Prepared in cooperation with the city of Wichita, Kansas

Status of Groundwater Levels, Storage Volume, and Chloride Concentrations in the *Equus* Beds Aquifer near Wichita, Kansas, January 2012

By Cristi V. Hansen, Andrew C. Ziegler, and Jennifer L. Lanning-Rush

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Suggested citation:
Hansen, C.V., 2012, Status of groundwater levels and storage volume in the *Equus* Beds aquifer near Wichita, Kansas, January 2012: U.S. Geological Survey Scientific Investigations Map xxxx. Available at: *http://pubs.usgs.gov/sim/xxxx*

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)

Vertical coordinate information is referenced to the North Americ~~a~~n Vertical Datum of 1988 (NAVD 88).

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

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

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Abstract

The part of the *Equus* Beds aquifer in southwestern Harvey County and northwestern Sedgwick County was developed to supply water to the city of Wichita and for irrigation in south-central Kansas. The 165 square-mile study area represents about one-eighth of the 1,400 square-mile *Equus* Beds aquifer and accounts for about one-third of the withdrawals from the aquifer. Water-level and storage-volume decreases that began with the development of the aquifer in the 1940s reached record to near-record lows in January 1993. Since 1993, generally higher water levels and partial storage-volume recoveries have been recorded in the aquifer.

Potentiometric maps of the shallow and deep layers of the aquifer show flow in both aquifer layers is generally from west to east. The January 2012 water-level altitudes in the shallow aquifer layer ranged from a high of about 1,470 feet in the northwest corner of the study area to a low of about 1,330 feet in the southeast corner of the study area; water-level altitudes in the deep aquifer layer ranged from a high of about 1,435 feet on the west edge of the study area to a low of about 1,330 feet in the southeast corner of the study area. In the northwest part of the study area, water levels can be more than 50 feet

higher in the shallow layer than in the deep layer of the *Equus* Beds aquifer. Measured water-level changes for August 1940 to January 2012 ranged from a decline of 22.77 feet to a decline of 0.58 feet and averaged 9.73 feet. The largest August 1940 to January 2012 water-level changes of 20 feet of more occurred about 2 miles southeast of Halstead, Kansas.

The change in storage volume from August 1940 to January 2012 in the study area was a decrease of about 168,000 acre-feet. This volume represents a recovery of about 87,000 acre-feet, or about 34 percent of the storage volume previously lost between August 1940 and January 1993. The largest post-1993 storage-volume recovery to date in the study area was about 161,300 acre-feet in July 2010. This was followed by a loss of approximately 115,000 acre-feet in storage volume from July 2010 to January 2012 in the study area. About 41,000 acre-feet of this loss was recovered from July 2011 to January 2012. Major factors in this recovery were seasonal decreases in irrigation pumpage and recharge from near-normal precipitation.

A linear regression equation of the relation of average water-level changes to changes in storage volume since August 1940 may provide a simple empirical method for estimating the amount of storage-volume change for periods when maps of water-level change used for the computation of storage-volume change are not available.

Chloride data from wells throughout the area collected in 2011 indicate that concentrations have increased by more than 10 percent in comparison to pre-2006 values in deep groundwater in the area near Burrton, Kansas, especially near the Phase 1 recharge sites RB-01 and RRW04 and along the Arkansas River. These increases and current concentrations indicate that the chloride contamination from past oil and gas activities and the Arkansas River continues to migrate downgradient in the deep groundwater at a rate of about 1 foot per day. Chloride concentrations in shallow groundwater have increased in the areas near Burrton in comparison to the pre-2006 values, but have decreased by more than 10% in the areas near IW14 and 15 in the central part of the study area and along the Arkansas River near Bentley, indicated a possible improvement in water quality from infiltrating precipitation or the water quality in the Arkansas River.

Introduction

Beginning in the 1940s, the Wichita well field was developed in the *Equus* Beds aquifer in southwestern Harvey County and northwestern Sedgwick County to supply water to the city of Wichita, which has been the largest city in Kansas since the mid-1940s (Williams and Lohman, 1949; Gibson, 1998; U.S. Census Bureau, 2010). In addition to supplying drinking water for Wichita, the other primary use of water from the *Equus* Beds aquifer is crop irrigation in this agriculturally dominated part of south-central Kansas (Rich Eubank, Kansas Department of Agriculture, Division of Water Resources, oral commun., 2008). The decline of water levels in the aquifer was noted soon after the development of the Wichita well field began (Williams and Lohman, 1949). As water levels in the aquifer decline, the volume of water stored in the aquifer decreases and less water is available to supply future needs. Since 1940, the U.S. Geological Survey (USGS), in cooperation with the city of Wichita, has monitored changes in water levels and the resulting changes in storage volume in the *Equus* Beds aquifer as part of Wichita's effort to effectively manage this resource; this report documents these changes to January 2012.

In 1993, the city of Wichita adopted the Integrated Local Water Supply Program (ILWSP) to ensure an adequate water supply for the city through 2050 and as part of its effort to effectively manage the part of the *Equus* Beds aquifer it uses (City of Wichita, [2007] and 2008; Warren and others, 1995). ILWSP uses several strategies to do this including (a) greater reliance on other sources of water from outside the study area (for example, the Bentley Wellfield south of the Arkansas River, Cheney Reservoir on the North Fork of the Ninnescah River, and the Wichita's Local Wellfield at the confluence of the Arkansas and Little Arkansas Rivers), (b) encouraging conservation, and (c) developing the Aquifer Storage and Recovery (ASR) project with an artificial-recharge capacity of as much as 100 million gallons a day. The ASR project also is designed to help protect the part of the aquifer used by the city from the encroachment of oilfield brines near Burrton and saline water from the Arkansas River. In 2007, the city of Wichita began using Phase 1 of the *Equus* Beds ASR project to increase the long-term sustainability of the *Equus* Beds aquifer through large-scale artificial recharge (City of Wichita, [2007]). The ASR project uses water from the Little Arkansas River—either pumped from the river directly or from wells in the riverbank that obtain their water from the river by induced infiltration—as the source of artificial recharge to the *Equus* Beds aquifer (City of Wichita, [2007]). For Phase 1, the water pumped directly from the Little Arkansas River is treated to reduce sediment and remove atrazine before being recharged to the aquifer through recharge basins; water pumped from wells in the riverbank does not receive additional treatment before being recharged to the aquifer through recharge wells (Debra Ary, city of Wichita, written commun., 2012).

Purpose and Scope

The purpose of this report is to describe for a part of the *Equus* Beds aquifer northwest of Wichita the status of the groundwater levels and storage volume in January 2012 as compared with predevelopment (before large-scale withdrawals began in September 1940) groundwater levels, to update changes in aquifer storage since 1940, and to present chloride concentrations in the aquifer in 2011. Maps of related groundwater-level measurements, water-level changes, and chloride concentrations are presented. Two hydrographs of groundwater levels were selected to show historical water-level variations. Regression lines of average water-level changes with storage-volume changes are presented. Information in this report can be used to document and improve understanding of the effects of climate, water use, and water-resource management practices on water supplies in the *Equus* Beds aquifer, an important source of water for the city of Wichita and the surrounding area.

Acknowledgments

The author acknowledges the invaluable assistance of Debra Ary of the city of Wichita and Tim Boese of the *Equus* Beds Groundwater Management District Number 2 (GMD2) for providing water-level and water-quality data and for their technical reviews, which contributed to improved technical and editorial clarity of the report.

Technical reviews by USGS employees Linda Pickett and Brian Kelly also contributed to improved technical and editorial clarity of the report.

Hydrogeology of the Study Area

The approximately 165 square-mile (mi^2) study area is located northwest of Wichita, Kansas in Harvey and Sedgwick Counties (fig. 1). It is bounded on the southwest by the Arkansas River and on the northeast by the Little Arkansas River. The land surface in the study area typically slopes gently toward the major streams from an altitude of about 1,495 feet (ft) in the northwest to a low of about 1,295 ft in the southeast. The study area represents about one-eighth of the 1,400 mi^2 *Equus* Beds aquifer and about one-third of the pumpage from the aquifer occurs in the study area (Kansas Department of Agriculture, 2011). Pumpage from the *Equus* Beds aquifer in the study area is dominated by irrigation and city use (Hansen and Aucott, 2010). Pumpage from the study area in 2011 was about 43,700 acre-feet (acre-ft) for irrigation (Kenneth Kopp, Kansas Department of Agriculture, Division of Water Resources, written commun.. data, May 16, 2012) and about 20,900 acre-ft for the city of Wichita (Shelly Bloesser, city of Wichita, written commun., June 18, 2012).

The central part of the study area (fig. 1), which covers about 55 mi^2 or about one-third of the study area, is the historic center of pumping in the study area. The central part of the study area includes wells used to supply water to the city of Wichita and many wells used for irrigation (Kansas Department of Agriculture, Division of Water Resources, unpub. data, 2011). Pumpage from the central part of the study area in 2011 was about 13,100 acre-ft for irrigation (Kenneth Kopp, Kansas Department of Agriculture, Division of Water Resources, written commun., May 16, 2012) and about 20,900 acre-ft was for the city of Wichita (Shelly Bloesser, city of Wichita, written commun., June 18, 2012) .

FIGURE 1 NEAR HERE

Figure 1. Location of study area near Wichita, south-central Kansas (modified from Aucott and Myers, 1998).

The *Equus* Beds aquifer is the easternmost extension of the High Plains aquifer in Kansas (Stullken and others, 1985; Hansen and Aucott, 2001). The *Equus* Beds aquifer covers about 1,400 mi^2 in Kansas, or about 5 percent of the approximately 30,900 mi^2 covered by the High Plains aquifer in Kansas (fig. 1). The *Equus* Beds aquifer is an important source of water because of the generally shallow depth to the water table, the large saturated thickness, and generally good water quality.

The *Equus* Beds aquifer primarily consists of Quaternary-age alluvial deposits, locally known as the *Equus* beds, with some dune sand and loess (Myers and others, 1996). The alluvial deposits are as much as 250 ft thick in the study area (Leonard and Kleinschmidt, 1976). The *Equus* beds primarily consist of sand and gravel interbedded with clay or silt, but locally may consist primarily of clay with thin sand and gravel layers (Lane and Miller, 1965a; Myers and others, 1996). The middle part of the *Equus* beds generally has more fine-grained material than the lower and upper parts (Lane and Miller, 1965b, Myers and others, 1996). The approximately 700-ft-thick Permian-age Wellington Formation underlies the *Equus* beds in the study area and forms the bedrock confining unit below them (Bayne, 1956; Myers and others, 1996). Storage volume (the amount of water available for use) of the *Equus* Beds aquifer in the study area in 2006 was estimated at about 2,100,000 acre-ft (Hansen, 2007). Near the Arkansas River and in the western part of the study area, the water table in the *Equus* Beds aquifer can be less than 10 ft below land surface. Farther from the Arkansas River and near the Little Arkansas River, the water table can be at a greater depth (about 50 ft below land surface in January 2012), depending on the altitude of the land surface and the amount of water-level decline that has been caused by groundwater withdrawals. The saturated thickness of the *Equus* Beds aquifer within the study area ranges from about 75 ft near the Little Arkansas River to almost 250 ft near the Arkansas River where the lowest areas of the underlying bedrock surface occur (Spinazola and others, 1985). The *Equus* Beds aquifer is considered to be an unconfined aquifer, but the presence of clay layers has resulted in semiconfined conditions in some areas (Spinazola and others, 1985; Stramel, 1967). These semiconfined conditions may have resulted in the substantial water-level and water-quality differences, especially for chloride concentrations in the shallow and deep parts of the *Equus* Beds aquifer in some parts of the study area (Stramel, 1956; Whittemore, 2007, Ziegler and others, 2010, and Whittemore, 2012). These substantial differences, along with a need to monitor the effects of artificial recharge on the shallow and deep parts of the aquifer, lead to the construction for this report of separate potentiometric-surface maps of the shallow and deep layers of the aquifer and the chloride concentrations.

Methods

Aquifer Layers

For the purposes of this report, wells completed and screened in the *Equus* Beds aquifer were assigned to either the shallow or deep aquifer layer. These layer assignments were based on *Equus* Beds

Groundwater Management District No. 2 (GMD2) aquifer zone designations and on well completion and screen depths. GMD2 has identified up to four aquifer zones (designated AA, A, B, and C, in order of descending depth) within the *Equus* Beds aquifer where there are competent clay layers separating them (Tim Boese, *Equus* Beds Groundwater Management District No. 2, written commun., 2009). The A, B, and C zones are similar to the upper, middle, and lower aquifer units defined by Myers and others (1996) and previously discussed in the “Hydrogeology of the Study Area” section. GMD2 monitoring wells generally are in clusters (closely spaced wells screened to different depths) with each well screened in a different aquifer zone. For this report, wells designated by GMD2 as completed in zones A or C were assigned to the shallow or deep aquifer layers, respectively; no wells designated as completed in zones AA or B were used in this study. The city of Wichita monitors clusters of monitoring wells. The shallower well in each city well cluster was assumed to be in and assigned to the shallow aquifer layer; the deeper well in each cluster was assumed to be in and assigned to the deep aquifer layer. Ziegler and others (2010) used a depth of 80 ft as the dividing point between the shallow and deep parts of the *Equus* Beds aquifer. An analysis of the GMD2 and city of Wichita well clusters in the study area shows about 90 percent of the GMD2 zone A wells and shallower wells in city well clusters were completed and screened to a depth of 80 ft or less, and about 90 percent of the GMD2 C zone wells and deeper wells in city well clusters were completed and screened to a depth of greater than 80 ft. This indicates that the use of the 80 ft depth as the dividing point between shallow and deep aquifer layers was reasonable when assigning the city of Wichita monitoring wells not in clusters into either the shallow or deep layer of the *Equus* Beds aquifer and no other information was available.

Water Levels

Groundwater levels were measured from January 3 through 31, 2012, at 126 historic monitoring wells, 76 index wells, 50 GMD2 monitoring wells, and 2 ASR Phase 1 monitoring wells. The historic monitoring wells have been used by the city of Wichita for monitoring water levels in the *Equus* Beds aquifer for years, many since the 1940s (Stramel, 1956). The index wells were installed in 2001 and 2002 to monitor the effects of artificial recharge on the water quality and water levels in the *Equus* Beds aquifer and to determine if there are water-quality differences between the shallow and deep layers of the aquifer (Andrew Ziegler, U.S. Geological Survey, oral commun., September 2003). The GMD2 monitoring wells were installed for GMD2 or are existing wells used by GMD2 to monitor the *Equus* Beds aquifer. The ASR Phase 1 monitoring wells were installed to monitor the effects of recharge around the six ASR Phase 1 artificial recharge sites; only two of the wells around recharge site RB1 were measured in January 2012.

Water levels in the historic monitoring wells were measured by city of Wichita personnel (January 3, 19, 20, and 25, 2012); water levels in the index wells and GMD2 monitoring wells were measured by GMD2 personnel (January 4, 5, 6, 9, 12, 13, 16, 17, and 18, 2012). Water levels in the Phase 1 monitoring wells were measured by USGS personnel (January 31, 2012). All agencies used standard water-level measurement techniques that are similar to USGS methods described in Cunningham and Schalk (2011). The historic monitoring well data are on file, in paper and electronic form, with the city of Wichita's Public Works and Utilities Department in Wichita, Kansas; the index and GMD2 monitoring well data collected by GMD2 are stored in the Kansas Geological Survey's (KGS's) Water Information and Storage and Retrieval Database (WIZARD) (Kansas Geological Survey, 2012); and well data collected by the USGS are stored in the USGS's National Water Information System (NWIS) database (U.S. Geological Survey, 2012b). All the water-level data used in this report also are stored in NWIS.

Data Quality and Limitations

The quality of the water-level data for each well was evaluated by examining hydrographs of the all the water levels available for the well. Where the January 2012 data looked questionable, the data provider was questioned about the values and any corrections they provided were applied. To maintain consistency with past interpretations, no attempt was made to remove water levels affected by pumping from nearby wells. As a result, the interpretation made using these water levels also will show the effects of these nearby pumping wells and cannot be considered reflective of static water-level conditions.

Water-Level Altitudes

The January 2012 water-level altitudes depicted in the potentiometric-surface maps of the shallow and deep layers of the *Equus* Beds aquifer were calculated by subtracting the depth to water below land surface in a well from the altitude of land surface at the well. Land-surface altitudes are those stored for the wells in NWIS or WIZARD or determined from the National Elevation Dataset (U.S. Geological Survey, 2009). Monitoring wells used in this report were divided into two groups to describe differences between the water levels in the shallow and deep layers of the aquifer. The well was assigned to the shallow or deep layer of the *Equus* Beds aquifer based on the layer in which the bottom of the well's casing or screened interval occurred (as described in the "Aquifer Layers" section). The 173 wells assigned to the shallow layer of the aquifer range in depth from 7 to 101 ft in depth, with about 96 percent of the wells 80 ft or less in depth. The 81 wells assigned to the deep layer of the aquifer range in depth from 76 to 285 ft in depth with about 96 percent of the wells greater than 80 ft in depth.

Average daily surface-water-altitude measurements from data collected by sensors at six USGS streamflow-gaging stations on the Arkansas and Little Arkansas Rivers (fig. 1) were used to estimate the surface-water altitude along these streams. These measurements were used along with the groundwater-level measurements in the construction of the potentiomentric-surface map of the shallow *Equus* Beds aquifer layer created for this report. Because the groundwater-level measurements used for the shallow aquifer layer were collected over several weeks, each streamflow-gaging station's average surface-water altitude for the day at the midpoint of the groundwater-level measurement period was used (U.S. Geological Survey, 2012a).

The January 2012 surface-water and groundwater-level altitudes were plotted on the potentiometric-surface map of their assigned aquifer layer and manually contoured. Where well clusters exist, the difference between water levels in the shallow and deep aquifer layers commonly was less than 2 ft (less than one-half of the 5-ft contour interval used for the potentiometric maps) in the same well cluster. Therefore, where water-level data did not exist for one layer but did exist for the other layer and the surrounding well clusters indicated the water-level differences between the shallow and deep layers were small, the data from the other aquifer layer were used as supplemental data to guide the placement of the potentiometric-surface contours. The locations of points of groundwater diversions and the 2011 water-use associated with these points (Kenneth Kopp, Kansas Department of Agriculture, Division of Water Resources, written commun., May 16, 2012) also were used to guide the location of the contours.

Water-Level Change

The water-level change at a well since August 1940 was determined by subtracting the depth to water below land surface in January 2012 from the depth to water below land surface at the same well in August 1940. All wells used for the water-level change maps were historic monitoring wells or index wells. Of the 126 wells used for the water-level change map in the shallow layer of the aquifer, 114 are in the shallow layer of the aquifer. Only 23 of the 126 wells used for the water-level change map had measured water levels for August 1940. If an August 1940 water-level measurement did not exist for a well in the study area, one was estimated from the August 1940 water-level altitude map of Stramel (1956) as modified by Aucott and Myers (1998). The August 1940 to January 2012 water-level-change values for the measured wells were plotted on the map and manually contoured.

Storage-Volume Change

Change in storage volume for the purposes of this report is defined as the change in saturated aquifer volume multiplied by the specific yield of the aquifer. Specific yield is the ratio of (1) the volume of water a rock or soil will yield by gravity to (2) the volume of rock or soil (Lohman and others, 1972). A specific yield of 0.2 has been used to compute the changes in storage volume in the *Equus* Beds aquifer since Stramel (1956) first computed storage volume for the aquifer. The use of a specific yield of 0.2 was retained in this report because, as noted by Hansen and Aucott (2001), it is within the range of most estimates of specific yield, has been the basis of many historical computations, and because there is no general agreement on an average value of specific yield for the *Equus* Beds aquifer in the study area.

The change in storage volume from August 1940 to January 2012 was computed using computer-generated Thiessen polygons (Thiessen, 1911) that were based on the measured water-level changes at wells and the manually drawn lines of equal water-level change. Thiessen polygons apportion the water-level change at each well and the estimated value at points representing the lines of equal water-level change to the area around the wells and points. The volume of storage change was computed by summing the area of each Thiessen polygon multiplied by the water-level-change value associated with the Thiessen polygon, and then multiplied by the specific yield. To determine the storage-volume change since August 1940 in the whole study area and in the central part of the study area, the computation was done for the Thiessen polygons within each of these areas.

Changes in storage volume for periods that do not begin with August 1940 were calculated as the difference between changes in storage volume for August 1940 to the beginning of the selected time period, and for August 1940 to the end of the selected time period. For example, the change in storage volume for January 1993 to January 2012 was calculated as the change in storage volume for August 1940 to January 2012 minus the change in storage volume for August 1940 to January 1993.

Precipitation

Precipitation for the study area for 2011 was estimated as the arithmetic average of precipitation for the five Cooperative weather stations in or near Halstead, Hutchinson, Mount Hope, Newton, and Wichita (station numbers 143366, 143930, 145539, 145744, and 148830, respectively; fig. 1). Values for normal precipitation currently (2011) used by the National Oceanic and Atmospheric Administration (NOAA) are the averages for 1981–2010 (National Oceanic and Atmospheric Administration, 2011b). Standard normal (annual or monthly) precipitation data for weather stations in or near Hutchinson, Mount Hope, Newton, and Wichita, the representative normal precipitation data for the weather station near Sedgwick (Cooperative station number 147313; fig. 1), and the pseudonormal precipitation data for the weather station near Halstead reported by NOAA were averaged to determine the normal precipitation for the study area. Standard normal precipitation values were not available for either the Sedgwick or Halstead weather station because collection of precipitation data at Sedgwick was discontinued in 2004 and precipitation data were not collected at Halstead before 2001. As described by NOAA, a representative normal is “scaled or based on filled values to be representative of the full period of record” for stations where the observed record is incomplete (National Oceanic and Atmospheric Administration, 2011c). A pseudonormal is based on linear combinations of the normals from neighboring stations and is used where the station’s record is missing data, commonly because the station did not begin until after the start of the normal period (National Oceanic and Atmospheric

Administration, 2011a). Normal annual precipitation for the study area is about 32.14 inches (in.). This is similar to the long-term (1940–2010) average annual precipitation of 31.52 in. that was estimated for the study area by Hansen and Aucott (2010). Average study-area precipitation for 2011 was only 20.84 in. and was less than two-thirds of normal precipitation for the study area. Precipitation for August 2011 through January 2012 was about 11.63 in. (National Oceanic and Atmospheric Administration, 2012a, 2012b, and 2012c; and Kansas State Research and Extension, 2012), which was about 1 inch less than the August through January study-area normal of 12.63 in. (National Oceanic and Atmospheric Administration, 2011b).

Chloride Concentrations

Water samples were collected from wells in the study area by GMD2 and USGS during 2011 and analyzed for chloride concentrations. Samples collected by GMD2 were collected and analyzed using protocols and procedures developed by GMD2; samples collected by USGS were collected and analyzed using protocols and procedures described in detail in Ziegler and others (2010). In most cases, only one sample was collected from a well in 2011; however, if more than one sample was collected from a well, the analysis results for the well were averaged. No analysis results were below the detection limit. The chloride concentrations in samples collected in 2011 were compared to historical sample concentrations and were used to develop contours of various concentrations of chloride in the shallow and deep parts of the aquifer.

Groundwater Levels and Storage Volume

Groundwater-level declines can result from a combination of factors, with the primary factors in the study area being pumpage and decreased recharge resulting from less-than-normal precipitation. Droughts and other periods of less-than-normal precipitation tend to decrease the amount of recharge available and increase demand for, and thus pumpage of, groundwater, resulting in increased water-level declines. Periods of greater-than-normal rainfall tend to increase the amount of recharge available and decrease the demand for, and thus pumpage of, groundwater, resulting in water-level rises. If the water-level declines or rises are large enough, they may locally alter the direction of groundwater flow. An annual cycle of water-level declines and rises generally occurs in the study area. Typically, the largest water-level declines occur during the summer or fall when agricultural-irrigation and city pumpage are greatest (Aucott and Myers, 1998). This cycle of annual water-level declines and rises is reflected in the annual fluctuations in the water levels in wells shown in figure 2. The consistently large seasonal water-level fluctuations (commonly from 5 to 20 ft) in well 104 probably are caused by nearby agricultural-irrigation pumpage.

FIGURE 2 NEAR HERE

Figure 2. Water-level altitudes in monitoring wells 104 and 886 and *Equus* Beds aquifer storage-volume change in the study area and the central part of the study area (water-level-altitude data are from Stramel (1956, 1967) and data collected by city of Wichita that are on file with U.S. Geological Survey in Lawrence, Kansas; storage-volume changes are from Stramel (1956, 1967), Aucott and Myers (1998), Aucott and others (1998), Hansen and Aucott (2010), Hansen (2011a, 2011b, 2012), and unpublished data on file with U.S. Geological Survey in Lawrence, Kansas). Locations of monitoring wells are shown in figures 1 and 5.

Record to near-record water-level declines in the *Equus* Beds aquifer occurred in October 1992 and January 1993 (Aucott and Myers, 1998; Hansen and Aucott, 2001). Although the maximum recorded decline in storage volume in the *Equus* Beds aquifer occurred in October 1992, the January 1993 storage-volume decline is used for comparison purposes to minimize the effect of seasonal factors (Hansen and Aucott, 2001). Recent reports have indicated that from January 1993 to July 2011, higher water levels have been recorded in the *Equus* Beds aquifer because of near-normal to greater-than-normal precipitation in most years and decreased city pumpage (Aucott and Myers, 1998; Hansen and Aucott, 2001, 2004, 2010; Hansen, 2007, 2009a, 2009b, 2011a, 2011b, 2012). City pumpage from the aquifer in the study area during 1993 through 2011 averaged about 23,100 acre-ft compared to an average of 32,100 acre-ft for 1965 (when Wichita began supplementing water from the *Equus* Beds aquifer with water from Cheney Reservoir) through 1992 (Hansen and Aucott, 2010; Kansas Department of Agriculture, Division of Water Resources, unpub. data, 2011). Pumpage for agricultural irrigation, which averaged about 30,800 acre-ft per year for 1993 through 2011 and can vary as much as 40 percent from year to year, tended to decrease in years of greater-than-normal precipitation and increase in years of normal to less-than-normal precipitation (Hansen, 2007; Hansen and Aucott, 2010); thus, decreased pumpage for agricultural irrigation likely contributed to the higher water levels only in years of greater-than-normal precipitation. Large-scale artificial recharge by the city of Wichita, which began in 2007, probably contributed to the continuation of these higher water levels near the recharge sites (Hansen, 2011b) through January 2011. Phase 1 artificial recharge through January 2012 totaled about 2,900 acre-ft; no artificial recharge occurred from December 2010 to January 2012 (U.S. Geological Survey, 2012a).

Potentiometric Surfaces of the Shallow and Deep Aquifer Layers, January 2012

The potentiometric-surface contours of the shallow and deep layers of the *Equus* Beds aquifer (figs. 3 and 4, respectively) indicate movement of water in the aquifer is generally from west to east across the area. Hachured areas indicate cones of depression that likely are related to pumping wells and present exceptions to the generally easterly flow pattern. Water-level altitudes in the shallow aquifer layer range from a high of about 1,470 ft near the northwest corner of the study area to a low of about 1,330 ft in the southeast corner of the study area. Water-level altitudes in the deep aquifer layer range from a high of about 1,435 ft on the west edge of the study area to a low of about 1,330 ft near the southeast corner of the study area. Where the potentiometric-surface contours bow out to the west (for example, in the north half of T. 24 S. R. 2 W. on fig. 4) or are hachured (for example, near wells EB10A, IW05A, and 873, on fig. 3 and near wells EB14C and 46D on fig. 4), they indicate areas where the water levels are lower than in the surrounding area, probably because of pumping at nearby wells. The potentiometric contours in the northwest part of the study area on the map of the shallow layer of the aquifer have a different orientation and water-level altitudes up to 50 ft higher than the contours in the same area on the map of the deep layer of the aquifer. These differences probably are caused by thicker clay layers in this area reducing the hydraulic connection between the shallow and deep layers of the aquifer. No obvious effects of artificial recharge can be seen on the potentiometric surfaces of either of the shallow or deep aquifer layers (figs. 3 and 4), probably because no artificial recharge had occurred at any of the ASR Phase 1 sites since November 2010 (U.S. Geological Survey, 2012a).

FIGURE 3 NEAR HERE

Figure 3. Potentiometric surface and chloride concentrations in the shallow layer of the *Equus* Beds aquifer, January 2012.

FIGURE 4 NEAR HERE

Figure 4. Potentiometric surface and chloride concentrations in the deep layer of the *Equus* Beds aquifer, January 2012.

Where water-levels in the shallower wells differ from those in the deeper wells in the same cluster, they indicate there is a vertical component of flow within the aquifer. A downward vertical gradient is indicated where the water levels are higher in the shallower wells than in the deeper wells within a cluster; an upward vertical gradient is indicated where the water levels are lower in the shallower wells than in the deeper wells within a cluster. Within 35 of the 77 clusters shown in figures 3 and 4, the water-level differences in January 2012 between the shallower and deeper wells were 1 ft or less and probably do not indicate a substantial vertical component of flow. However, within 40 of the 77 clusters in the study area, the shallower water levels were more than 1 ft higher than in the deeper wells, indicating that a downward component of flow in the aquifer may have been common during January 2012. In 2 well clusters (36 and 49) water levels were between 1 and 2 ft higher in the deeper wells than in the shallower wells in January 2012, indicating there may have been a small upward component of flow at these sites. In 18 of the 77 clusters in the study area, the water levels ranged from more than 5 to about 57 ft higher in the shallower wells than in the deeper wells in January 2012. These larger differences indicate that at these clusters the two aquifer layers may be less well-connected than in the areas with smaller water-level differences. Some of these larger differences may be associated with pumping from nearby wells. If nearby wells pump from only one aquifer layer, the water-level differences between wells within a cluster may be greater than if the nearby wells were not pumping.

Chloride Concentrations

Sources of chloride in the *Equus* Beds aquifer include the Arkansas River, past disposal of oil-field brines, and salt beds in the underlying Permian-age Wellington Formation . Natural water from the unconsolidated aquifer normally contains less than 100 milligrams per liter (mg/L) chloride, whereas larger concentrations (100 to 500 mg/L) are common in the western part of the study area near the Burrton oil field and along the Arkansas River. Chloride concentrations in the Arkansas River averaged about 600 mg/L from 1988 through 1991 (Myers and others, 1996). From 1997 through 2006, concentrations of chloride in the Arkansas River between Hutchison and Maize averaged about 500 mg/L (Kansas Department of Health and Environment, 2006a). Upwelling of brines from the underlying

Permian salt beds enter tributaries upstream from Hutchison, Kansas that flow into the Arkansas River (Kansas Department of Health and Environment, 2006a; Whittemore, 2007, 2012). From 1985 through 2005, chloride concentrations averaged 267 mg/L in the Little Arkansas River near Alta Mills, Kansas (station 07143665, fig. 1) (Kansas Department of Health and Environment, 2006b). Sources of chloride in the Little Arkansas River include contamination from past oil and gas activities in McPherson County and municipal and industrial wastewater discharges (Leonard and Kleinschmidt, 1976; Kansas Department of Health and Environment, 2006b; Schmidt and others, 2007; Whittemore, 2007).

The U.S. Environmental Protection Agency (USEPA) established a Federal Secondary Drinking Water Regulation (SDWR) of 250 mg/L for chloride (U.S. Environmental Protection Agency, 1986). Constituents listed under the Federal SDWRs do not create health issues for humans, but limits are set for aesthetic reasons, such as taste and odor. When chloride concentrations are larger than 250 mg/L, consumers notice a bleach odor and salty taste in the water. In addition, large concentrations of chloride also can contribute to corrosion and staining of plumbing and fixtures (U.S. Environmental Protection Agency, 2005). Irrigation water with concentrations exceeding 350 mg/L chloride is likely to cause severe effects on crops (Bauder and others, 2007).

Chloride data from wells throughout the area collected in 2011 indicate that concentrations have increased by more than 10 percent in comparison to pre-2006 values in groundwater in the deep part of the aquifer area near Burrton, Kansas, especially near the Phase 1 recharge sites RB-01 and RRW04 and along the Arkansas River. These increases and current concentrations indicate that the chloride contamination from past oil and gas activities and the Arkansas River continues to migrate downgradient in the deep groundwater at a rate of about 1 foot per day. Chloride concentrations in groundwater in the shallow part of the aquifer have increased in the areas near Burrton in comparison to the pre-2006 values, but have decreased by more than 10% in the areas near IW14 and IW15 in the central part of the study area and along the Arkansas River near Bentley, indicated a possible improvement in water quality from infiltrating precipitation or the water quality in the Arkansas River.

Water-Level Changes, August 1940 to January 2012

Water-level changes from August 1940 to January 2012 are shown in figure 5. Water-level changes from August 1940 to January 2012 ranged from a decline of 22.77 ft at well 12B in the central part of the study area to a decline of 0.58 ft at well 118 near north of Halstead (fig. 5). The average August 1940 to January 2012 water-level change for the wells shown in figure 5 was a decline of about 9.73 ft (table 1). No obvious effects of artificial recharge are documented at the Phase 1 sites in this report, probably because before January 2012, artificial recharge last occurred in November 2010 (U.S. Geological Survey, 2011a). Water-level declines of 10 ft or more occurred in much of the central part of the study area and in T. 23 S. R. 3 W.; declines of 20 ft or more about 2 miles (mi) southeast of Halstead, Kansas (fig. 5). These declines likely were caused by reduced recharge from decreased precipitation and by pumping in the area.

FIGURE 5 NEAR HERE

Figure 5. Water-level changes in the *Equus* Beds aquifer in the study area, August 1940 to January 2012.

TABLE 1 NEAR HERE

Table 1. Storage-volume changes and average water-level changes in the *Equus* Beds aquifer near Wichita, south-central Kansas, August 1940 to January 2012.

Precipitation during January 2011 to January 2012 at the five weather stations in and near the study area (Halstead, Hutchinson, Mount Hope, Newton, and Wichita; fig. 1) ranged from about 17.79 in. at Halstead to about 25.92 in. at Wichita and averaged about 20.84 in. (National Oceanic and Atmospheric Administration, 2012a, 2012b, and 2012c; Kansas State Research and Extension, 2012). Average precipitation in the study area for August 2011 (the end of the last reporting period) through January 2012 was about 11.63 in., about 1 in. less than the study-area normal of 12.63 in. for August through January (National Oceanic and Atmospheric Administration, 2011b).

Pumpage in the part of the study area outside the central part of the study area tends to be dominated by irrigation, whereas city pumpage tends to dominate the central part of the study area (Hansen and Aucott, 2010). For example, in the part of the study area outside the central part of the study area in 2011, the latest year for which preliminary pumpage data were available, irrigation pumpage was about 30,600 acre-ft and no city pumpage occurred; within the central part of the study area in 2011, irrigation pumpage was about 13,100 acre-ft and city pumpage about 20,900 acre-ft (Kenneth Kopp, Kansas Department of Agriculture, Division of Water Resources, written commun., May 16, 2012; Shelly Bloesser, city of Wichita, written commun., June 18, 2012). In figure 5, therefore, the area of decline of 10 ft or more outside the central part of the study area likely was caused by irrigation pumpage and the area of decline of 10 ft or more within the central part of the study probably was mostly caused by city pumpage. Almost all pumpage for municipal use from the *Equus* Beds aquifer in the study area is for the city of Wichita. A comparison of 2010 reported and 2011 preliminary municipal and irrigation pumpage data in table 2 indicate irrigation pumpage increased by a larger percentage than than did city pumpage (Kenneth Kopp, Kansas Department of Agriculture, Division of Water Resources, written commun., May 16, 2012; Kansas Department of Agriculture, unpublished data, 2012; Shelly Bloesser, city of Wichita, written commun., June 18, 2012). Therefore, irrigation pumpage probably had a larger impact on the water-level declines in 2011 than in 2010.

TABLE 2 NEAR HERE

Table 2. Comparison of 2010 reported and 2011 preliminary pumpage data from the *Equus* Beds aquifer for the study area and the city of Wichita.

Table 1 includes average water-level changes for the wells used to make the water-level change maps associated with the storage-volume changes that are also shown in table 1. Average water-level changes since August 1940 are larger declines in the central part of the study area than in the whole study area (table 1). However, the changes since January 1993, July 2010, and January and July 2011 shown in table 1 generally are larger rises or smaller declines in the central part of the study area than in the whole study area. An exception is the July 2011 to January 2012 period when the average water-level changes were substantially smaller rises in the central part of the study area than in the study area (table 1). These rises followed water levels that in July 2011 were a substantial decline from the largest recorded post-January recoveries to date that occurred in July 2010 (Hansen, 2012). Smaller July 2011 to January 2012 water-level rises probably occurred in the central part of the study area because it is dominated by city pumpage, which continues throughout the year; the rest of the study area is dominated by irrigation pumpage, which decreases in the fall and winter and when combined with recharge from near-normal precipitation may have allowed larger water-level recoveries.

This is probably because the annual fall and winter decreases in irrigation pumpage and increases recharge from near-normal precipitation from August 2011 through January 2011 allowed a larger partial recovery of water levels in from the large decreases that occurred from January 2011 to

July 2011 (Hansen, 2012) in the part of the study area dominated by irrigation while in the central part of the study area pumpage for city use, which occurs in the central part of the study area, continues throughout the year.

Storage-Volume Change, January 2012

Storage-volume change in the *Equus* Beds aquifer is greatly affected by irrigation and city pumpage. Commonly, only about one-third of irrigation pumpage from the *Equus* Beds aquifer in the study area occurs within the central part of the study area and the other two-thirds occurs outside of it; all city pumpage from the *Equus* Beds aquifer generally occurs within the central part of the study area (Kansas Department of Agriculture, Division of Water Resources, unpub. data, 2011). Therefore, changes in city pumpage have more effect in the central part of the study area and changes in irrigation pumpage have more effect in the rest of the study area.

Study Area

The storage volume of water in the *Equus* Beds aquifer decreased in the study area from August 1940 to January 2012 by about 168,000 acre-ft (fig. 2, table 1). The storage volume in the study area in January 2012 was about 41,000 acre-ft more than in July 2011 (table 1); storage-volume generally increases from July to January. Storage-volume amounts in January 2012 were similar to those seen in the late 1990s and early 1980s (fig. 2).

From August 1940 (just before Wichita began pumping water from the study area) to January 1993 (when near-record low water levels and storage volumes occurred in the study area because of a combination of drought conditions and increased usage), storage volume decreased by about 255,000 acre-ft in the study area (Aucott and Myers, 1998). The change in storage volume from January 1993 to January 2012 represents a recovery of 87,000 acre-ft (table 1) or about 34 percent of storage volume lost between August 1940 and January 1993. Between January 1993 and July 2010, when the largest post-1993 recorded recovery to date occurred, about 161,300 acre-ft of storage volume was recovered in the study area (table 1); this represented a recovery of about 63 percent of the storage volume lost between August 1940 and January 1993. These recoveries were attributed by Hansen and Aucott (2010) and Hansen (2011a) to the approximately 50-percent decrease in city pumpage as a part of Wichita's ILWSP and to decreased irrigation pumpage and increased recharge associated with greater-than-normal precipitation in most years. The approximately 2,800 acre-ft of water that was artificially recharged to the aquifer by the city of Wichita through the six Phase 1 recharge sites (fig. 3) from March 2007 to July 2010 was only a minor factor in the January 1993 to July 2010 storage-volume recovery (U.S. Geological Survey, 2012a).

From July 2010 to July 2011, storage-volume loss of about 115,000 acre-ft occurred in the study area (table 1) because of precipitation was much less than normal resulting in reduced recharge to the aquifer and increased pumpage from the aquifer (Hansen, 2012). From July 2011 to January 2012, storage volume increased by about 41,000 acre-ft, which represents a recovery of about 36 percent of the storage volume lost from July 2010 to July 2011. Artificial recharge was not a factor in this recovery because none occurred from July 2011 to January 2012 (U.S. Geological Survey, 2012a). Major factors in the July 2011 to January 2012 recovery probably are seasonal decreases in irrigation pumpage and increased recharge from near-normal precipitation.

Central Part of Study Area

The change in storage volume in the *Equus* Beds aquifer in the central part of the study area (where Wichita city wells are located) from August 1940 to January 2012 was a decrease of about 77,100 acre-ft (fig. 2, table 1). Storage volume in the central part of the study area in January 2012 was about 8,800 acre-ft more than in July 2011 (table 1). From January 1993 to January 2012, storage volume in the central part of the study area increased by about 76,900 acre-ft (table 1) or about a 50-percent recovery of the storage volume previously lost from August 1940 to January 1993 because of increase recharge from above-normal precipitation and city pumpage that decreased as part of Wichita’s ILWSP (Hansen and Aucott, 2010; Hansen, 2011a).

Between January 1993 and July 2010 (when the largest recorded recovery to date occurred) about 98,000 acre-ft of storage volume was recovered in the central part of the study area (table 1). About 21,100 acre-ft of this recovery was lost from July 2010 to July 2011 (table 1) because of drought conditions and pumpage from the aquifer (Hansen, 2012). The increase of approximately 8,800 acre-ft of storage volume from July 2011 to January 2012 represents a recovery if about 29 percent of the storage volume lost from July 2010 to July 2011 in the central part of the study area (table 1). Seasonal decreases in pumpage and increased recharge from near-normal precipitation probably were major factors in this this recovery.

Estimating storage volume changes from average water-level changes

The average water-level changes since August 1940 and since January 1993 computed for 3 sets of wells and the storage volume changes since August 1940 and January 1993 for the study area and central part of the study area from table 2 were plotted in relation to each other (fig 6). Both the average water-level changes for the study area and for the index wells were plotted against the storage-volume changes for the study area; the average water-level changes for the central part of the study area were plotted against the storage-volume changes for the central part of the study area (fig. 6). The point data shown in figure 6 do not display any pronounced seasonal effect. The slopes of the regression lines for the study area and the index wells indicate that for each average water-level change of 1 ft, there is change in storage volume of between 13,000 and 16,000 acre-ft (fig. 6). The regression lines for the index wells are similar to but somewhat offset from those for the study area. This probably is because none of the index wells are located near city public-supply wells. Thus, the storage volumes computed from the regression lines of the index wells are less affected by city pumpage. As a result, for the same decreases in storage volumes since August 1940, the average water-level change for the set of index wells will be a smaller decline than that for the study-area set of wells; similarly, for the same increase in storage volume since January1993, the average water-level change for the set of index wells will be a smaller rise than that for study-area set of wells.

TABLE 3 NEAR HERE

Table 3. Average water-level change in the study area, index wells, and central part of the study area and change in storage volume in the study area and central part of the study area, August 1940 to January 2012.

FIGURE 6 NEAR HERE

Figure 6. Statistical relation between average change in water levels and change in storage volumes in the study area and central part of the study area since August 1940 and January 1993. Average water-level changes computed from wells used to make water-level change maps. Symbols: square, study area since 1940; triangle, central part of study area since 1940; X, index wells since 1940; circle, study area since 1993; diamond, central part of study area since 1993; and asterisk, index wells since 1993. Winter (January) values in blue, spring (April) values in purple, summer (July) values in green, and fall (October) values in orange.

The slope of the regression lines for the central part of the study area indicate that for each average water-level change of 1 ft, there is a change in storage volume in the central part of the study area of about 6,300 acre-ft. The smaller change in storage volume for each 1 ft change in average water level for the central part of the study area than for the study area is because the central part of the study area is only about one-third the size of the study area. As might be expected, the largest average water-level decreases (between about 17 to 25 ft) and increases (between 11 to 15 ft) are in the central part of the study area where city pumpage regularly causes large declines and decreases in city pumpage that are part of Wichita's ILWSP have contributed to large recoveries (figs. 2 and 6).

Calculating the differences between measured water levels and the averaging of these differences are computations more easily made than are the construction of water-level change maps, computation of storage-volumes from these maps, and calculating the changes in storage volume from those computations. The linear regression equation for the study area since August 1940 may provide a simple empirical method for estimating the amount of storage-volume change from the average measured water-level changes (fig.6, table 2). This may be especially useful for estimating storage-volume changes for periods when maps of water-level changes used for the computation of storage-volume change are not available.

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Table 1. Storage-volume changes and average water-level changes in the *Equus* Beds aquifer near Wichita, south-central Kansas, August 1940 to January 2012.

[Data on file with U.S. Geological Survey, Lawrence, Kansas.]

	Study area		**Central part of study area**	
Time period	**Storage-volume changes (acre-feet)**	**Average water-level change (feet)**	**Storage-volume changes (acre-feet)**	**Average water-level change (feet)**
August 1940 to January 1993	[1]-255,000	[4]-16.07	[1]-154,000	[4]-24.09
August 1940 to July 2010	[2]-93,700	[4]-6.72	[2]-56,000	[4]-10.13
August 1940 to January 2011	[3]-104,000	[4]-6.99	[3]-57,100	[4]-9.80
August 1940 to July 2011	[4]-209,000	[4]-12.45	[4]-85,900	[4]-14.62
August 1940 to January 2012	-168,000	-9.73	-77,100	-12.69
January 1993 to July 2010	[2]+161,300	[4]10.20	[2]+98,000	[4]14.19
January 1993 to July 2011	[4]+46,000	[4]5.00	[4]+68,100	[4]9.84
January 1993 to January 2012	+87,000	6.34	+76,900	10.20
July 2010 to July 2011	[4]-115,300	[4]-5.73	[4]-29,900	[4]-4.35
July 2010 to January 2012	-74,300	-3.99	-21,100	-3.29
January 2011 to July 2011	[4]-105,000	[4]-5.20	[4]-28,800	[4]-4.83
January 2011 to January 2012	-64,000	-3.45	-20,000	-3.53
July 2011 to January 2012	+41,000	1.83	+8,800	0.73

[1] Storage-volume change previously reported by Aucott and Myers (1998).

[2] Storage-volume change previously reported by Hansen (2011a).

[3] Storage-volume change previously reported by Hansen (2011b).

[4] Storage-volume change previously reported by Hansen (2012).

Table 2. Comparison of 2010 reported and 2011 preliminary pumpage data from the *Equus* Beds aquifer for the city of Wichita and the study area.

[Data from city of Wichita, written commun., 2012; Kansas Department of Agriculture, written commun., 2012; and Kansas Department of Agriculture, unpub. data, 2012]

Area	Pumpage from the *Equus* Beds aquifer (acre-feet)		Pumpage change from 2010 to 2011 (percent)
	2010	2011	
City of Wichita in the central part of the study area	20,100	20,900	104
Central part of study area	28,900	34,000	118
Study area	50,200	64,700	129
Equus Beds Groundwater Management District Number 2	155,000	248,000	160

Table 3. Average water-level change in the study area, in central part of study area, and in index wells and change in storage volume in the study area and central part of the study area, August 1940 to January 2012.

[August 1940 water levels measured in 47 wells used to make water-level change maps; August 1940 water levels estimated for all other wells. January 1993 water levels estimated for all index wells. Index wells not measured before July 2002. Average water-level changes are computed from wells used to make water-level change maps]

	Beginning of time period									
	August 1940					January 1993				
	In study area			In central part of study area		In study area			In central part of study area	
End of time period	Average water-level change (feet)		Change in storage volume (acre-feet)	Average water-level change (feet)	Change in storage volume (acre-feet)	Average water-level change (feet)		Change in storage volume (acre-feet)	Average water-level change (feet)	Change in storage volume (acre-feet)
	Study area	Index wells				Study area	Index wells			
August 1940	0.00	—	0	0.00	0	—	—	—	—	—
January 1957	-13.62	—	-171,000	-19.23	-93,800	—	—	—	—	—
January 1970	-7.29	—	-108,000	-11.17	-68,500	—	—	—	—	—
January 1978	-6.35	—	-93,500	-10.73	-64,500	—	—	—	—	—
January 1979	-9.80	—	-146,000	-14.18	-84,400	—	—	—	—	—
January 1984	-13.05	—	-198,000	-18.49	-112,000	—	—	—	—	—
January 1989	-13.58	—	-209,000	-19.02	-115,000	—	—	—	—	—
January 1991	-15.50	—	-241,000	-21.52	-132,000	—	—	—	—	—
July 1992	-15.55	—	-252,000	-22.96	-145,000	—	—	—	—	—
October 1992	-16.75	—	-283,000	-24.24	-159,000	—	—	—	—	—
January 1993	-16.07	—	-255,000	-24.09	-154,000	0.00	—	0	0.00	0
July 1993	-12.71	—	-198,000	-20.95	-130,000	3.37	—	57,000	3.00	24,000
January 1994	-12.89	—	-192,000	-19.80	-122,000	3.52	—	63,000	4.66	32,000
January 1995	-15.52	—	-245,000	-21.87	-137,000	0.88	—	10,000	2.52	17,000
January 1996	-13.97	—	-210,000	-19.82	-122,000	2.95	—	45,000	4.74	32,000
October 1996	-14.74	—	-215,000	-20.57	-125,000	2.46	—	40,000	4.21	29,000
January 1997	-14.17	—	-205,000	-20.32	-123,000	2.92	—	50,000	4.50	31,000
April 1997	-13.65	—	-195,000	-19.71	-120,000	3.66	—	60,000	5.21	34,000
July 1997	-13.82	—	-210,000	-19.27	-119,000	3.18	—	45,000	5.35	35,000
October 1997	-13.01	—	-186,000	-18.79	-114,000	4.21	—	69,000	5.96	40,000
January 1998	-12.26	—	-176,000	-17.71	-110,000	5.05	—	79,000	7.20	44,000
April 1998	-11.41	—	-167,000	-16.82	-104,000	5.83	—	88,000	8.09	50,000
July 1998	-13.85	—	-216,000	-18.81	-117,000	3.16	—	39,000	5.70	37,000
October 1998	-13.16	—	-201,000	-18.24	-113,000	4.14	—	54,000	6.51	41,000
January 1999	-9.93	—	-142,000	-15.29	-96,300	7.60	—	113,000	9.83	57,700
April 1999	-8.98	—	-126,000	-13.80	-87,000	8.74	—	129,000	11.36	67,000
July 1999	-10.50	—	-159,000	-15.23	-92,700	6.75	—	96,000	9.96	61,300
October 1999	-9.90	—	-142,000	-14.52	-89,300	7.62	—	113,000	10.78	64,700
January 2000	-9.08	—	-126,000	-13.30	-70,600	8.59	—	129,000	11.76	83,400
April 2000	-7.27	—	-101,000	-11.76	-74,500	10.30	—	154,000	13.39	79,500
July 2000	-9.61	—	-152,000	-12.48	-76,700	7.59	—	103,000	12.57	77,300
October 2000	-10.44	—	-159,000	-14.27	-87,000	6.83	—	96,000	10.65	67,000
January 2001	-8.91	—	-134,000	-12.61	-78,900	8.39	—	121,000	12.37	75,100
April 2001	-7.69	—	-110,000	-11.55	-72,500	9.95	—	145,000	13.56	81,500

	Beginning of time period									
	August 1940					January 1993				
	In study area			In central part of study area		In study area			In central part of study area	
	Average water-level change (feet)		Change in storage volume (acre-feet)	Average water-level change (feet)	Change in storage volume (acre-feet)	Average water-level change (feet)		Change in storage volume (acre-feet)	Average water-level change (feet)	Change in storage volume (acre-feet)
End of time period	Study area	Index wells				Study area	Index wells			
July 2001	-9.93	—	-149,000	-12.10	-74,900	8.31	—	106,000	12.93	79,100
October 2001	-9.26	—	-146,000	-12.54	-76,700	7.74	—	109,000	12.23	77,300
January 2002	-9.06	—	-142,000	-12.37	-77,100	7.93	—	113,000	12.25	76,900
April 2002	-9.07	—	-141,000	-12.27	-74,900	8.02	—	114,000	12.57	79,100
July 2002	-9.75	-8.43	-162,000	-13.00	-78,600	6.81	4.38	93,000	11.28	75,400
October 2002	-11.59	-11.33	-187,000	-14.93	-90,100	5.40	1.47	68,000	9.48	63,900
January 2003	-9.94	-9.01	-159,000	-13.56	-83,400	6.96	3.79	96,000	10.93	70,600
April 2003	-9.52	-7.72	-153,000	-13.71	-84,400	7.10	5.08	102,000	10.60	69,600
July 2003	-11.79	-12.70	-197,000	-14.71	-89,300	5.36	0.10	58,000	9.93	64,700
October 2003	-11.53	-10.27	-186,000	-15.29	-92,300	5.29	2.79	69,000	9.05	61,700
January 2004	-10.41	-9.03	-170,000	-14.48	-89,900	6.23	3.77	85,000	9.83	64,100
April 2004	-9.29	-7.99	-147,000	-13.54	-83,600	7.65	5.16	108,000	10.84	70,400
July 2004	-10.66	-10.45	-166,000	-14.52	-86,900	6.60	3.01	89,000	10.08	67,100
October 2004	-9.89	-8.65	-158,000	-14.04	-86,200	6.89	4.15	97,000	10.30	67,800
January 2005	-9.24	-7.80	-143,000	-13.36	-82,700	7.67	5.01	112,000	11.09	71,300
April 2005	-8.85	-6.94	-131,000	-13.18	-80,500	8.33	5.87	124,000	11.33	73,500
July 2005	-8.79	-4.73	-137,000	-12.26	-74,300	8.39	5.06	118,000	12.20	79,700
October 2005	-8.59	-7.07	-131,000	-12.36	-74,300	8.44	5.73	124,000	12.16	79,700
January 2006	-8.09	-6.92	-127,000	-11.43	-68,900	8.89	5.88	128,000	13.20	85,100
April 2006	-8.60	-8.17	-135,000	-12.01	-72,300	8.60	4.64	120,000	12.72	81,700
July 2006	-10.74	-10.82	-180,000	-13.15	-78,300	6.61	1.32	75,000	11.57	75,700
October 2006	-11.19	-10.36	-182,000	-14.63	-86,700	5.90	2.45	73,000	9.76	67,300
January 2007	-10.42	-9.82	-167,000	-13.78	-82,900	6.60	2.99	88,000	10.82	71,100
April 2007	-10.50	-9.00	-161,000	-14.18	-84,800	6.76	3.80	94,000	10.50	69,200
July 2007	-8.34	-7.00	-123,000	-12.40	-75,300	8.93	5.81	132,000	12.24	78,700
October 2007	-9.83	-8.50	-154,000	-13.66	-81,100	7.02	4.30	101,000	10.71	72,900
January 2008	-9.32	-7.77	-141,000	-12.99	-78,400	7.81	5.03	114,000	11.46	75,600
April 2008	-8.71	-7.20	-135,000	-12.39	-75,600	8.49	5.60	120,000	12.13	78,400
July 2008	-8.71	-8.07	-134,000	-11.82	-71,200	8.55	4.73	121,000	12.85	82,800
January 2009	-7.49	-6.03	-111,000	-11.02	-66,600	9.54	6.77	144,000	13.34	87,400
July 2009	-8.08	-7.12	-124,000	-11.00	-64,100	9.23	5.68	131,000	13.53	89,900
January 2010	-6.40	-5.39	-100,000	-9.32	-57,600	10.60	7.41	155,000	15.10	96,400
July 2010	-6.72	-4.36	-93,700	-10.13	-56,000	10.06	8.44	161,300	13.96	98,000
January 2011	-6.99	-5.98	-104,000	-9.80	-57,100	10.13	6.90	151,000	14.56	96,900
July 2011	-12.45	-12.27	-209,000	-14.62	-85,900	4.77	0.53	46,000	9.75	68,100
January 2012	-9.73	-9.55	-168,000	-12.69	-77,100	5.35	3.25	87,000	9.98	76,900

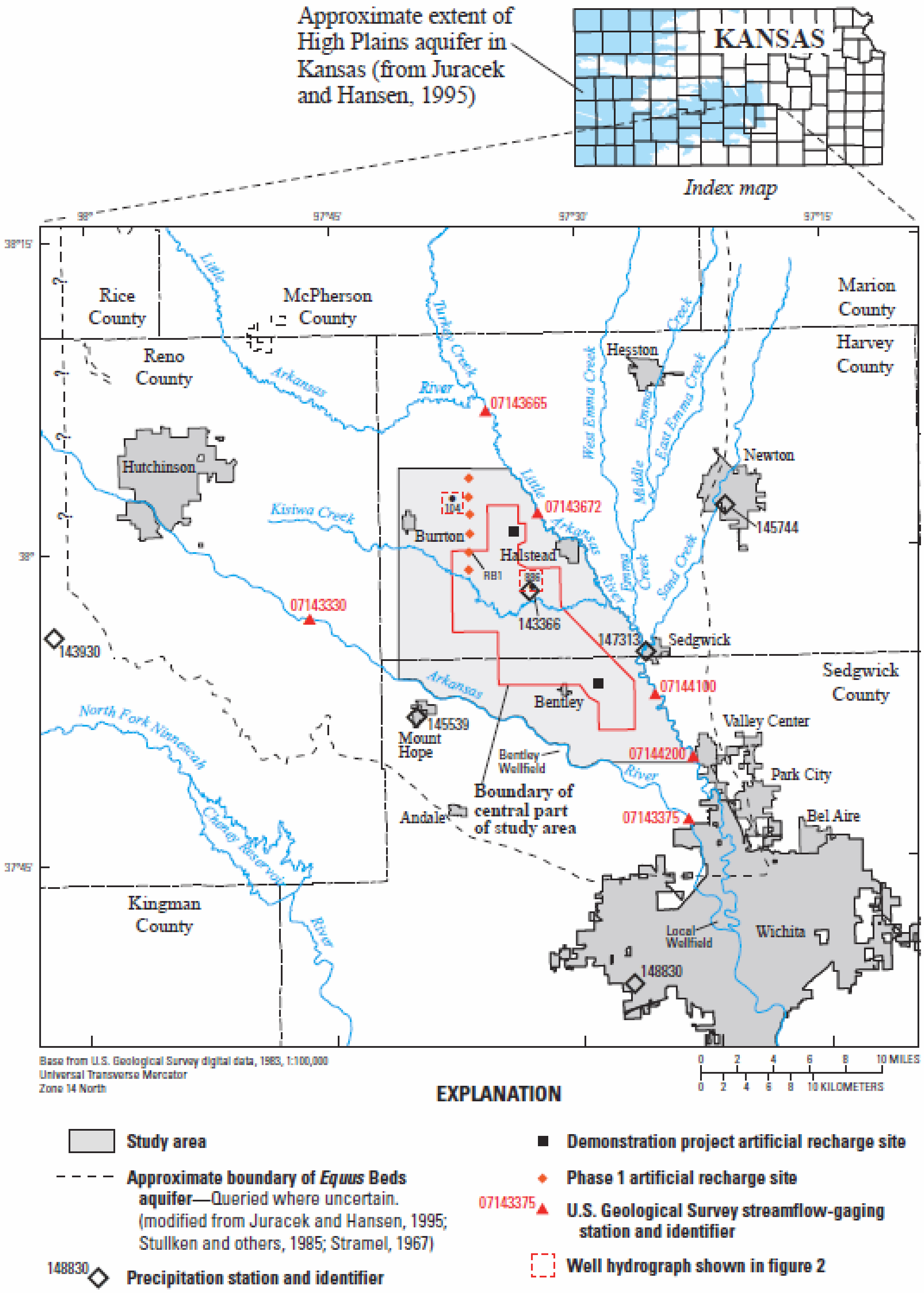

Figure 1. Location of study area near Wichita, south-central Kansas (modified from Aucott and Myers, 1998).

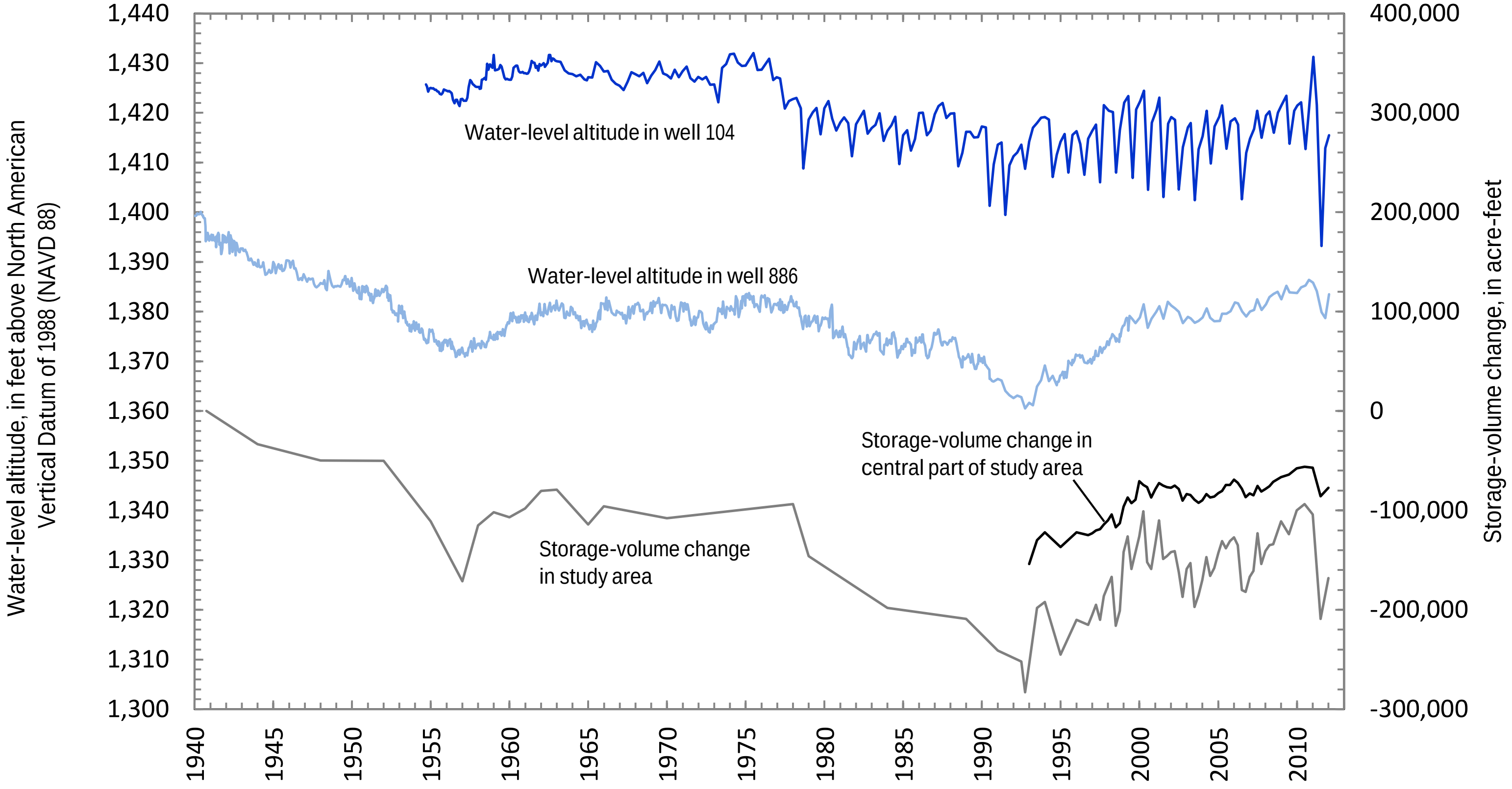

Figure 2. Water-level altitudes in observation wells 104 and 886 and *Equus* Beds aquifer storage-volume change in the study area and the central part of the study area (water-level altitude data are from Stramel (1956, 1967), and from data collected by city of Wichita that are on file with U.S. Geological Survey in Lawrence, Kansas; storage-volume changes are from Stramel (1956, 1967), Aucott and Myers (1998), Aucott and others (1998), Hansen and Aucott (2010), Hansen (2011a, 2011b, 2012), and unpublished data on file with the U.S. Geological Survey in Lawrence, Kansas). Locations of observation wells are shown in figure 1.

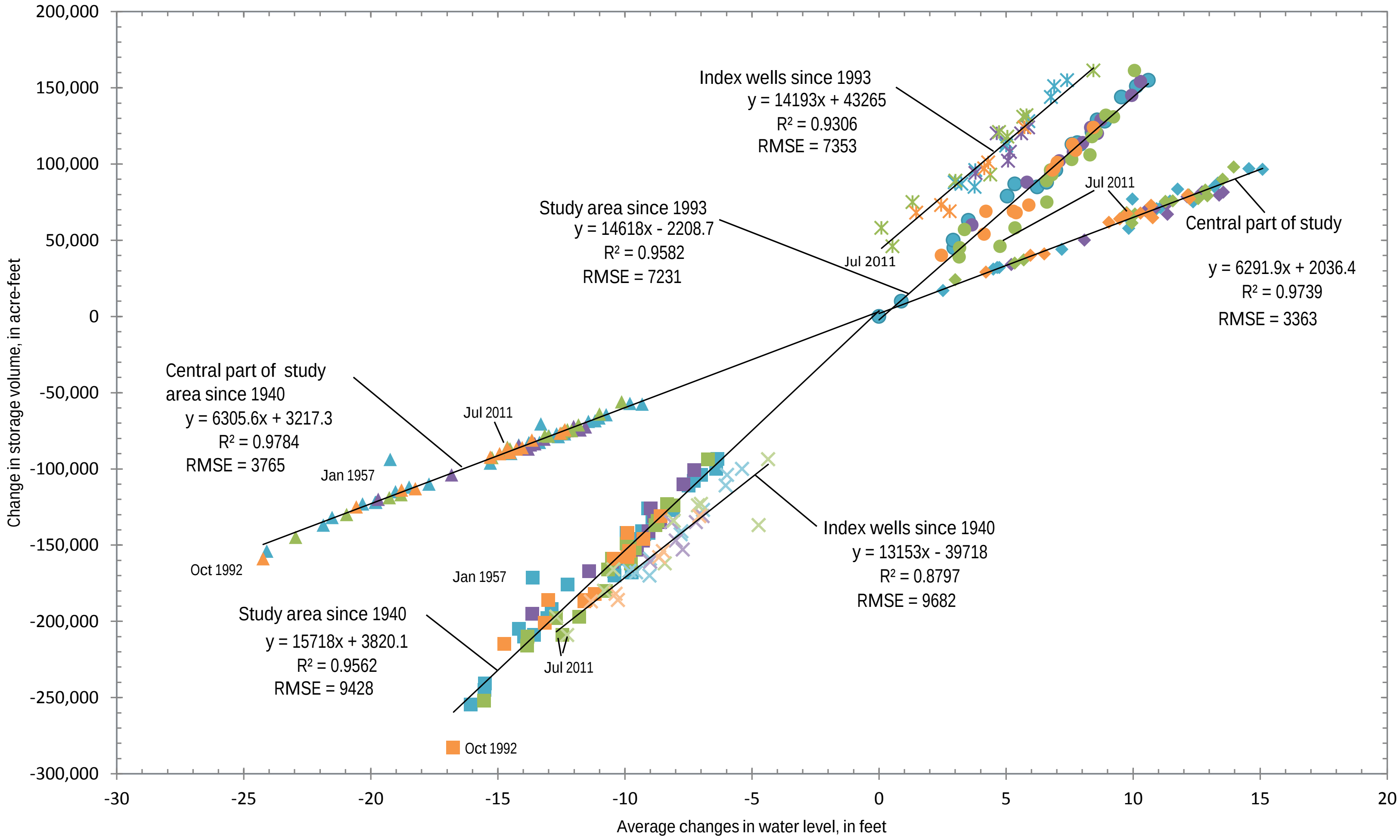

Figure 6. Statistical relation between average change in water levels and change in storage volumes in the study area and the central part of the study area since August 1940 and since January 1993. Average water-level changes computed from wells used to make water-level change maps. Symbols: square, study area since 1940; triangle, central part of study area since 1940; X, index wells since 1940; circle, study area since 1993; diamond, central part of study area since 1993; and asterisk, index wells since 1993. Winter (January) values in blue, spring (April) values in purple, summer (July) values in green, and fall (October) values in orange.