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SCIENTIFIC INVESTIGATIONS MAP 3192
Status of groundwater levels and storage volume in the *Equus* Beds aquifer
Hansen, C.V., 2011, Status of groundwater levels and storage volume in the *Equus* Beds aquifer near Wichita, Kansas, January 2011

Abstract

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. 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, the aquifer has been experiencing higher water levels and a partial recovery of storage volume. Potentiometric maps of the shallow and deep layers of the map show flow in both aquifer layers is generally from west to east. 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 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 1,440 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 up to 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 2011 ranged from a decline of 16.52 feet to a rise of 2.22 feet. The change in storage volume from August 1940 to January 2011 was a decrease of about 104,000 acre-feet. This volume represents a recovery of about 151,000 acre-feet, or about 59 percent of the storage volume previously lost between August 1940 and January 1993. It also represents a recovery of about 63,000 acre-feet, or about 38 percent of the storage volume lost between August 1940 and January 2007. Major factors in these storage-volume recoveries are increased recharge from greater-than-normal precipitation and planned decreases in city pumpage that are part of Wichita's Integrated Local Water Supply Plan; however, part of the recovery may be because city and irrigation pumpage probably decreased in response to greater-than-normal precipitation in the study area. Storage volume from July 2010 to January 2011 did not increase as it commonly does from July to January. The change in storage volume from July 2010 to January 2011 was a decrease of 10,300 acre-feet, probably because average precipitation in the study area during August 2010 through January 2011 was about 3.01 inches less than the August through January normal of 12.63 inches for the study area.

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 these 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 2011. In 2007, the city of Wichita began using Phase I of the *Equus* Beds Aquifer Storage and Recovery (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?]). The water from the Little Arkansas River is treated to drinking-water standards before being recharged to the aquifer (City of Wichita, [2007?]).

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 central part of the study area (fig. 1), which covers about 55 mi^2, 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, 2010).

The *Equus* Beds aquifer consists of Quaternary-age deposits in the study area. Quaternary-age deposits in the study area primarily are alluvial deposits with some dune sand and loess (Myers and others, 1996). The alluvial deposits, known locally as the *Equus* beds, 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).

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 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. 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-feet (acre-ft) (Hansen, 2007). Near the Arkansas River and in the western part of the study area, the water table 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 2011), 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).

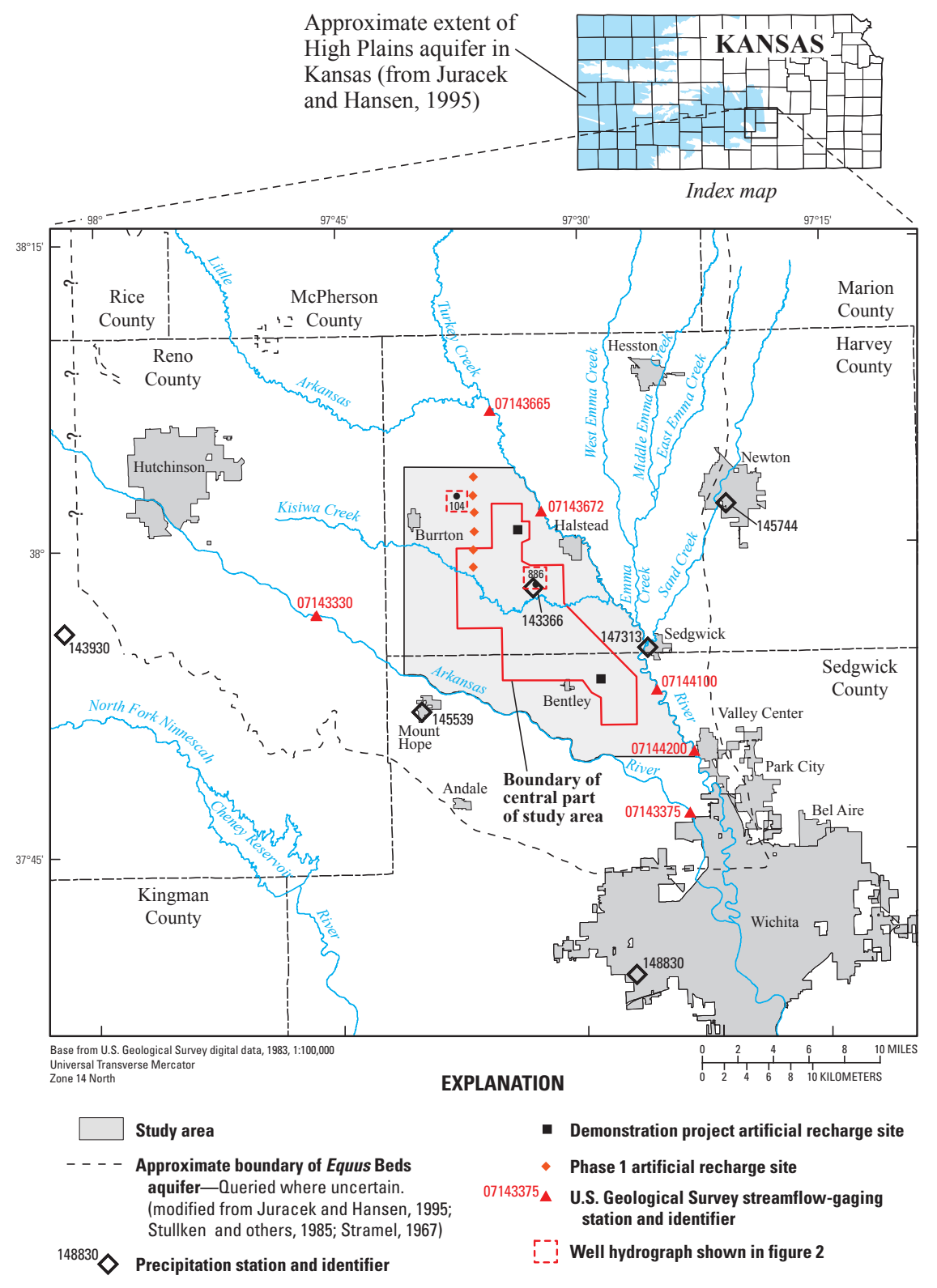

Figure 1. Location of study area near Wichita, south-central Kansas (modified from Aucott and Myers, 1998).

These semiconfined conditions probably resulted in the substantial differences seen between the shallow and deep parts of the *Equus* Beds aquifer in water levels (Stramel, 1956) and water quality (Ziegler and others, 2010) in some parts of the study area. 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 of separate potentiometric-surface maps of the shallow and deep layers of the aquifer.

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 has clusters of historic and index monitoring wells. The shallower well in each historic or index 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 historic and index wells were completed and screened to a depth of 80 ft or less, and about 90 percent of the GMD2 C zone wells and deeper historic and index wells 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 aquifer layers was reasonable when assigning the city of Wichita historic 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 January 24, 2011, at 158 historic monitoring wells, 75 index wells, 2 ASR Phase 1 monitoring wells, and 55 other 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 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 2011. The other monitoring wells were installed for GMD2 or are existing wells used by GMD2 to monitor the *Equus* Beds aquifer. Water levels in the historic monitoring wells were measured by city of Wichita personnel; water levels in the index wells were measured by GMD2 personnel. Water levels in the Phase 1 monitoring wells are from USGS-maintained multi-sensor monitors that continuously collect physical properties, including water-level altitude. Water levels in the other monitoring wells were measured by GMD2. 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 Water and Sewer Department in Wichita, Kansas; the index and other 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, 2011); and well data collected by the USGS are stored in the USGS's National Water Information System (NWIS) database (U.S. Geological Survey, 2011b). The water-level data used in this report from the historic monitoring wells, the index wells, ASR Phase 1 monitoring wells, and the other monitoring wells also are stored in NWIS.

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. Because the groundwater-level measurements used for the shallow aquifer layer were collected over several days, 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, 2011b). These measurements were used along with the groundwater-level measurements in the construction of the shallow layer potentiomentric-surface map created for this report.

Water-Level Altitudes

The January 2011 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 (NED) (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 201 wells assigned to the shallow layer of the aquifer range in depth from 7 to 135 ft in depth, with about 95 percent of the wells 80 ft or less in depth. The 89 wells assigned to the deep layer of the aquifer range in depth from 50 to 285 ft in depth with about 95 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.

The January 2011 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 the 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 preliminary 2010 water-use associated with these points (Kansas Department of Agriculture, Division of Water Resources, unpub. data., May 2011) 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 2011 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 146 wells used for the water-level change map, only 33 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 2011 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, 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 2011 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 2011 was calculated as the change in storage volume for August 1940 to January 2011 minus the change in storage volume for August 1940 to January 1993.

Precipitation

Precipitation for the study area for 2010 and 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, 2011c). 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, 2011d). 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, 2011b). 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).

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 agricultural-irrigation pumpage.

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 since January 1993, higher water levels have been recorded in the *Equus* Beds aquifer because of near-normal to greater-than-normal precipitation and decreased city pumpage (Aucott and Myers, 1998; Hansen and Aucott, 2001, 2004, 2010; Hansen, 2007, 2009a, 2009b, 2011). Pumpage for agricultural irrigation, which 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. Water levels in wells in the study area have continued to remain relatively high (fig. 2), indicating this period of higher water levels that began in 1993 continued through January 2011. 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 and Aucott, 2010).

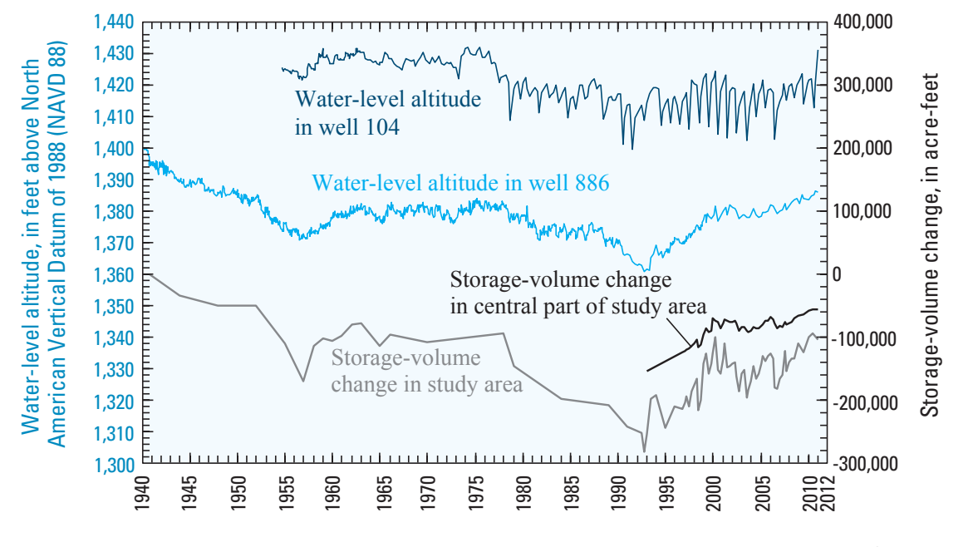

Figure 2. Water-level altitudes in monitoring wells 104 and 886 and *Equus* Beds aquifer storage-volume change in the study area and the central part of the study area (water-level-altitude data are from Stramel (1956, 1967) and data collected by city of Wichita that are on file with U.S. Geological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

Potentiometric Surfaces of the Shallow and Deep Aquifer Layers, January 2011

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. Water-level altitudes in the shallow aquifer layer range from a high of about 1,470 ft in 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 1,440 ft on the west edge of the study area to a low of about 1,330 ft at the southeast corner of the study area. Where the potentiometric-surface contours bow out to the west (for example, from the southeast to northwest corners of T. 24 S., R. 2 W. on fig. 3) or are hachured (for example, near wells EB10A and IW05A on fig. 3 and near wells EB14C, 42D, 46D, and 50D 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, 2011a).

Where water-levels in the shallower wells differ from those in the deeper wells in the same cluster, it may indicate there is a vertical component of flow within the aquifer. A downward vertical gradient may be indicated where the water levels are higher in the shallower wells than in the deeper wells within a cluster; an upward vertical gradient may be indicated where the water levels are lower in the shallower wells than in the deeper wells within a cluster. Within 36 of the 84 clusters in the study area, the water-level differences in January 2011 between the shallower and deeper wells were 1 ft or less and probably do not indicate a substantial vertical component of flow. However, within 48 of the 84 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 2011. In 17 of the 84 clusters in the study area, the water levels ranged from about 6 to about 28 ft higher in the shallower wells than in the deeper wells in January 2011. These larger differences may indicate that at these clusters the two aquifer layers probably are not well connected.

Water-Level Changes, August 1940 to January 2011

Water-level changes from August 1940 to January 2010 are shown in figure 5. Water levels were measured in the historic monitoring wells by city of Wichita personnel on January 3, 2011, and from January 11 through 20, 2011; water levels were measured in the index wells by GMD2 personnel on January 20 and 21, 2011. Water-level changes from August 1940 to January 2011 ranged from a decline of 16.52 ft at well 12B in the central part of the study area to a rise of 2.22 ft at well 118 near the Little Arkansas River in the northern part of the study area (fig. 5). Water-level declines of 10 ft or more occurred in much of the central part of the study area (fig. 5), probably because of pumping in this area and decreased precipitation. Precipitation during August 2010 through January 2011 at the five weather stations in and near the study area (Halstead, Hutchinson, Mount Hope, Newton, and Wichita; fig. 1) ranged from about 8.90 in. at Mount Hope to about 10.62 in. at Hutchinson and averaged about 9.62 in. (National Oceanic and Atmospheric Administration, 2011a and 2011c; Kansas State Research and Extension, 2011; and Mary Knapp, State Climatologist, written commun., July 19, 2011). Precipitation in the study area during August 2010 through January 2011 averaged about 3.01 in. less than the study-area normal of 12.63 in. for August through January (National Oceanic and Atmospheric Administration, 2011c). The small water-level rises in the southwest and northeast parts of the study area (fig. 5) may be because of decreased pumpage in these areas or infiltration from the nearby streams. No obvious effects of artificial recharge are documented at the Phase 1 sites in this report, probably because artificial recharge last occurred in November 2010, only at the four northern Phase 1 sites, and totaled only 20 acre-ft. Previous to November, artificial recharge last occurred in August 2010 (U.S. Geological Survey, 2011a).

Storage-Volume Change, January 2011

The storage volume decreased in the study area from August 1940 to January 2011 by about 104,000 acre-ft (fig. 2, table 1). Storage-volume amounts in January 2011 were similar to those seen in the 1970s (fig. 2). The storage volume in the study area in January 2011 was about 10,300 acre-ft less than in July 2010, and about 4,000 acre-ft less than in January 2010 (table 1). 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 2011 represents a recovery of about 151,000 acre-ft (table 1) or about 59 percent of the storage volume previously lost from August 1940 to January 1993. From August 1940 to January 2007 (when the last set of water-level measurements were made before large-scale artificial recharge began), storage volume decreased by about 167,000 acre-ft (table 1). The change in storage volume from January 2007 to January 2011 represents a recovery of about 63,000 acre-ft, or about 38 percent of the storage volume previously lost from August 1940 to January 2007. Most of these recoveries probably can be attributed to planned decreases in city pumpage (Warren and others, 1995) and to reduced irrigation pumpage and increased recharge associated with increased precipitation (Hansen and Aucott, 2010). Since March 2007, when Wichita began large-scale artificial recharge, about 2,869 acre-ft (about 934 million gallons) of water have been artificially recharged into the aquifer through the six Phase 1 recharge sites shown in figure 3 (U.S. Geological Survey, 2011a). Hansen and Aucott (2010) documented the amount of artificial recharge is relatively small compared to the amount of the city and agricultural-irrigation pumpage from the *Equus* Beds aquifer in the study area for the same period.

Table 1. Storage-volume changes in *Equus* Beds aquifer near Wichita, south-central Kansas, August 1940 to January 2011.

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

Time period	Storage-volume changes, in acre-feet	
	Study area	"Central part of study area"
August 1940 to January 1993	[1]-255,000	[1]-154,000
August 1940 to January 2007	[2]-167,000	[2]-82,900
August 1940 to January 2010	[2]-100,000	[2]-57,600
August 1940 to July 2010	[3]-93,700	[3]-56,000
August 1940 to January 2011	-104,000	-57,100
January 1993 to January 2011	+151,000	+96,900
January 2007 to January 2011	+63,000	+25,800
January 2010 to January 2011	-4,000	+500
July 2010 to January 2011	-10,300	-1,100

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

[2] Storage-volume change previously reported by Hansen and Aucott (2010).

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

The commonly observed increase in storage volume from July to January did not occur from July 2010 to January 2011 when storage volume in the study area decreased by about 10,300 acre-ft (table 1). Reduced recharge and increased pumpage associated with less than normal precipitation during this period is the probable cause. Although the annual precipitation in the study area for 2010 of 32.12 in. was just 0.02 in. less than normal, precipitation from August 2010 through January 2011 was about 3.01 in. less than the study-area normal of 12.63 in. for August through January (National Oceanic and Atmospheric Administration, 2011a and 2011c; Kansas State Research and Extension, 2011; and Mary Knapp, State Climatologist, written commun., July 19, 2011).

The change in storage volume in the central part of the study area (where Wichita city wells are located) from August 1940 to January 2011 was a decrease of about 57,100 acre-ft (fig. 2, table 1). Storage volume in the central part of the study area in January 2011 was about 500 acre-ft more than in January 2010 and about 1,100 acre-ft less than in July 2010 (table 1). From January 1993 to January 2011, storage volume in the central part of the study area increased by about 96,900 acre-ft (table 1) or about 63 percent of the storage volume previously lost from August 1940 to January 1993. From January 2007 (just before large-scale artificial recharge began) to January 2011, storage volume in the central part of the study area increased by about 25,800 acre-ft or about 31 percent of the storage volume previously lost from August 1940 to January 2007. Major factors in the recovery in storage volumes seen in the study area and the central part of the study area (table 1) are increased recharge from greater-than-normal precipitation and planned decreases in city pumpage that are part of Wichita's Local Integrated Water Supply Plan (City of Wichita, [2007?]; Hansen and Aucott, 2010; Warren and others, 1995); however, part of the recovery may be because city and irrigation pumpage decreased in response to greater-than-normal to normal annual precipitation. Annual precipitation in the study area during January 2007 to January 2011 averaged about 36.18 in. or about 4.14 in. greater than normal (National Oceanic and Atmospheric Administration, 2008, 2009, 2010, 2011a, and 2011c).

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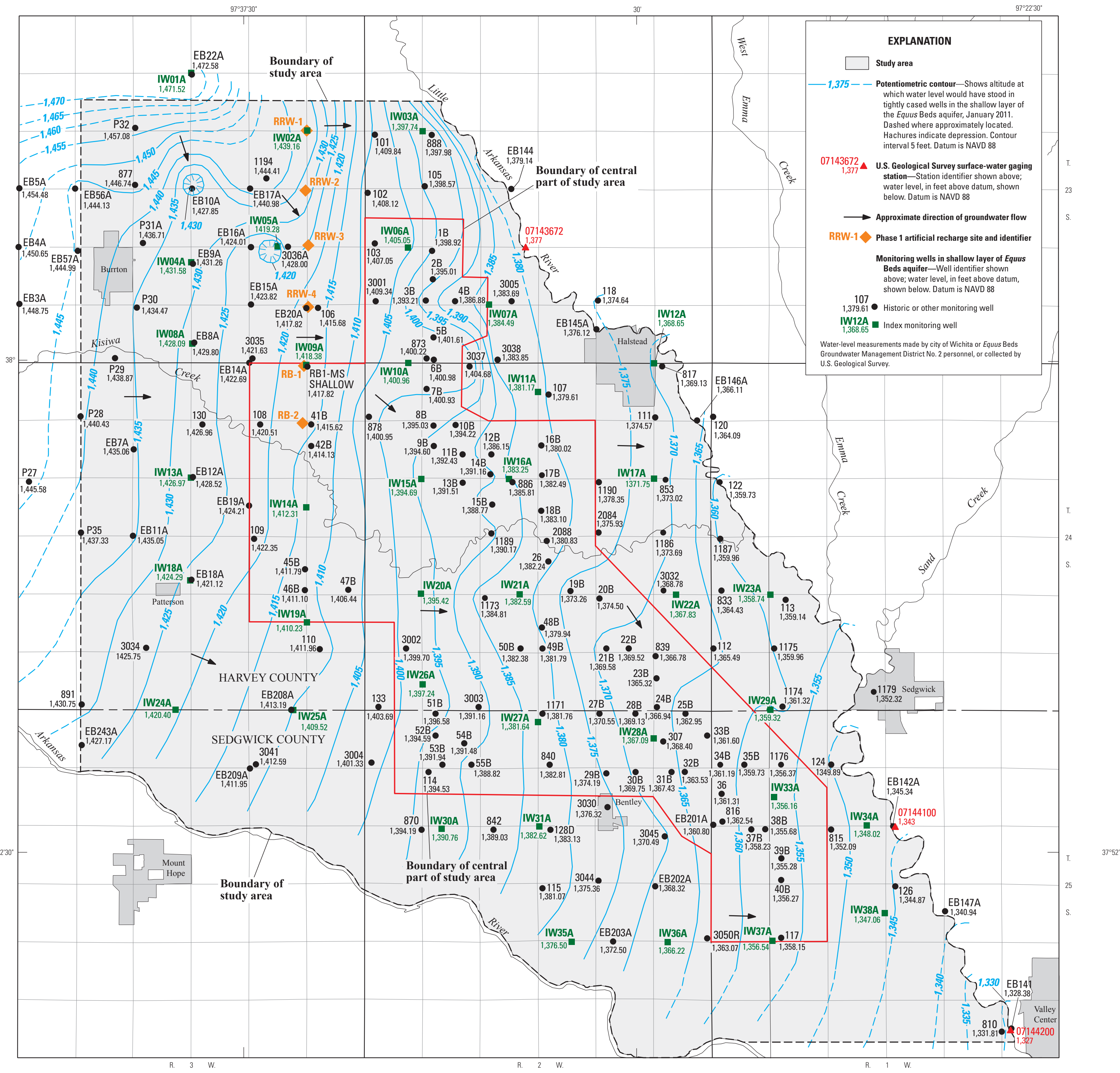

Figure 3. Potentiometric surface of the shallow layer of the *Equus* Beds aquifer, January 2011.

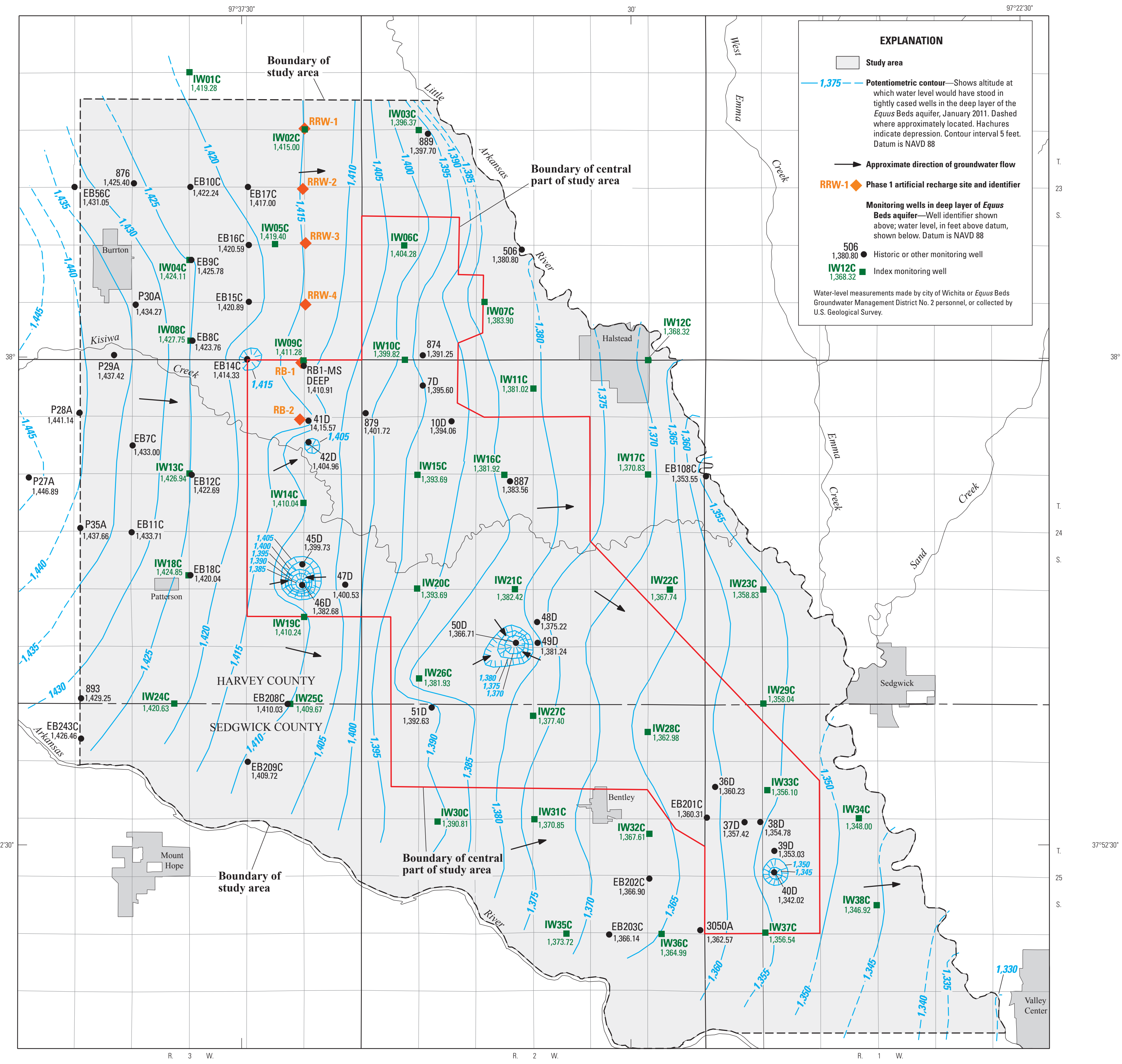

Figure 4. Potentiometric surface of the deep layer of the *Equus* Beds aquifer, January 2011.

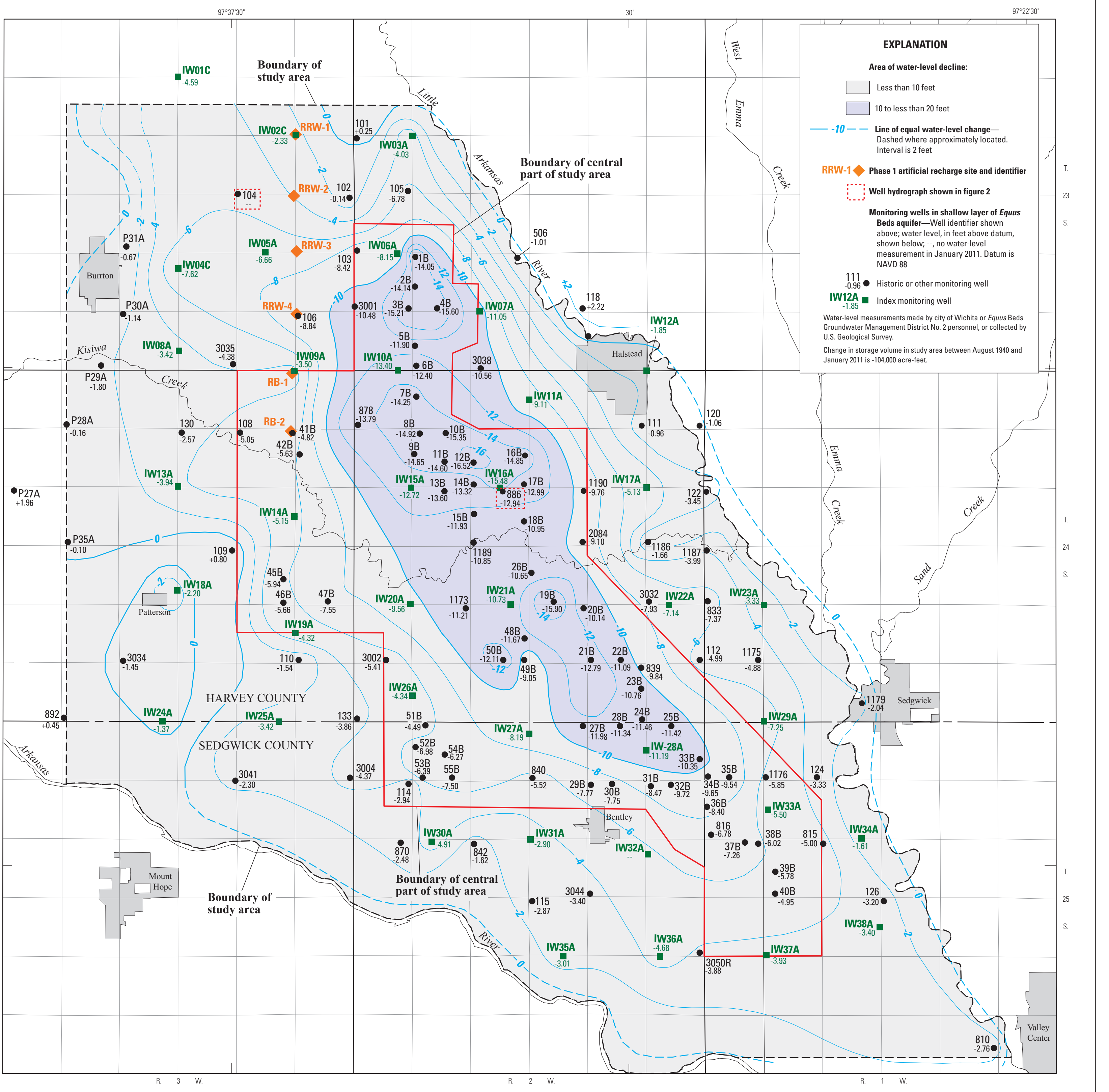

Figure 5. Water-level changes in the *Equus* Beds aquifer in the study area, August 1940 to January 2011.

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By

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