit line. If that point is removed, R^2 increases to 0.64 and the relationship is significant at the 0.01 level; the Q_{stable} value for the 2005–2014 period decreases to 1,483 ac-ft/yr, 19% below the average reported water use. The difference in precipitation between the drought year of 2012 and the very wet year of 2013 was the greatest of any years during 1996–2014. This difference, along with the location of this defined area along the Little Arkansas River and in an area of a relatively shallow water table, likely caused the large water-level rise shown in the figure.

The conclusion for the assessment of the East Little Arkansas River South defined area is that this part of the aquifer appears to be developed for an average water use that is somewhat above the sustainable level. However, this area appears to be heavily dependent on infrequent high inflow years to maintain the aquifer at near-sustainable levels.

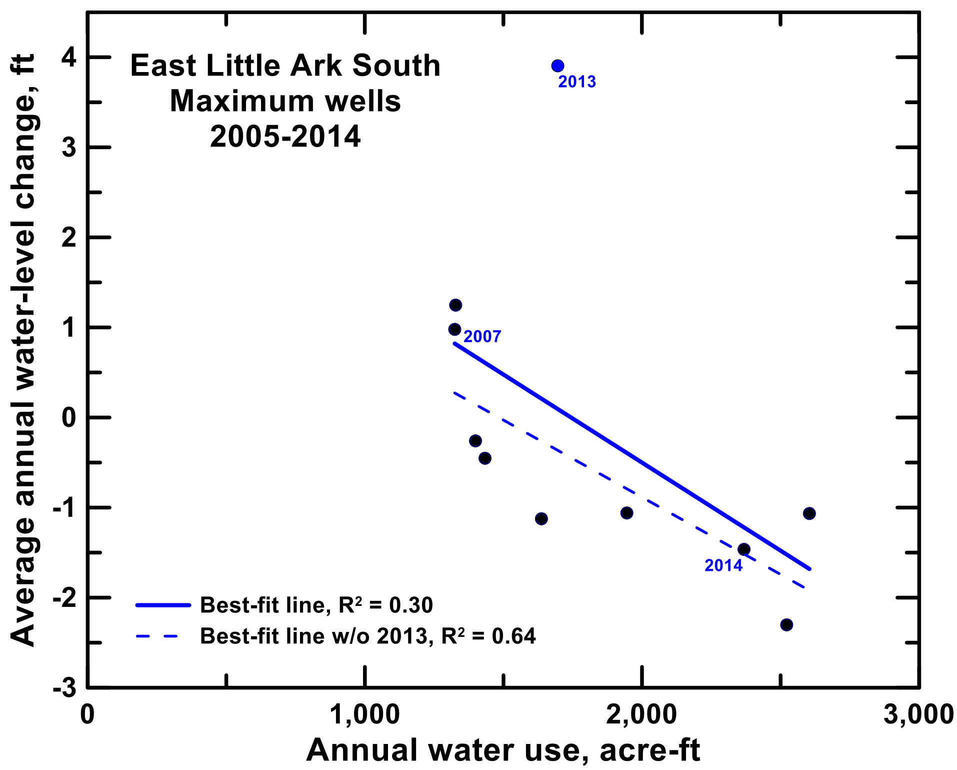

Figure III.D.6. Plots of annual water use versus average annual water-level change for the East Little Arkansas River South defined area. The analysis uses the 53 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit lines are given in the spreadsheet in Appendix A.

f) Harvey RWD: No wells were measured continuously from 1996 to 2014 and only two wells from 2005 to 2014. More wells were measured sporadically in the 2005–2014 period and those wells appeared to be distributed in the areas of concentrated groundwater use. As a result, the analysis was applied to the 2005–2014 maximum well dataset. The Q_{stable} value for the 2005–2014 maximum well dataset is 2,073 ac-ft/yr, 13.5% below the average reported water use for the period. The R^2 value is 0.41, an indication of considerable noise in the dataset, most likely as a result of the small number of monitoring wells and one value (2006) that is distinctly different from the others.

Figure III.D.6 displays the plot for the analysis of the maximum wells for 2005–2014 for the Harvey RWD defined area. Efforts to reduce the noise by applying a two-year average led to only slight improvements in R^2 and a small change in Q_{stable}. The 2006 value, which is possibly the result of late-season pumping, falls well below the best-fit line. Removal of that value yielded a Q_{stable} value of 2,302 ac-ft/yr, just 4.0% below the average reported water use for the period; the R^2 value increased to 0.62.

The conclusion for the assessment of the Harvey RWD defined area is that this part of the aquifer appears to be developed for an average water use that is somewhat above the sustainable level.

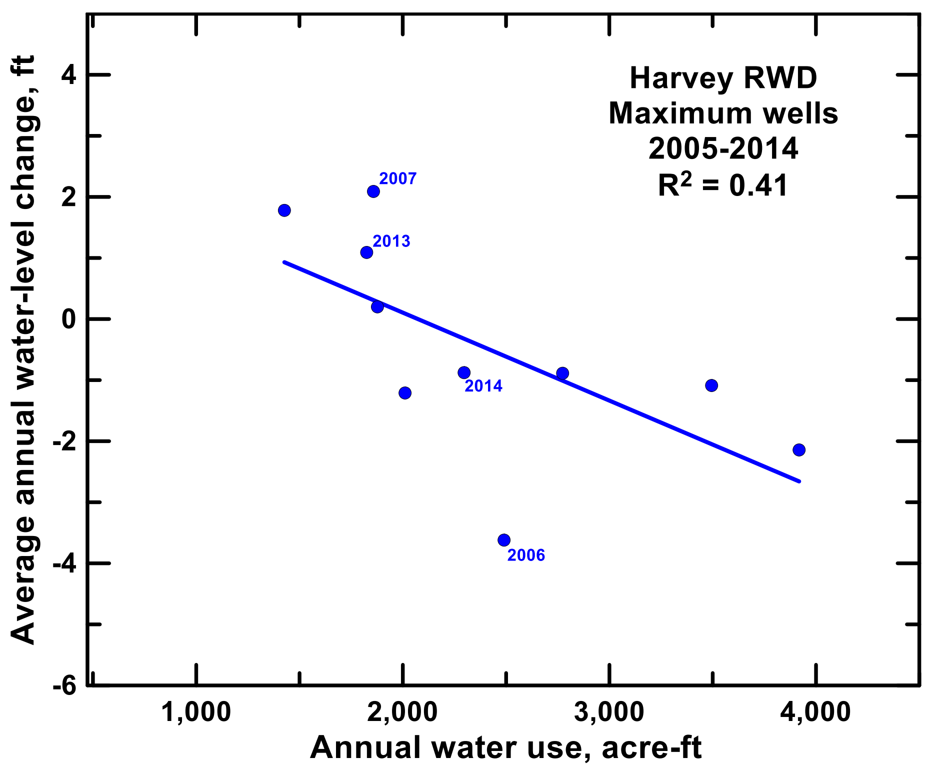

Figure III.D.7. Plot of annual water use versus average annual water-level change for the Harvey RWD defined area. The analysis uses the 59 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The equation for the best-fit line is given in the spreadsheet in Appendix A.

g) Maize: None of the datasets produced statistically significant results for this area (fig. III.D.8a). Industrial use was the major water use for 11 of the 19 years from 1996 to 2014. Industrial use varied from 1,609 to 4,984 ac-ft/yr over this period, while irrigation use varied from 2,126 to 4,291 ac-ft/yr (average total water use of 6,718 ac-ft/yr; industrial and irrigation use accounted for between 83% and 100% of total water use for 1996 to 2014). The monitoring wells are primarily located in the area of irrigation pumping, so there is little correlation between annual industrial water use and the average water-level change or between annual non-irrigation use (includes industrial, municipal, other, and recreation uses) and the average water-level change (fig. III.D.8b and III.D.8c). A much stronger relationship is observed for the maximum well 1996–2014 analysis with the annual irrigation use (fig. III.D.2d). The Q_{stable} value is 2,996 ac-ft/yr, 2.3% below the average irrigation use for that period; the R^2 value is 0.37 and is significantly affected by one value (2013) that is distinctly different from the others. Removal of that value results in a Q_{stable} value of 2,917 ac-ft/yr, 4.8% below the average irrigation use; the R^2 value increases to 0.52. That year, 2013, was a year of high precipitation following two drought years. As with many of the previous assessments, the drought appears to have lowered water levels such that the aquifer could accept more net inflow in that year than in a typical year.

The conclusion for the assessment of the Maize defined area is that the part of the aquifer that is dominated by irrigation pumping appears to be developed for an average annual water use that is slightly above the sustainable level. The lack of monitoring wells in the portion of the defined area dominated by non-irrigation pumping prevents estimation of Q_{stable} for that portion of the area. However, even in the portions of the defined area that appear to be dominated by irrigation pumping, the noise in the relationship, likely introduced by non-irrigation pumping, makes it difficult to reach a conclusive assessment of conditions for that area.

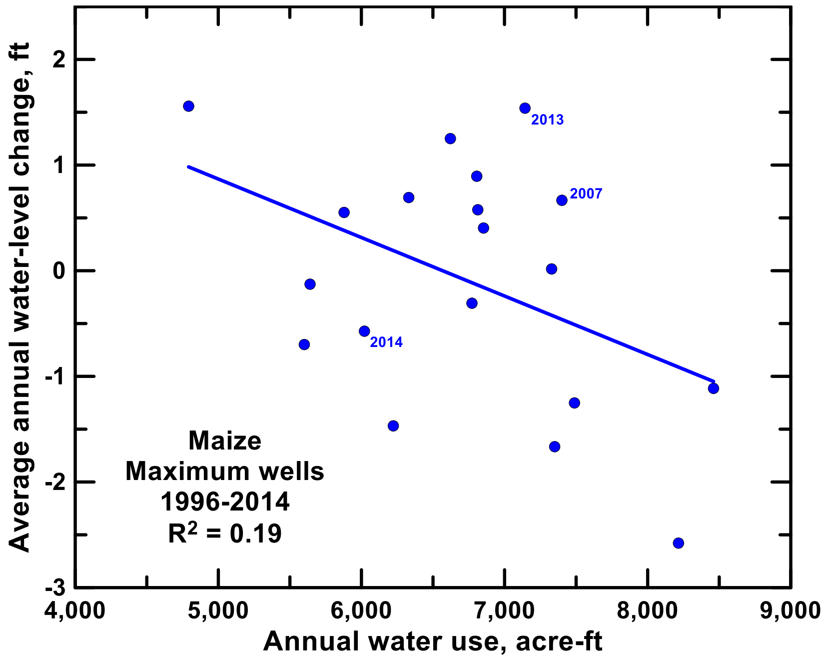

Figure III.D.8a. Plot of annual water use versus average annual water-level change for the Maize defined area. The analysis uses the 139 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The equation for the best-fit line is given in the spreadsheet in Appendix A.

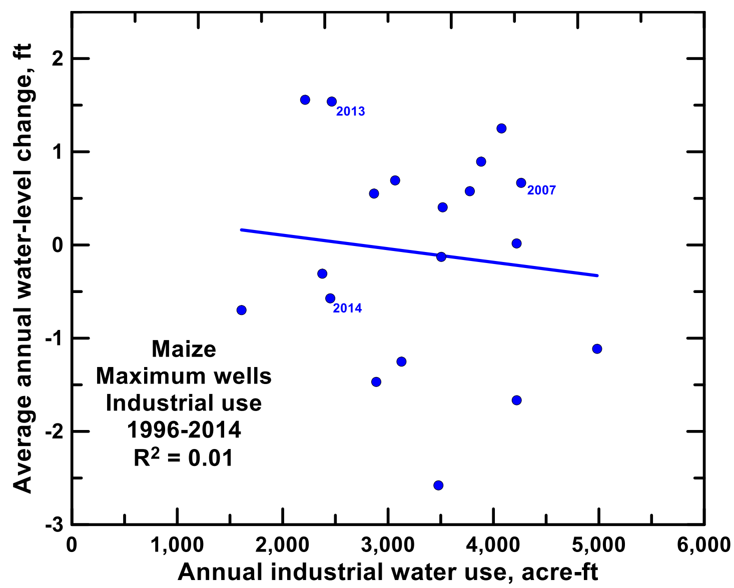

Figure III.D.8b. Plot of annual industrial water use versus average annual water-level change for the Maize defined area.

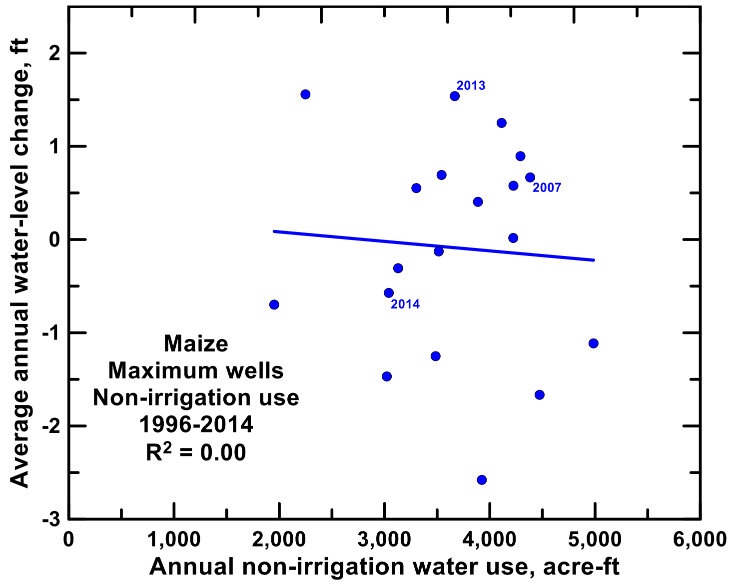

Figure III.D.8c. Plot of annual non-irrigation water use versus average annual water-level change for the Maize defined area.

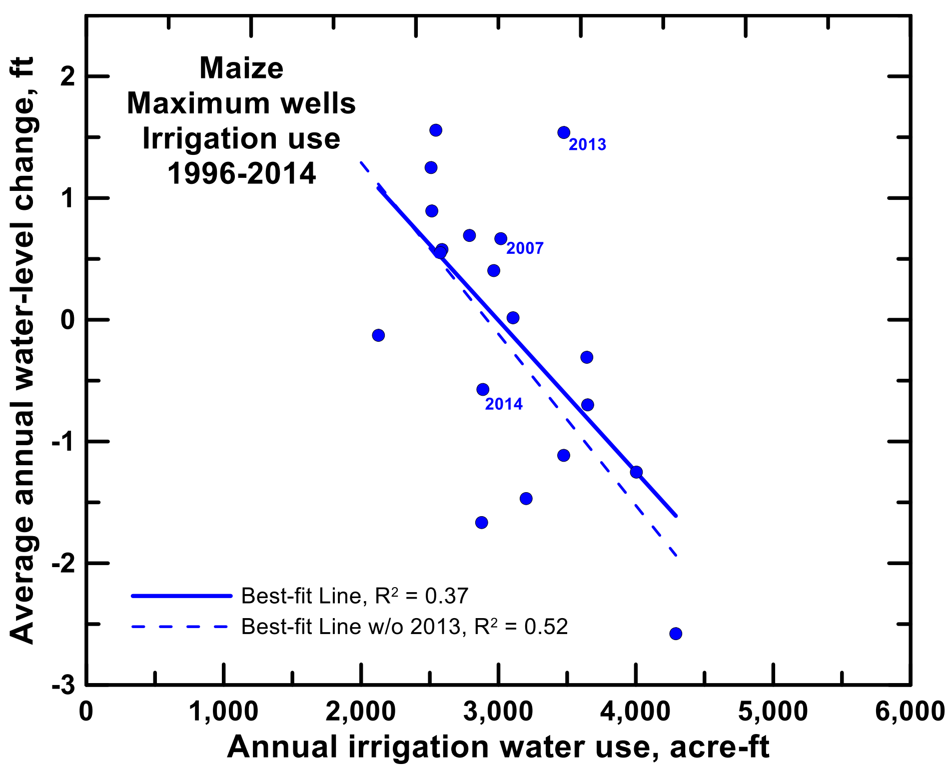

Figure III.D.8d. Plot of annual irrigation water use versus average annual water-level change for the Maize defined area. The equations for the best-fit lines are given in the spreadsheet in Appendix A.

h) Moundridge: There are few monitoring wells in this area; only two measured continuously from 1996 to 2014 and three from 2005 to 2014. The distribution of the 2005–2014 wells is more consistent with the distribution of pumping wells so the focus was on that time period. The results of the continuous and maximum well analyses are the same (datasets were the same). The Q_{stable} value is 1,453 ac-ft/yr, 8.5% below the average reported water use; the R^2 value is 0.87.

Figure III.D.9 displays the plot for the analysis of the continuous wells for 2005–2014 for the Moundridge defined area. All of the points fall close to the best-fit line, consistent with the results for most of the township-scale analyses for McPherson County.

The conclusion of the assessment of the Moundridge defined area is that this part of the aquifer appears to be developed for an average water use that is above the sustainable level.

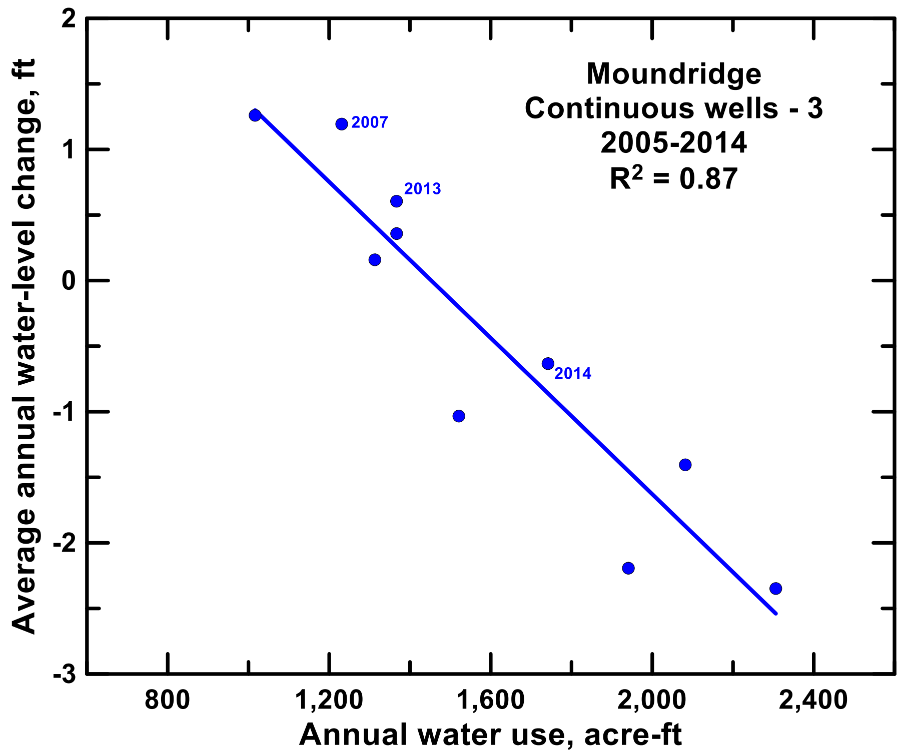

Figure III.D.9. Plot of annual water use versus average annual water-level change for the Moundridge defined area. The analysis uses the 73 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The equation for the best-fit line is given in the spreadsheet in Appendix A.

i) Park City to Valley Center: There are few monitoring wells in this area; only one well was measured continuously from 1996 to 2014 and only two from 2005 to 2014. More wells were measured sporadically during the 2005–2014 period, so the focus was on the maximum well analysis for 2005–2014. However, there are no monitoring wells in the southeastern portions of the area. The Q_{stable} value for the 2005–2014 period is 2,354 ac-ft/yr, 2.5% below the average reported water use for the period; the

R^2 value is 0.57. Similar results were obtained using the continuous well dataset and for the 1996–2014 period. The lower correlation for this area is likely related to the small number of monitoring wells and the lack of monitoring wells in the southeastern portions of the area. The water use is dominated by municipal water use, which ranged from 68% to 74% of the average total water use for 1996–2014 and 2005–2014, respectively (industrial use was insignificant); municipal use appears to be reasonably correlated with the water-level change (R^2 value is 0.51 for the 2005–2014 period).

Figure III.D.10 displays the plot for the analysis of the maximum wells for 2005–2014 for the Park City to Valley Center defined area. Note the considerable degree of noise in the data, most likely introduced by the small number of monitoring wells. A two-year average was applied in an effort to reduce the noise. The resulting Q_{stable} is 2,364 ac-ft/yr (2.1% less than the average reported water use) and the R^2 increases to 0.77.

The conclusion of the assessment of the Park City to Valley Center defined area is that this part of the aquifer appears to be developed for an average water use that is slightly below the sustainable level. However, the lack of wells in the southeastern portion of the area makes it difficult to characterize conditions there.

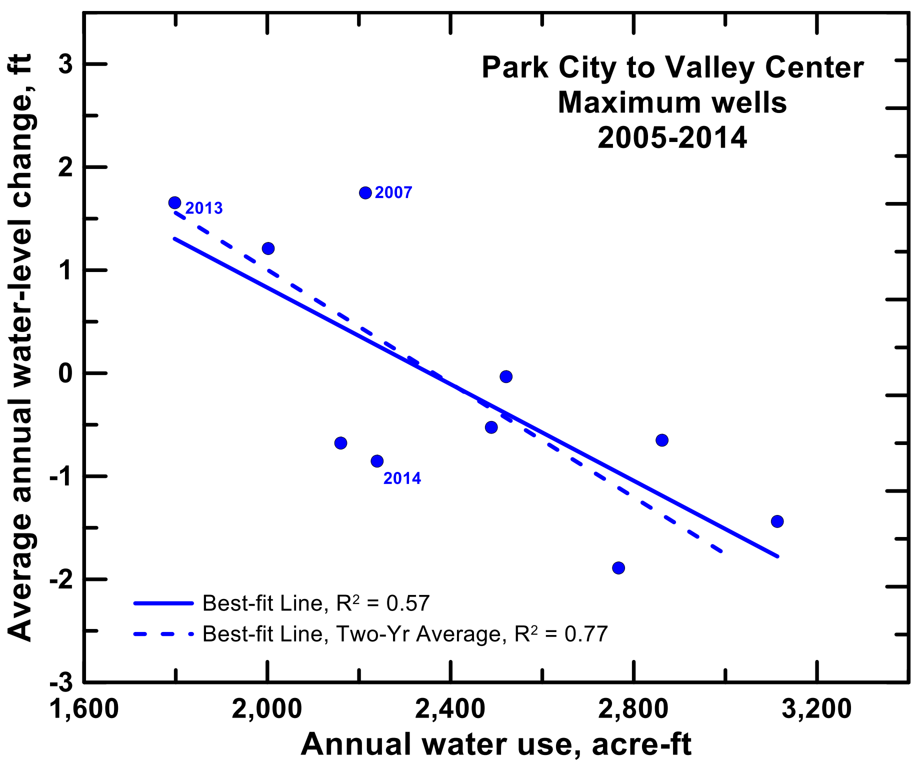

Figure III.D.10. Plots of annual water use versus average annual water-level change for the Park City to Valley Center defined area. The analysis uses the 66 points of diversion with groundwater-based water rights that reported water use for at least one year during this period (total varied slightly from year to year). The equations for the best-fit lines are given in the spreadsheet in Appendix A.

2. Presentation of results and comparison with authorized quantities

Figure III.D.11 presents a comparison of the sustainability assessment results with the authorized quantities for each of the defined areas in GMD2. As with the township-scale analysis, the average annual water use is considerably less than the authorized annual quantity. In only two of the defined areas (Pretty Prairie and Bedrock West Flank) is the annual average water use within 30% of the authorized quantity. Q_{stable} is less than the authorized quantity in every defined area in which a sustainability assessment could be performed.

Average Sustainable Water Use, Average Water Usage, and Authorized Annual Quantity, in Acre-Feet, by GMD2 Defined Area

* indicates the area is heavily dependent on infrequent high inflow years

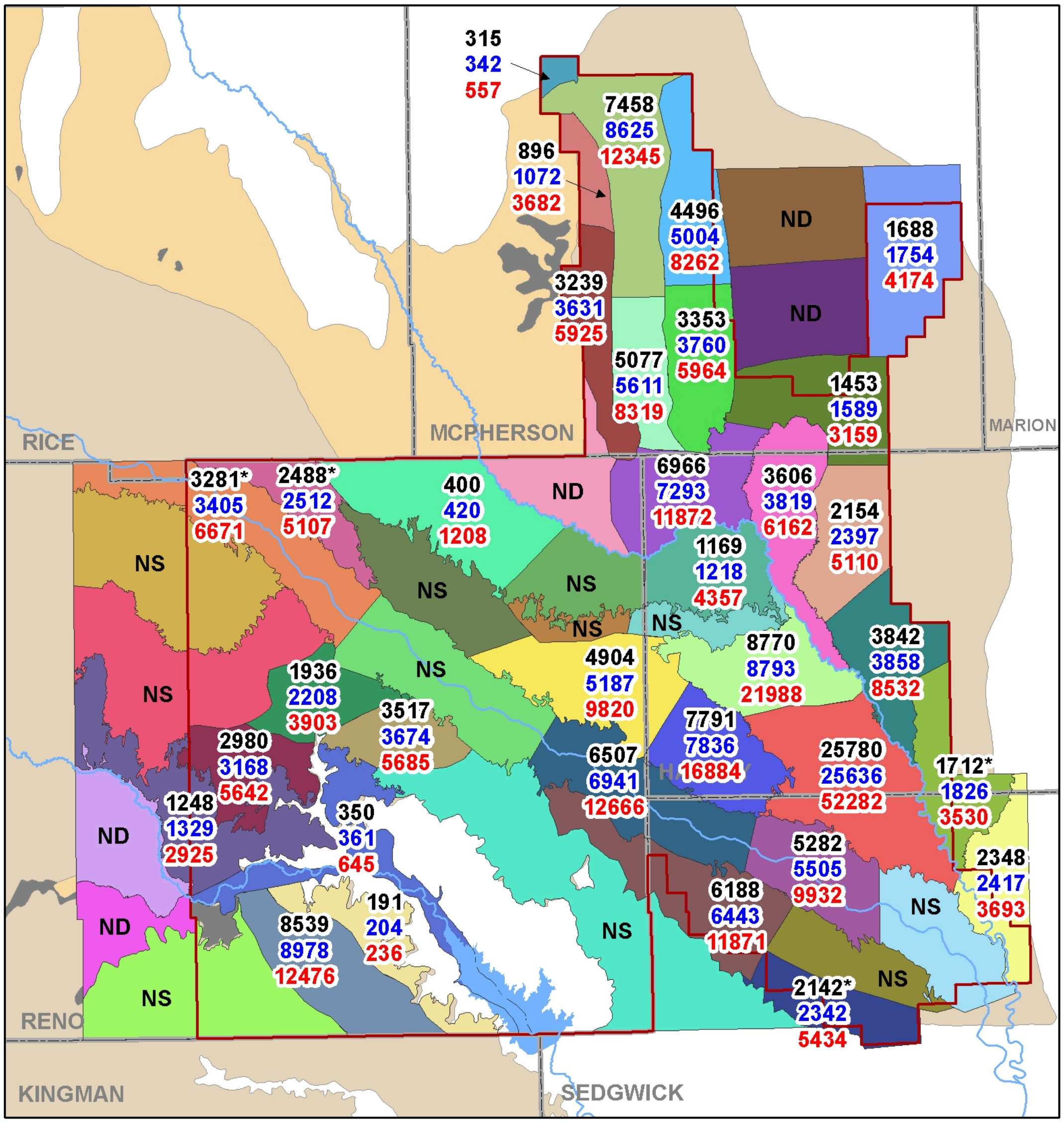

Figure III.D.11. Comparison of the average sustainable water use (black numbers), the average annual water use (blue), and the authorized annual quantity (red) at the scale of individual defined areas. ND in an area indicates that the sustainability analysis could not be performed because of insufficient water-level or water-use data. NS in an area indicates that the analysis was so far below statistical significance that no valid result could be reported.

IV. Major Findings and Discussion

The major conclusion of this study is that the average annual water use over much of the HPA in GMD2 has been close to a sustainable level during the periods considered in this study (1996–2014 and 2005–2014). This conclusion is consistent with the maps of water-level changes over the study periods (figs. IV.1–2), which show modest water-level declines (do not exceed 10 ft) over most of the area with relatively large water-level increases (exceeding 10 ft) restricted to an area that primarily lies within Harvey County. The relative sustainability of the HPA within GMD2, however, varies with the scale and location of the analysis. The major findings of the sustainability assessment for the different scales of analysis are briefly summarized in the next section.

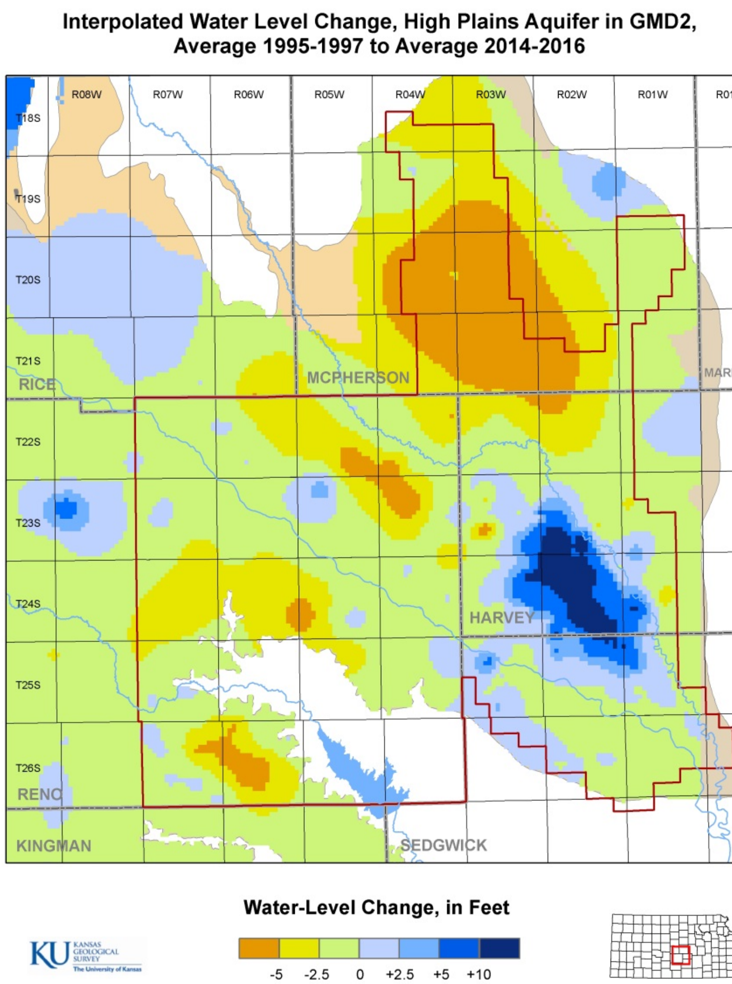

Figure IV.1. Map of interpolated water-level changes (average 1995–1997 to average 2014–2016) for the High Plains aquifer within GMD2. The bold red lines are boundaries of GMD2, the dashed black lines underlain by a wider gray line are county boundaries, and the solid black lines are township borders.

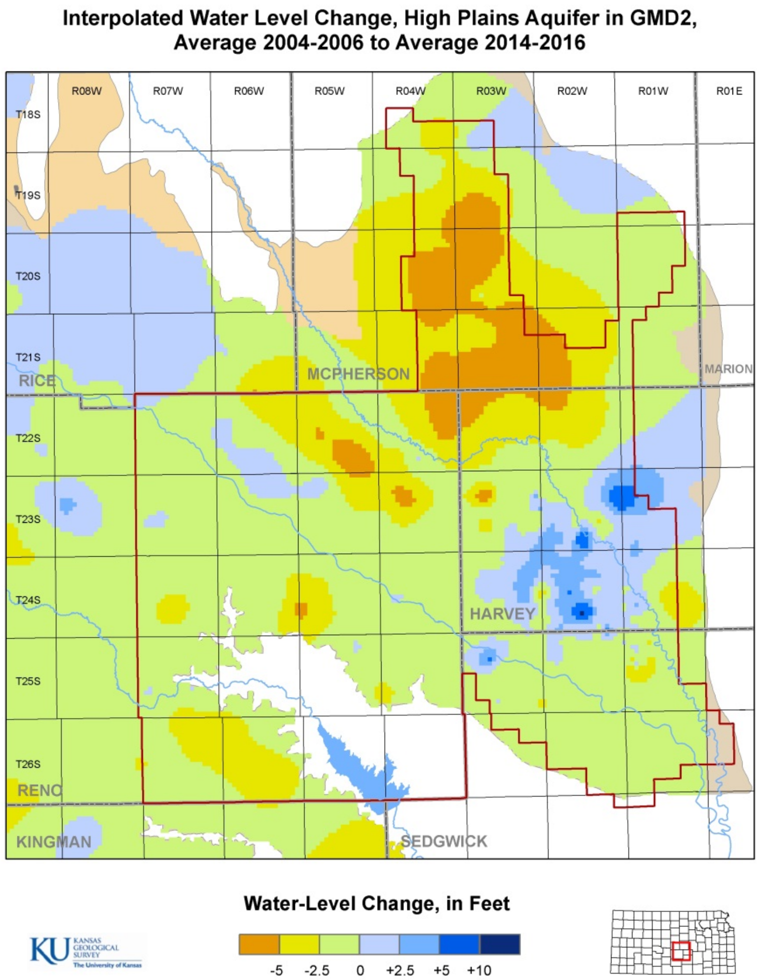

Figure IV.2. Map of interpolated water-level changes (average 2004–2006 to average 2014–2016) for the High Plains aquifer within GMD2. See Figure IV.1 for additional descriptions.

A. Summary of Results

1. *District-level assessment*

The average annual reported water use appears to have been very close to the sustainable level for both assessment periods. Considering the results from all analyses, the average Q_{stable} is 180,308 ac-ft/yr, 1.2% below the average annual reported water use for GMD2.

2. *County-level assessment*

The findings of this assessment vary among the counties (figs. III.B.5–6). All but McPherson County are at least somewhat dependent on infrequent years of high inflow to maintain near-stable water levels.

a) Harvey County—The average annual reported water use is very close to (0.2% above) Q_{stable} (48,060 ac-ft/yr), consistent with the water-level rises and modest water-level declines observed during the periods of analysis (figs. IV.1–2). However, the aquifer appears to be somewhat dependent on inflows produced by years of high precipitation following drought years to maintain near-stable water levels.

b) McPherson County—The average annual reported water use is above (8.0%) Q_{stable} (29,485 ac-ft/yr), consistent with the water-level declines observed throughout the portions of the county in GMD2 during the periods of analysis (figs. IV.1–2). This is the largest difference from Q_{stable} of any of the four counties and is largely attributable to greater thicknesses of low permeability material between the land surface and the water table than in the other counties (e.g., see geologic cross sections in Williams and Lohman, 1949) and the lack of significant stream-aquifer interactions in this portion of GMD2.

c) Reno County—The average annual reported water use is slightly above (2.6%) Q_{stable} (59,695 ac-ft/yr), consistent with the modest water-level declines observed throughout the portions of the county in GMD2 during the periods of analysis (figs. IV.1–2). However, the aquifer appears to be heavily dependent on inflows produced by years of high precipitation following drought years to maintain near-stable water levels.

d) Sedgwick County—The average annual reported water use is close to (0.5% above) Q_{stable} (41,343 ac-ft/yr), consistent with the water-level rises and modest declines observed in the portions of the county within GMD2 during the periods of analysis (figs. IV.1–2). However, the aquifer appears to be somewhat dependent on inflows produced by years of high precipitation following drought years to maintain near-stable water levels.

3. Township-level assessment

The findings of this assessment vary among the township-range units within GMD2 (figs. III.C.16–17, 19). In general, the findings are consistent with those of the county-level assessments. The findings are summarized here by county.

a) Harvey County—Portions of nine township-range units in this county lie within GMD2, eight of which have sufficient data for analysis. Other than in T22S-02W, the aquifer in these units has an average annual water use that is slightly above to very slightly below the sustainable level, consistent with the water-level rises and modest water-level declines observed during the periods of analysis (figs. IV.1–2). However, three of the nine township-range units (T22S-03W, T23S-03W, and T24S-01W) appear to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the average annual water use would be appreciably above the sustainable level in these units (fig. III.C.17). Only one unit (T22S-02W) has an average annual water use that is considerably above (14%) Q_{stable}, which may be reflective of poorer aquifer conditions in that area. Two of the units (T24S-02W and -03W) have reported water use below Q_{stable} (indicated by the negative values in fig. III.C.16c), consistent with their location within the area of relatively large water-level increases observed during the periods of analysis (figs. IV.1–2).

b) McPherson County—Portions of 12 township-range units in this county lie within GMD2, 11 of which have sufficient data for analysis. In general, the aquifer in these units has an average annual water use that is much further above the sustainable level than in the other counties in GMD2, consistent with the relatively large water-level declines observed during the periods of analysis (figs. IV.1–2). In terms of percentage of the average reported annual use, the amount above the sustainable level ranges from 3.5% (T18S-03W) to 19.8% (T20S-04W). This is undoubtedly a reflection of lower natural recharge and less stream-aquifer interactions as a result of low permeability material between the land surface and the water table in most areas of the county. One of the township-range units (T20S-01W) appears to be dependent on inflows produced by years of high precipitation following drought years; this is likely a result of the shallower water table in this unit compared to most of the other portions of the HPA within the county, coupled with the presence of West Emma Creek and tributaries.

c) Reno County—Twenty township-range units in this county lie within GMD2, 17 of which have sufficient data for analysis. In general, the aquifer in these units has an average annual water use that is very slightly to somewhat above the sustainable level, consistent with the modest water-level declines observed during the periods of analysis (figs. IV.1–2). In terms of percentage of the average reported annual use, the maximum amount above the sustainable level was 7.8% in T22S-05W (fig. III.C.16c), an area of relatively large water-level declines observed during the periods of analysis (figs. IV.1–2). Twelve of the township-range units appear to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the average annual water use would be considerably above the sustainable level in those units, many of which are crossed by the Arkansas or Little Arkansas rivers (fig. III.C.17). Statistically significant relationships could not be obtained for two of the analyzed units in Reno County (T23S-05W and -06W); those areas are examined further in the analysis of the Arkansas River Hutchinson defined area.

d) Sedgwick County—Portions of nine township-range units in this county lie within GMD2, seven of which have sufficient data for analysis. Other than the small portion of T27S-01W lying within GMD2, the aquifer in these units has an average annual water use that is very slightly to somewhat above the sustainable level, consistent with the water-level rises and modest declines observed during the periods of analysis (figs. IV.1–2). One of the township-range units (T25S-03W) appears to be dependent on inflows produced by years of high precipitation following drought years. In the absence of those high inflow years, the average annual use would be considerably above the sustainable level in that unit (fig. III.C.17). Statistically significant relationships could not be obtained for one of the analyzed units in Sedgwick County (T26S-01W); that area is examined further in the analyses of the Arkansas River Wichita and Maize defined areas.

e) Western expansion area in Reno County—There are four full townships and one partial township in this expansion area. Three of the townships have sufficient data for analysis, but a trend in water use in one of these prevented the attainment of statistically significant correlations. The portion of the aquifer in the two other townships appears to be currently developed for an average annual water use that is somewhat above the sustainable level, although the continued increase in water use in these townships indicates that these areas may still be in a relatively early stage of development. In both townships, the system appears to be dependent on inflows produced by years of high precipitation following drought years. Water use has generally been increasing during 1996–2014 in the townships in this expansion area. For example, no water use was reported in two of the townships until 2012, and water use increased from zero to several hundred ac-ft in another township. Sustainability assessments will be difficult to perform in these townships until the average annual water use and the area over which the pumping wells are distributed begins to stabilize.

4. Defined area assessment

The findings of the assessment vary among the defined areas within GMD2. In general, the results for the defined areas are consistent with the results for the townships in which they are located, so results from only nine of the 45 areas will be summarized here (highlighted areas on fig. III.D.1b). Three of these areas are those for which statistically significant results could not be obtained at the township level (Group 1) and six are areas along the eastern boundary of GMD2 (Group 2). The findings are summarized here by these two groupings.

a) Group 1—The common factor linking these three areas is that they have a much higher proportion of industrial water use (Arkansas River Hutchinson and Arkansas River Wichita defined areas) or non-irrigation use that is neither industrial nor municipal (Maize defined area) than other areas. Moreover, in all three areas, the monitoring wells are primarily located in areas dominated by irrigation pumping. The portions of the aquifer dominated by irrigation pumping appear to be operating with an average annual water use that is above the sustainable level (Q_{stable} is 2.3% [Maize defined area] to 8.1% [Arkansas River Hutchinson defined area] below the average annual reported irrigation use) and, in all cases, appear to be heavily dependent on infrequent high inflow years to maintain the aquifer reasonably close to near stable water levels. The lack of monitoring wells in areas dominated by non-irrigation pumping prevents estimation of Q_{stable} for those portions of the defined areas.

b) Group 2—The common factors linking these six defined areas are their locations along the eastern border of GMD2 and their relatively small number of monitoring wells. These areas appear to be operating with an average annual water use that is slightly to considerably above the sustainable level (Q_{stable} is 0.4% [East Little Arkansas River defined area] to 13.5% [Harvey RWD defined area] below the average annual water use). Two of the areas (Dog Ear and East Little Arkansas River South defined areas) appear to be heavily dependent on infrequent high inflow years to maintain the aquifer reasonably close to near-stable water levels. One area (Park City to Valley Center) is dominated by municipal pumping and has no monitoring wells in the easternmost portion of the area where groundwater use is relatively high (fig. II.B.5).

B. Limitations

The sustainability assessment approach used in this project is based on a series of assumptions regarding the aquifer and the water-level and water-use data. Those assumptions and the limitations arising from them are described in this section.

1. Seasonally pumped aquifer at a mature stage of development

This approach was specifically developed for the Kansas HPA where, for decades, the major use of groundwater has been pumping for irrigation, i.e. the pumping is primarily restricted to the summer growing season. The water-level data used in the analysis are collected during the winter, a few to several months after the cessation of irrigation pumping. Thus, in areas where the major groundwater use is irrigation, the water-level data are relatively insensitive to year-to-year variations in the timing of the irrigation season. However, in areas where a significant amount of groundwater is used for purposes other than irrigation, noise can be introduced into the relationships if pumps are cut on or off shortly before the time of the water-level measurements. In general, the assumption of a seasonally pumped aquifer appears reasonable for the vast majority of GMD2. The noise introduced by pumps cutting on or off shortly before the water-level measurements can often be diminished by applying a two-year average to the water-level data. A number of townships appear to have been affected by late-year pumping in 2006. In those cases, the analysis can be repeated without the 2006 value.

2. Monitoring well distribution

This approach assumes that monitoring wells are distributed across an area so that the average annual water-level change for the area can be estimated with some degree of confidence. In GMD2, this assumption appears appropriate for analyses performed at the district and county scales. The appropriateness of the assumption can vary at the scale of townships and defined areas, but, in general, the distribution of monitoring wells appears sufficient for this purpose. Only the portion of township T26S-01E in Sedgwick County in GMD2 has a significant amount of groundwater use but no monitoring wells (27 groundwater-based water rights reported water use for at least one year during the 1996–2014 period [average annual reported water use is 1,054 ac-ft/yr]). As a result, the approach cannot be applied to that township. In three other townships (T23S-05W and -06W in Reno County and T26S-01W in Sedgwick County), the monitoring well data appear insensitive to non-irrigation groundwater use because of a lack of monitoring wells in the areas dominated by non-irrigation groundwater use. In those cases, the analysis is limited to the portions of the townships for which irrigation is the dominant use of groundwater.

3. Water-use data

This approach assumes that reliable water-use data are available for the analysis. This assumption appears appropriate for GMD2, particularly over the 2005–2014 period during which the percent of pumping wells with flowmeters increased from 71% to more than 93% (fig. II.B.4). However, six of the 50 township-range units (T21S-01W, T22S-01W, T25S-05W, T26S-04W and -05W, and T27S-02W) had either no or very little reported water-use data. Thus, the approach cannot be used for those areas. If adjacent areas with similar hydrogeologic conditions have undergone groundwater development, then the Q_{stable} values from those areas can provide some insight into conditions expected under groundwater development in the areas with little to no current groundwater use.

4. Constant specific yield

This approach assumes that the specific yield (drainable porosity) varies little from year to year. At relatively small scales (below the section level), heterogeneity in specific yield could introduce noise into the relationships. However, at the township scale or larger, the heterogeneity is averaged out and has little impact. Thus, the assumption of constant specific yield appears appropriate for GMD2 at the scales of this assessment.

5. Constant net inflow

This approach assumes that the net inflow varies little from year to year or that the data set can be subdivided into periods of near-constant net inflow. This assumption appears appropriate for GMD2 at the scales of this assessment. However, further discussion is needed for three situations. First, for many of the assessments performed at the county and smaller scales, there are two years, 2007 and 2013, for which net inflow appears to have been considerably greater than in most other years during the assessment period. These two years were years of high precipitation immediately following a drought year; the drought appears to have lowered water levels such that the aquifer could accept more net inflow than in a typical year. Two analyses were performed for those areas (marked by * on figs. III.C.16a–c); one analysis used all of the data for the assessment period (fig. III.C.16c) and one analysis used the data after removal of the high inflow years (fig. III.C.17). The analysis performed without the high inflow years should be considered a conservative lower bound on Q_{stable}, whereas the analysis using the entire dataset should be considered the best estimate of Q_{stable} because it incorporates the years of typical net inflow with the years of high inflow. Clearly, those infrequent years of high inflow are critical in many portions of GMD2 for maintaining near-stable water levels. Second, as shown in figs. IV.1–2, there are areas in the southern half of Harvey County and northern portion of Sedgwick County where the aquifer has experienced large water-table rises over the last 20 years as a result of pumping reductions. In those areas, the net inflow may still be adjusting to the more recent level of annual pumping. Thus, the estimates for those areas should be considered as upper bounds on the net inflow produced by the new level of pumping. Third, as illustrated by conditions in the western expansion area, net inflow can vary with time in the early stages of aquifer development, making it difficult to obtain statistically significant relationships. The temporal variation in net inflow will continue until annual average pumping and the area over which the pumping wells are distributed begin to stabilize.

The limitations described in this section must be considered when reviewing the results of the sustainability assessment. However, outside of the few areas affected by the distribution of monitoring wells or with little to no data, none of the limitations appear to have had a large impact on the reported results for GMD2.

C. Further Discussion and Conclusions

The sustainability assessment approach used here is directed at calculating the net inflow term (total inflows minus total outflows other than pumping) of the aquifer water balance. As described earlier, net inflow comprises recharge from the land surface, subsurface inflow from adjacent areas, water drawn into the aquifer from surface water sources by pumping, inflow from artificial recharge projects, and any additional pumping-induced inflows into the aquifer, minus discharge to streams, evapotranspiration, and subsurface outflow to adjacent areas. A great advantage of this approach is that the individual components of the water balance that contribute to net inflow (e.g., recharge from the land surface) do not have to be estimated separately; these components are lumped together to significantly reduce data requirements and the level of uncertainty in the calculated results. Depending on the particulars of the situation, net inflow can be greater than or less than the recharge component of the aquifer water balance as described further in the following discussion.

The long-term water balance for an aquifer such as the HPA in the GMD2 region prior to development would have been constant under stable long-term climatic conditions (net inflow is zero). Greater precipitation would have caused greater runoff and recharge, which would have been balanced primarily by greater stream discharge but also by greater evapotranspiration. During droughts, recharge and runoff would have been lower and would have been accompanied by decreased groundwater discharge to streams and less evapotranspiration. When groundwater pumping is introduced into the system, the water balance is disturbed, causing lower water tables in the areas of pumping. This results primarily in decreased stream discharge along with some decrease in evapotranspiration and changes in local groundwater flow (positive net inflow). Lower water tables in the vicinity of streams increase recharge near streams during substantial precipitation events by capturing runoff and shallow subsurface flow that otherwise moves relatively rapidly to the stream, resulting in further decreases in streamflow. Thus, both recharge and streamflow are expected to have been affected by development of the Equus Beds aquifer within GMD2.

The potential decreases in streamflow in the watersheds of the Little Arkansas and Arkansas rivers within GMD2 were assessed by examining the long-term changes in flow in the rivers at the USGS stream gage sites at Valley Center, for which annual flow data exist since 1923, and Wichita, for which data exist since 1935. Figures IV.C.1 and IV.C.2 display the mean annual flow for these two sites. The flow differences for the Arkansas River between Great Bend and Wichita and between Hutchinson and Wichita are shown in Figure IV.C.3 and IV.C.4, respectively. The flow data are color-coded in two portions, the start of the flow records to 1973 and from 1974 to 2015, based on two periods of groundwater development, one for pre- and early development and the second for substantial development. Figures IV.C.5 and IV.C.6 show the number of points of diversion and water rights within the portions of the watersheds of the Little Arkansas River to the Valley Center gage station and the Arkansas River to the Wichita gage station, respectively, in GMD2 since 1945, which illustrate the two periods of aquifer development. The start of the substantial period of development in the flow graphs was also selected based on obtaining a relatively similar value for the end of the linear fit line for the predevelopment period and the beginning of the linear fit for the development period. The start of the substantial development period is close to the date of the formation of GMD2 in 1975. Although the Wichita–Valley Center floodway system has decreased flows in the two rivers during very high flows, that process started within the first of the two periods shown in the flow figures; the system was constructed during 1955–1959.

The trends in the Little Arkansas and Arkansas rivers to 1973 indicate increasing flow. These increases appear to be related to the long-term increase in precipitation in the GMD2 area during the pre- to post-development period (fig. IV.C.7). The precipitation increase from 1923 to 2015 (the period for the fig. IV.C.1 flow graph) is 4.27 inches based on the linear regression for the data, an increase of 15% in the precipitation of 1923. Figure IV.C.7 also shows the 30-year normal precipitation of 31.9 inches for the area, which is close to the 32.0 inches value for the 2015 end of the linear regression. This long-term precipitation increase would be expected to be accompanied by a continued increase in the flow of the rivers (and an increase in the flow difference for the Arkansas River) after 1974. However, figs. IV.C.1–4 show a small decrease in flow; this flow decrease is likely the result of the capture of streamflow by pumping-induced declines in groundwater levels (increase in net inflow).

The flow in the Arkansas River entering GMD2 is affected by upstream flow changes. The flow difference in the Arkansas River between Great Bend and Wichita (fig. IV.C.3) represents the flow changes in the entire part of the watershed within GMD2, as well as in part of GMD5. The flow difference in the river between Hutchinson and Wichita (fig. IV.C.4) represents only part of the watershed in GMD2 because the Hutchinson gaging station is downstream of the city. The predevelopment portion of fig. IV.C.4 is relatively short due to the start of the Hutchinson station in 1960; the shorter record results in more sensitivity to the date for the end of the linear fit for the predevelopment period. Thus, the steepness of the linear regression for the predevelopment period is greater than would be expected for a longer period if such data were available for fig. IV.C.4. Both of the flow difference plots illustrate the change from an increasing flow difference consistent with the increasing precipitation to a slightly decreasing flow difference that is not consistent with the continuing increase in precipitation with time. These changes also illustrate the capture of stream flow resulting from declines in groundwater levels due to pumping.

The average volumes of total reported water use during 2005–2014 within the watersheds of the Little Arkansas River to the Valley Center gage station and the Arkansas River to the Wichita gage station in GMD2 were 91,694 ac-ft/yr and 169,623 ac-ft/yr, respectively. The average amounts of groundwater use for these two watershed areas for the same period were not much lower: 90,667 ac-ft/yr and 168,299 ac-ft/yr, respectively. The total water use values for the Little Arkansas River and Arkansas River watersheds within GMD2 are equivalent to streamflows of 127 ft^3/sec and 234 ft^3/sec, respectively. The apparent decreases in flow observed for the Little Arkansas River (fig. IV.C.1) and the flow differences for the Arkansas River (figs. IV.C.3 and IV.C.4), relative to what would have been expected for continued increases in precipitation (fig. IV.C.7), are on the order of the reported recent water use in GMD2. Thus, the effect of groundwater pumping can apparently be observed in the streamflow data, as a result of the pumping decreasing discharge to the streams as well as inducing flow from the streams to the aquifer (increasing net inflow). This stream-aquifer interactions component of the aquifer water balance is critically important for sustainability assessments and is incorporated into the net inflow (Q_{stable}) calculations that are the primary focus of the approach used here. However, this component is generally ignored in safe yield analyses that are focused on recharge-based calculations.

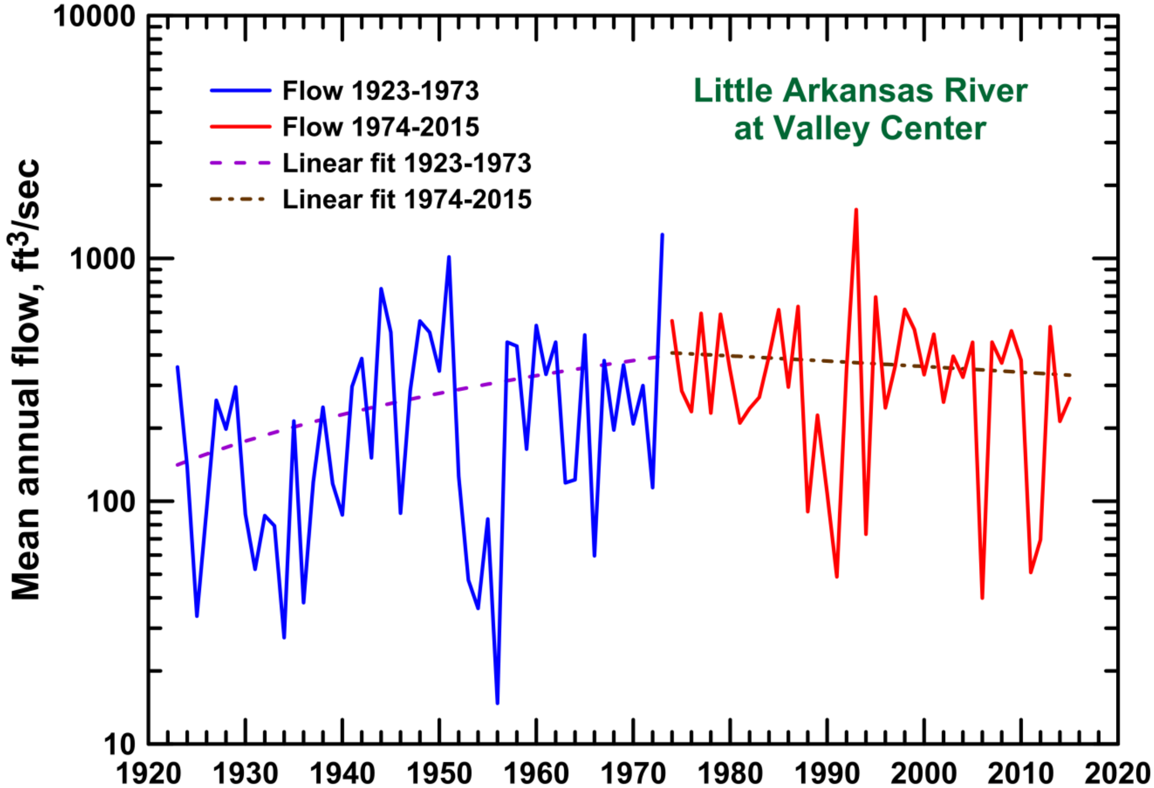

Figure IV.C.1. Mean annual flow of the Little Arkansas River at Valley Center.

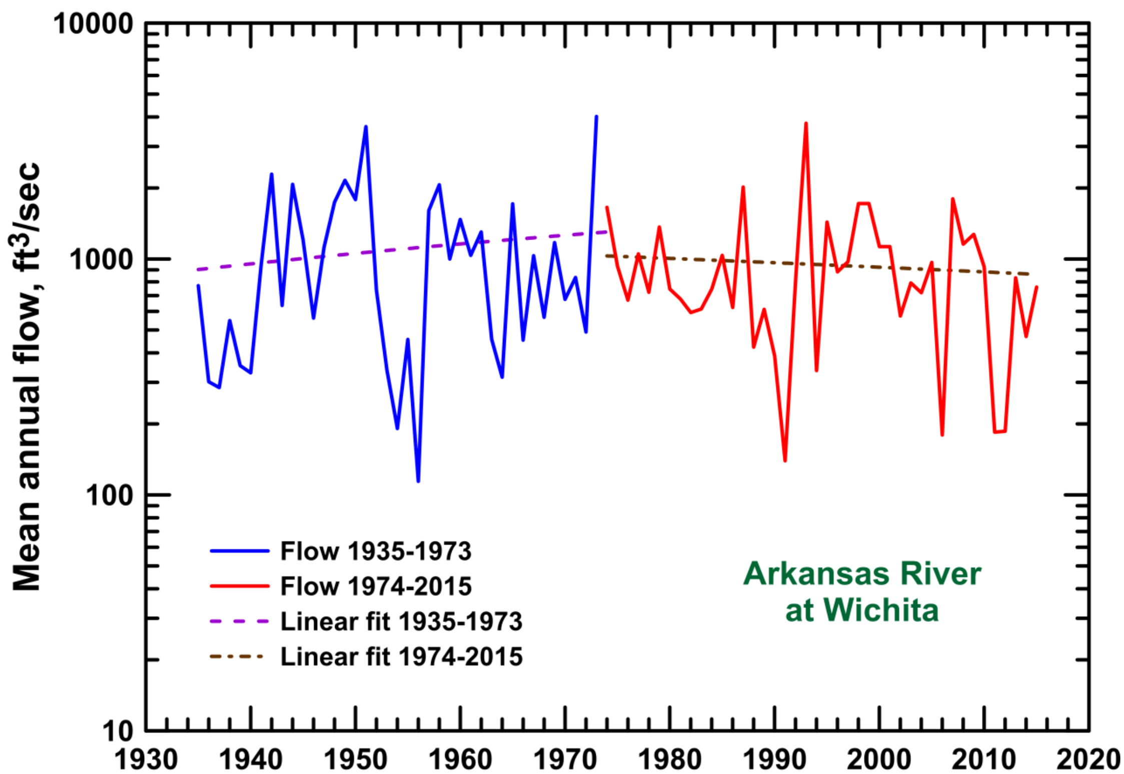

Figure IV.C.2. Mean annual flow of the Arkansas River at Wichita.

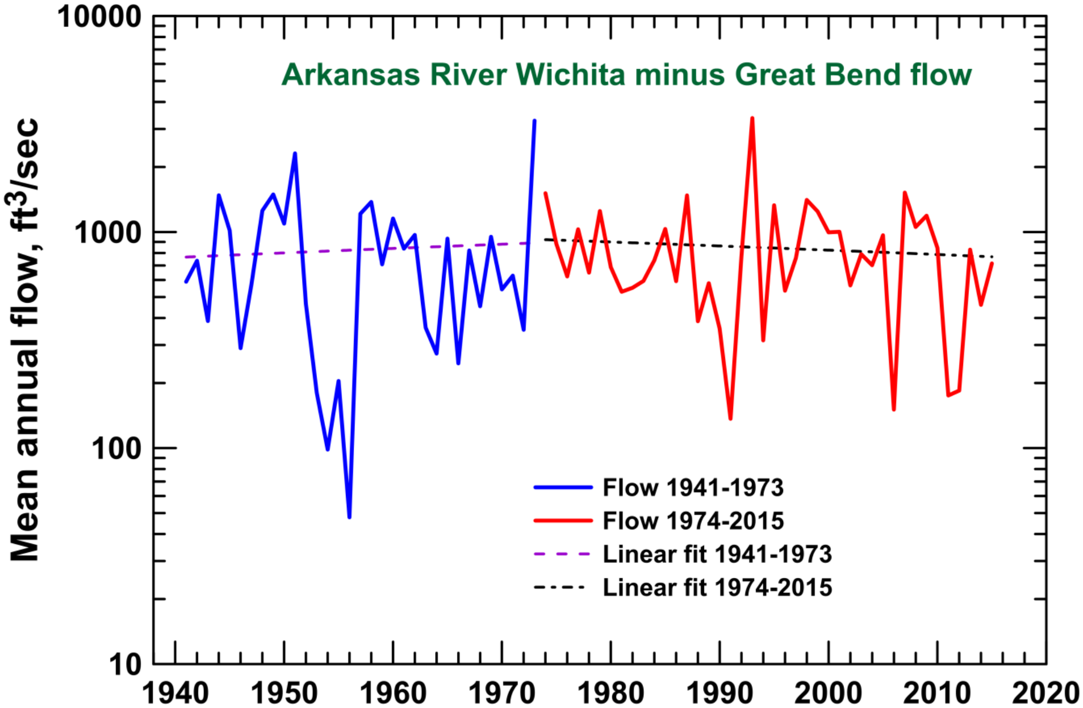

Figure IV.C.3. Mean annual flow difference between the Arkansas River at Great Bend and Wichita.

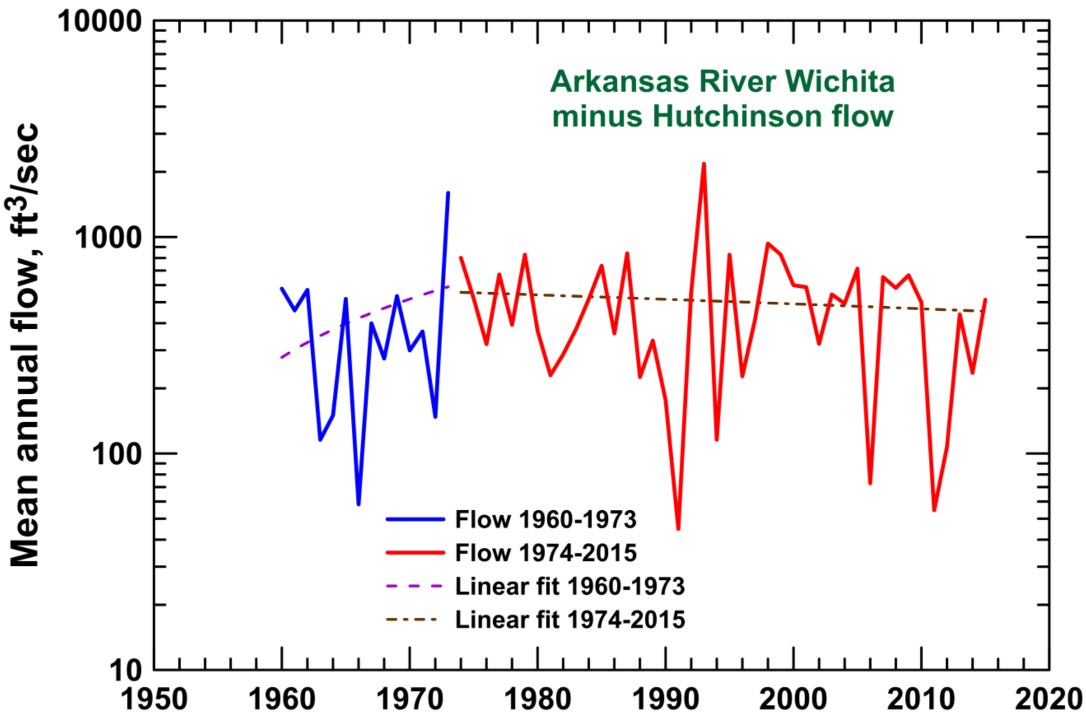

Figure IV.C.4. Mean annual flow difference between the Arkansas River at Hutchinson and Wichita.

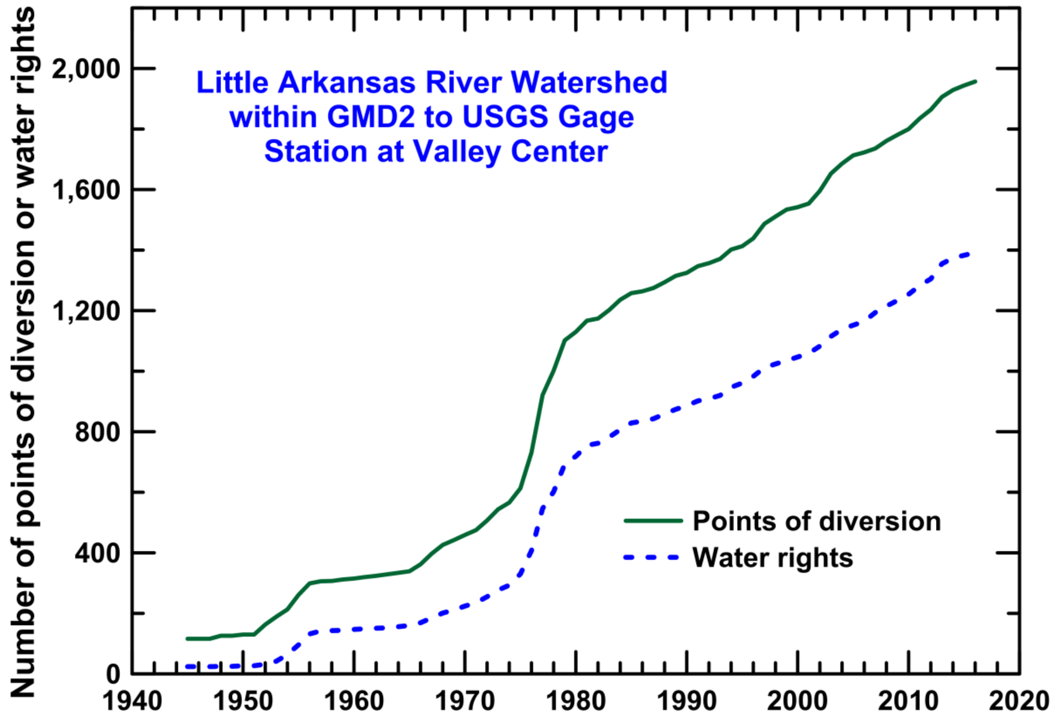

Figure IV.C.5. Number of points of diversion and water rights for the Little Arkansas River watershed within GMD2 to the USGS stream gage station at Valley Center during 1945–2016; date of water right is based on the most senior priority date for that right.

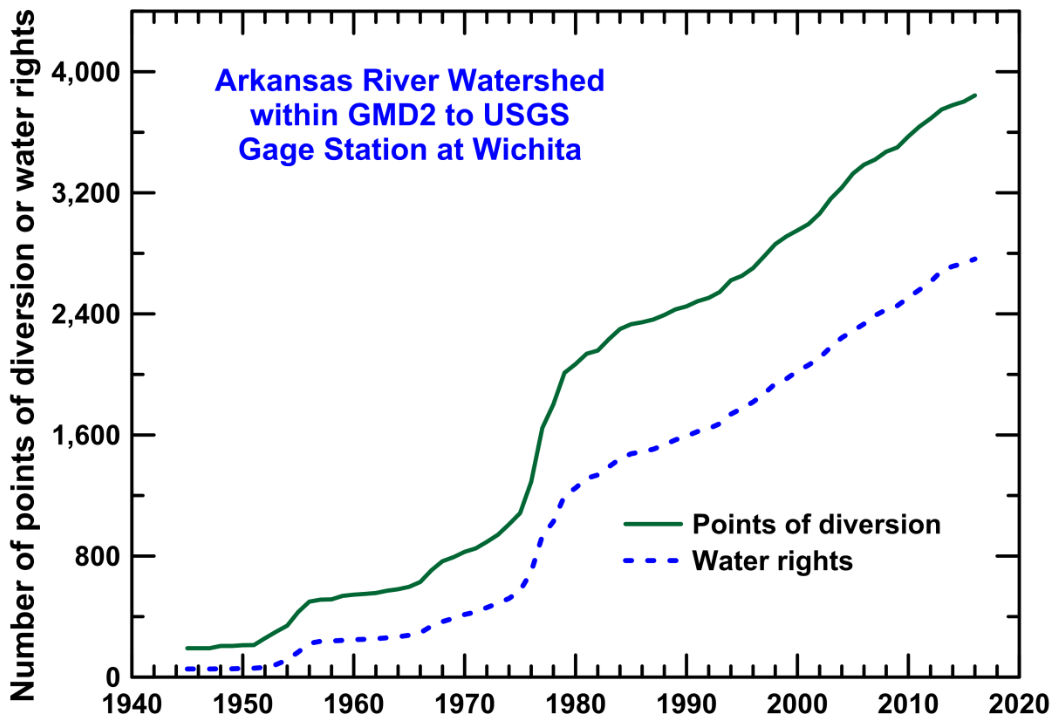

Figure IV.C.6. Number of points of diversion and water rights for the Arkansas River watershed within GMD2 to the USGS stream gage station at Wichita during 1945–2016; date of water right is based on the most senior priority date for that right.

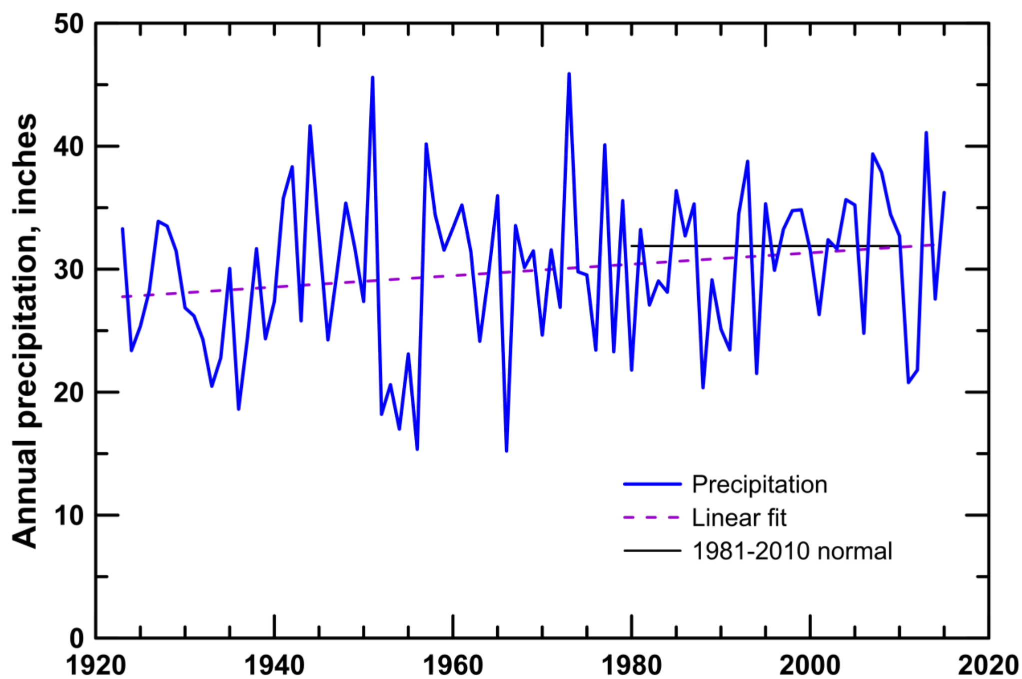

Figure IV.C.7. Average annual precipitation for the four county areas within GMD2. Data are from the spatial climate datasets of the PRISM Climate Group (http://prism.oregonstate.edu/).

D. Further Work

This sustainability assessment is the first phase of a larger project involving the modeling of past, current, and projected future conditions in Groundwater Management District No. 2. The assessment is complementary with the modeling activity as it provides important inputs into the groundwater flow model. In particular, it provides estimates of net inflow and specific yield on a scale of relevance for modeling activities. These estimates will help constrain the calibration process and reduce the uncertainty in the modeled aquifer responses to future development scenarios.

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