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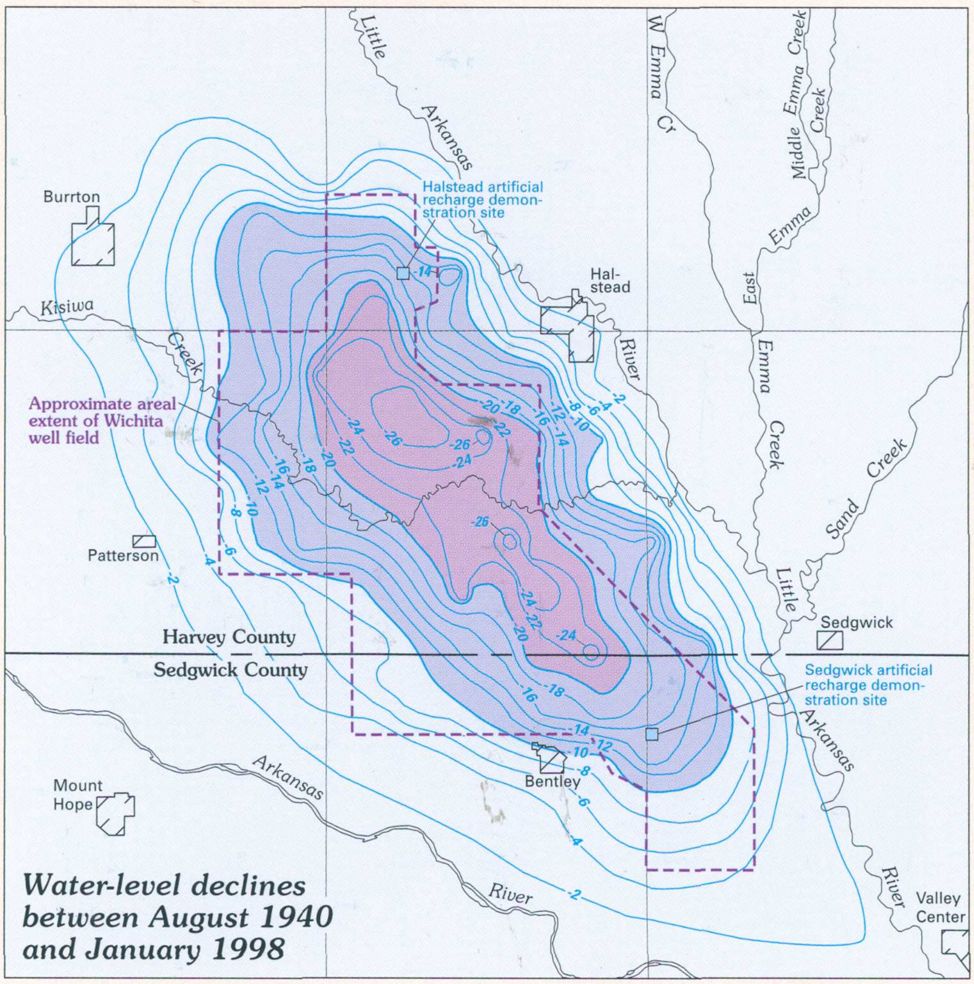
Changes in Ground-Water Levels and Storage in the Wichita Well Field Area, South-Central Kansas, 1940–98

Water-Resources Investigations Report 98–4141



Water-level declines between August 1940 and January 1998

U.S. Department of the Interior
U.S. Geological Survey

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Lawrence, Kansas
1998

U.S. Department of the Interior
Bruce Babbitt, Secretary

U.S. Geological Survey
Thomas J. Casadevall, Acting Director

For additional information write to:

District Chief
U.S. Geological Survey
4821 Quail Crest Place
Lawrence, KS 66049–3839

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CONTENTS

FIGURES

TABLE

CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
degree Fahrenheit (°F)	([1])	degree Celsius (°C)
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

[1] Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the equations:

$$°C = 5/9\ (°F-32)$$
$$°F = 9/5\ (°C) + 32.$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Changes in Ground-Water Levels and Storage in the Wichita Well Field Area, South-Central Kansas, 1940–98

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Abstract

The Wichita well field was developed in the *Equus* Beds aquifer northwest of Wichita, Kansas, to supply water to the city. On September 1, 1940, pumping began from 25 wells in the well field. City pumpage increased from then until the early 1950's and between the late 1970's and early 1990's. Since then, city withdrawals from the well field have decreased as withdrawals increased from Cheney Reservoir, the other major water-supply source for the city. Nearby agricultural withdrawals increased substantially in the 1970's and 1980's and, in the 1990's, was similar in magnitude to city withdrawals in the study area although more seasonal and variable in response to changing climatic conditions.

Ground-water withdrawals in the vicinity of the well field caused a large area of water-level declines to develop in the *Equus* Beds aquifer. Water levels declined from 1940 through the 1950's drought, stabilized in the 1960's and 1970's, continued to decline between the late 1970's and the 1988–92 drought, and reached their maximum to date of as much as 40 feet or more during 1991–93. Loss of ground water in storage since August 1940 followed a pattern similar to water-level declines, with a maximum loss of storage of 255,000 acre-feet reached in January 1993. Water-level declines encompassed an area of about 190 square miles at their maximum in January 1993 and extended from the Arkansas River to the Little Arkansas River in the vicinity of Halstead and Sedgwick. Ground-water levels have since recovered more than 10 feet in some areas and aquifer storage replenished by 79,000 acre-feet between 1993 and 1998 primarily as a result of decreased city withdrawals.

INTRODUCTION

Background

The Wichita well field was developed in the *Equus* Beds aquifer to supply water to the city of Wichita in south-central Kansas (fig. 1). On September 1, 1940, pumping began from 25 wells in the well field (Stramel, 1956). By 1959, there were 55 wells in use in the well field (Stramel, 1967). Ground-water pumping from the well field has caused water levels to decline over a large area. Much of the water-level decline occurred from 1940 to early 1957 (Stramel, 1967). Ground-water withdrawals for irrigation in the Wichita well field area also increased substantially in the 1970's and 1980's and contributed to the water-level decline (Myers and others, 1996). Although most of the water-level declines can be attributed to ground-water withdrawals, climatic conditions and thus recharge to the *Equus* Beds aquifer also have affected ground-water levels.

In 1965, the city of Wichita began using water from Cheney Reservoir (Stramel, 1967) in addition to water from the *Equus* Beds aquifer. Since 1995 (Warren and others, 1995), the city of Wichita, in cooperation with Equus Beds Groundwater Management District No. 2, the Bureau of Reclamation, U.S. Geo-

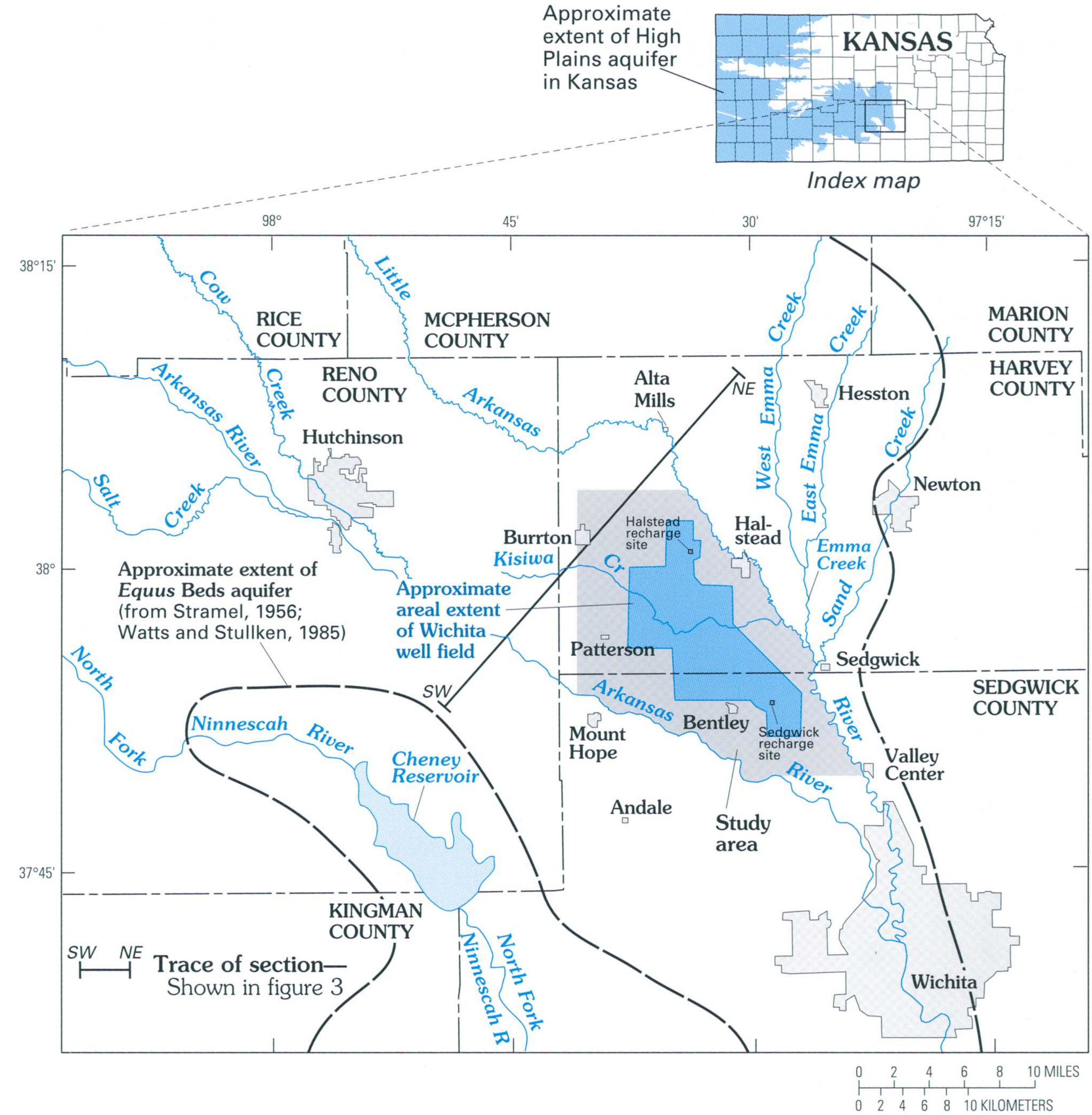


Figure 1. Location of study area and Wichita well field.

logical Survey, U.S. Environmental Protection Agency, Kansas State agencies, Burns and McDonnell Engineering Consultants, and Mid-Kansas Engineering Consultants, has been investigating the possibility of artificial ground-water recharge in the well field to meet future needs and to protect the aquifer from salt-water intrusion from natural and anthropogenic sources to the west. Because of the social and economic importance of ground-water resources and because of the changes that artificial recharge is expected to bring to the aquifer, the city of Wichita entered into a cooperative agreement with the U.S. Geological Survey (USGS) to document historical hydrologic conditions, their changes and causes, in the Wichita well field area (study area shown in fig. 1); to develop a baseline condition for evaluating the effects of artificial recharge on ground-water levels in the aquifer; and to annually review changes in the hydrologic system. The USGS and the city of Wichita have worked cooperatively for many years in evaluating the ground-water system and the interaction with streams in the area to further the understanding of the entire hydrologic system and to provide information to improve local decisionmaking.

Purpose and Scope

The purpose of this report is to present changes in ground-water levels and storage in the Wichita well field area from August 1940 to January 1998. Maps of ground-water levels and water-level changes were selected for significant periods in time. Ground-water levels presented as hydrographs were selected to show water-level fluctuations in various parts of the well field area.

Description of Study Area

The study area (fig. 1) includes 165 mi^2 and is located in Harvey and Sedgwick Counties, northwest of Wichita, Kansas. It is bounded to the southwest by the Arkansas River and to the northeast by the Little Arkansas River. The Wichita well field covers 55 mi^2 and is located within the study area.

The study area lies in the Arkansas River section of the Central Lowlands physiographic province (Schoewe, 1949). There is very little topographic relief in the study area. For the most part, the land surface slopes gently toward the major streams in the area.

South-central Kansas has a continental climate and is characterized by large variations in seasonal temperatures, moderate precipitation, and windy conditions. Seasonal temperatures range from daily averages of 30.6 ^{o}F in January to 79.6 ^{o}F in July for 1961–90 (National Oceanic and Atmospheric Administration, 1996). The mean annual precipitation at weather stations near the study area (at Hutchinson, Mount Hope, Newton, Sedgwick, and Wichita) is 31.06 in. for 1940–96 (National Oceanic and Atmospheric Administration, 1997) (fig. 2). Most of this precipitation occurs during spring and summer.

Previous Studies

Water-level data have been collected by the city of Wichita in the study area quarterly since 1940 and are on file with the USGS in Lawrence, Kansas. Water-level data have been collected in the *Equus* Beds aquifer by Equus Beds Groundwater Management District No. 2, and water-level change maps have been published by the district (Equus Beds Groundwater Management District No. 2, 1995). Annual water-level

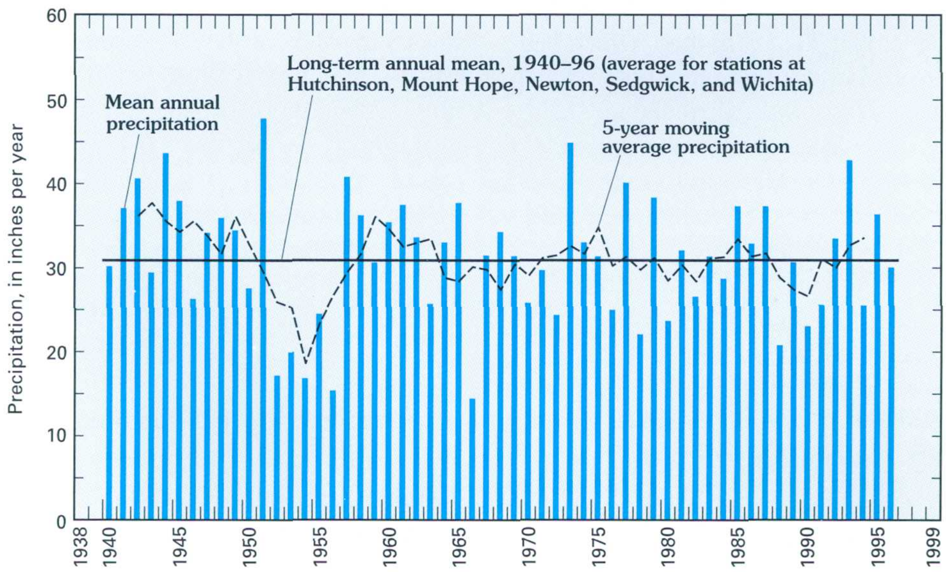


Figure 2. Mean annual, 1940–96 annual mean, and 5-year moving average precipitation at Hutchinson, Mount Hope, Newton, Sedgwick, and Wichita, Kansas (source of data: National Oceanic and Atmospheric Administration, 1997)

data for the High Plains aquifer (fig. 1), which includes the *Equus* Beds aquifer, have been collected by the Kansas Department of Agriculture (Division of Water Resources), USGS, and the Kansas Geological Survey, and are on file with the USGS in Lawrence, Kansas, and have been compiled by the Kansas Geological Survey (Schloss and others, 1997) and mapped by McGuire and Sharpe (1997).

Williams and Lohman (1949, plate 33) show potentiometric-surface maps for the Wichita well field area for June 1, 1940, through October 1, 1944. Water levels from June 1940 were used as the basis for calculating water-level declines in observation wells in the Wichita well field area. Williams and Lohman (1949, plate 34) also show water-level decline maps for the Wichita well field area for April 15, 1941, through October 1, 1944.

Stramel (1956) calculated the net decrease in ground-water storage in the Wichita well field area, which is the net result of natural discharge, discharge by pumping, and natural recharge. Assuming a specific-yield value of 0.20, Stramel (1956) calculated that the net storage decrease from August 30, 1940, to January 1, 1944, was 33,390 acre-ft; to January 1, 1948, was 49,800 acre-ft; to January 1, 1952, was 50,200 acre-ft; and to January 1, 1955, was 111,000 acre-ft.

Stramel (1967) calculated storage decreases for eight dates from December 31, 1957, through December 31, 1965. Stramel's (1967) maximum net storage decrease was 114,225 acre-ft calculated for December 31, 1964, although he did not compute a storage decrease for the December 31, 1956, map, which had the largest water-level declines up to that time. A net storage decrease 1 year later was calculated at 95,800 acre-ft, and this smaller net storage decrease was attributed to the use of water from Cheney Reservoir to supplement water from the Wichita well field (Stramel, 1967). Ross and others (1997) noted an increase in water levels in the *Equus* Beds aquifer from 1993–97 and attributed them largely to decreased withdrawals from the Wichita well field.

GEOLOGY AND GROUND WATER

Quaternary deposits, primarily alluvial, occur throughout the study area. These alluvial deposits, known as the *Equus* beds, are as much as 250 ft thick in the study area (fig. 3) (Lane and Miller, 1965a). The *Equus* beds consist primarily 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 deposits generally has more fine-grained material than the lower and upper parts (Lane and Miller, 1965b; Myers and others, 1996).

The Wellington Formation underlies the Quaternary alluvial deposits and is about 700 ft thick (Bayne, 1956). The Wellington Formation consists of three members—the lower anhydrite member, about 200 ft thick; the Hutchinson Salt Member, about 300 ft thick; and the upper shale member, about 200 ft thick (Bayne, 1956). Dissolution of the Hutchinson Salt Member has resulted in subsidence of the overlying upper shale member, formation of low areas in the bedrock surface, and accumulation of alluvial deposits that now comprise the *Equus* beds (fig. 3) (Myers and others, 1996).

The *Equus* Beds aquifer is the easternmost extension of the High Plains aquifer in Kansas (fig. 1). The extent of the *Equus* Beds aquifer is delineated in figure 1 as defined by Stramel (1956) and in the vicinity of Cheney Reservoir by a more recent regional study (Watts and Stullken, 1985). Watts and Stullken (1985) limit the areal extent of the aquifer north and west of Wichita but still include the *Equus* Beds aquifer in all of the study area. The *Equus* beds are an important source of ground water because of the generally shallow depth to the water table, the large saturated thickness, and the generally good quality of water. Near the Arkansas River, the water table may be as little as 10 ft below land surface. Farther from the river and near the Little Arkansas River, the water table is at a greater depth below land surface, depending on the altitude of land surface and the amount of water-level decline that has been caused by ground-water withdrawals. The maximum saturated thickness of the *Equus* Beds aquifer within the study area, almost 250 ft, is near the course of the Arkansas River and corresponds to the lowest areas of the underlying bedrock surface (fig. 3). The Wellington Formation acts as a confining unit underlying the *Equus* Beds aquifer.

CHANGES IN GROUND-WATER LEVELS AND STORAGE

Prior to pumpage from the Wichita well field in September 1940, near-predevelopment conditions existed for the *Equus* Beds aquifer in the study area

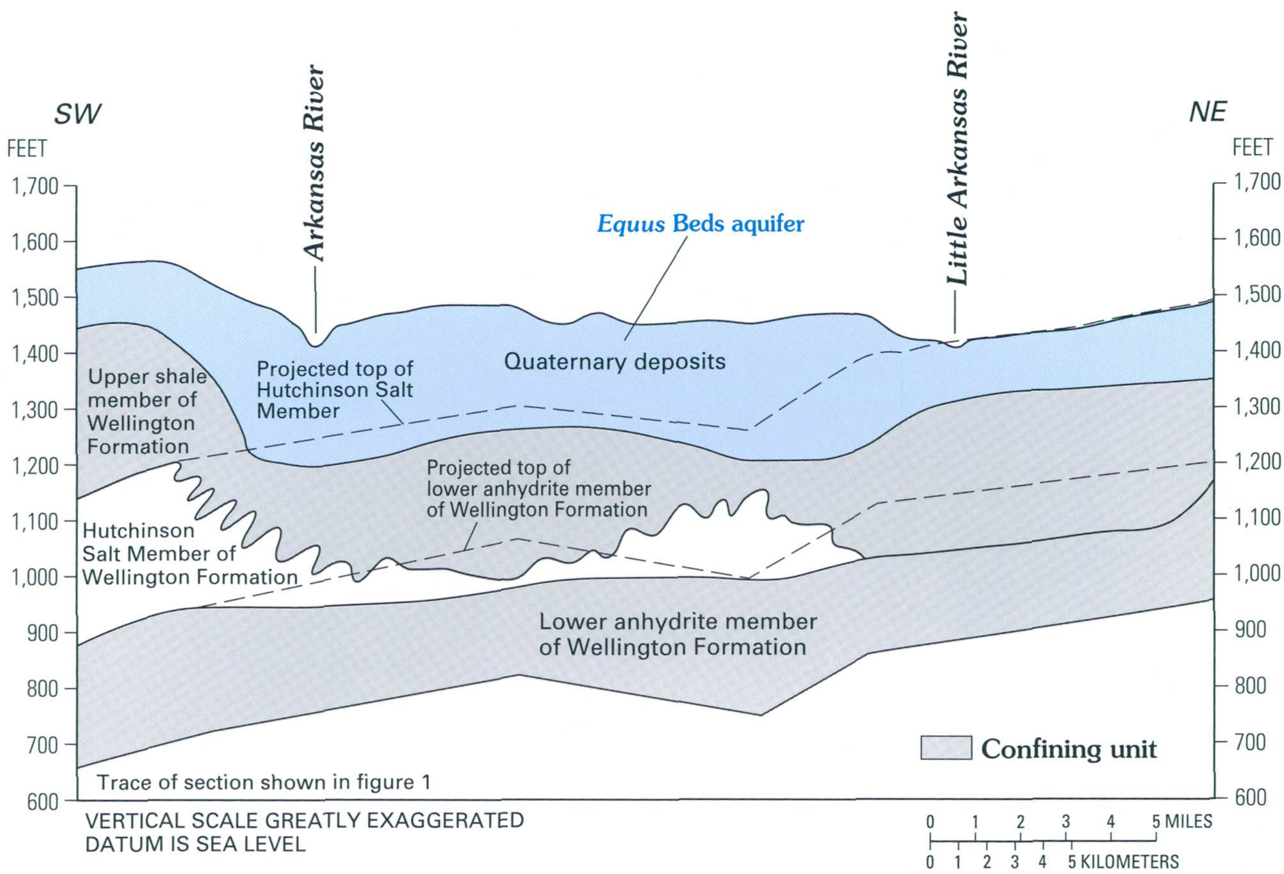


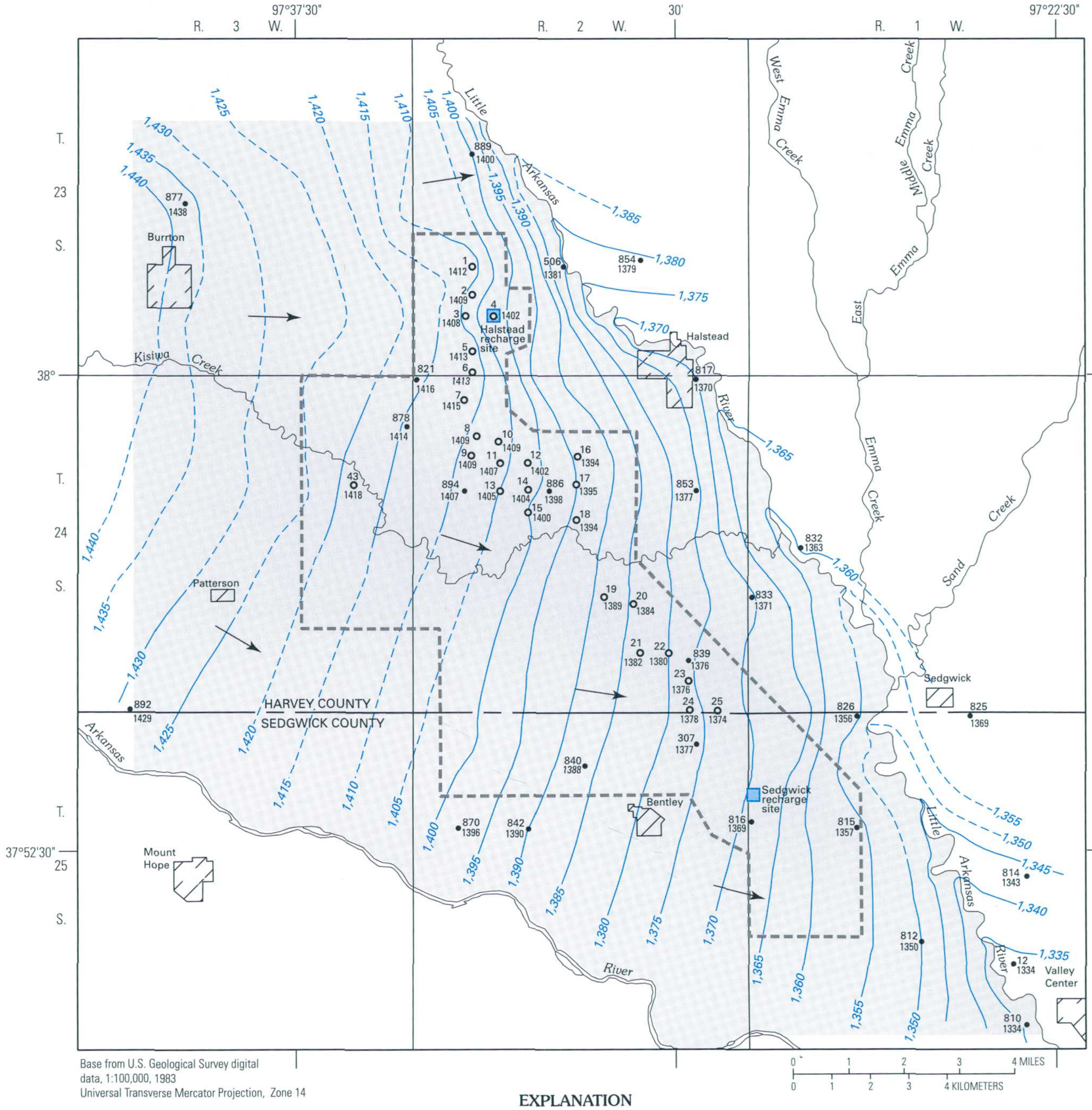
Figure 3. Generalized geologic section (from Leonard and Kleinschmidt, 1976; Myers and others, 1996).

(Williams and Lohman, 1949). Ground water flowed generally west to east and discharged to the Little Arkansas River prior to development, as indicated in figure 4. Water levels in about 50 observation wells measured in August 1940 were used to construct this map; most of these wells were associated with the Wichita well field.

Ground-water-level declines can result from pumpage and from decreased recharge resulting from less-than-average precipitation as well as other factors. Figure 2 indicates annual mean and 5-year moving average precipitation data for long-term stations in the vicinity of the study area. Droughts, such as occurred in 1952–56 and 1988–92, decrease the amount of recharge available and increase the demand for and thus withdrawals of ground water, resulting in increased water-level declines.

Since 1940, ground-water withdrawals for the city of Wichita, and later for agricultural uses, have become significant (fig. 5). City of Wichita withdrawals, which began in September 1940 in the study area, increased steadily into the early 1950's and then were relatively constant until the mid-1970's. City withdrawals increased sporadically from the late 1970's through the early 1990's in response to increased demand and droughts and have since decreased due to the increasing reliance of the city on Cheney Reservoir as a water-supply source. Agricultural withdrawals were relatively small until the early 1970's but have increased subtanstially since (Myers and others, 1996). Agricultural water-use amounts reported prior to the early 1990's are not plotted in figure 5 because of ongoing data-verification considerations.

Extensive information is available to describe hydrologic conditions in the study area. Water-level data have been collected periodically from more than 100 wells by city of Wichita personnel. Data collection began just prior to the beginning of city withdrawals in September 1940, and as well-field development proceeded, water levels in additional wells were measured. Measuring frequency varies from well to well, but most are measured quarterly or annually. Standard ground-water-level measurement techniques similar to USGS methods (Stallman, 1971) have been used by



EXPLANATION

- Study area
- —1,375— — Water-level contour—Shows altitude of water level, August 1940. Dashed where approximately located. Contour interval 5 feet. Datum is sea level
- Approximate areal extent of Wichita well field
- Drainage ditch
- Approximate direction of ground-water flow
- Artificial recharge demonstration site
- 1 / 1412 Observation well in vicinity of city of Wichita supply well
- 854 / 1379 Other observation well

Well number shown above symbol; water-level altitude, in feet above sea level, shown below.

Water-level measurements are made by city of Wichita personnel.

Figure 4. Water-level altitudes for August 1940 in the *Equus* Beds aquifer in the vicinity of the Wichita well field.

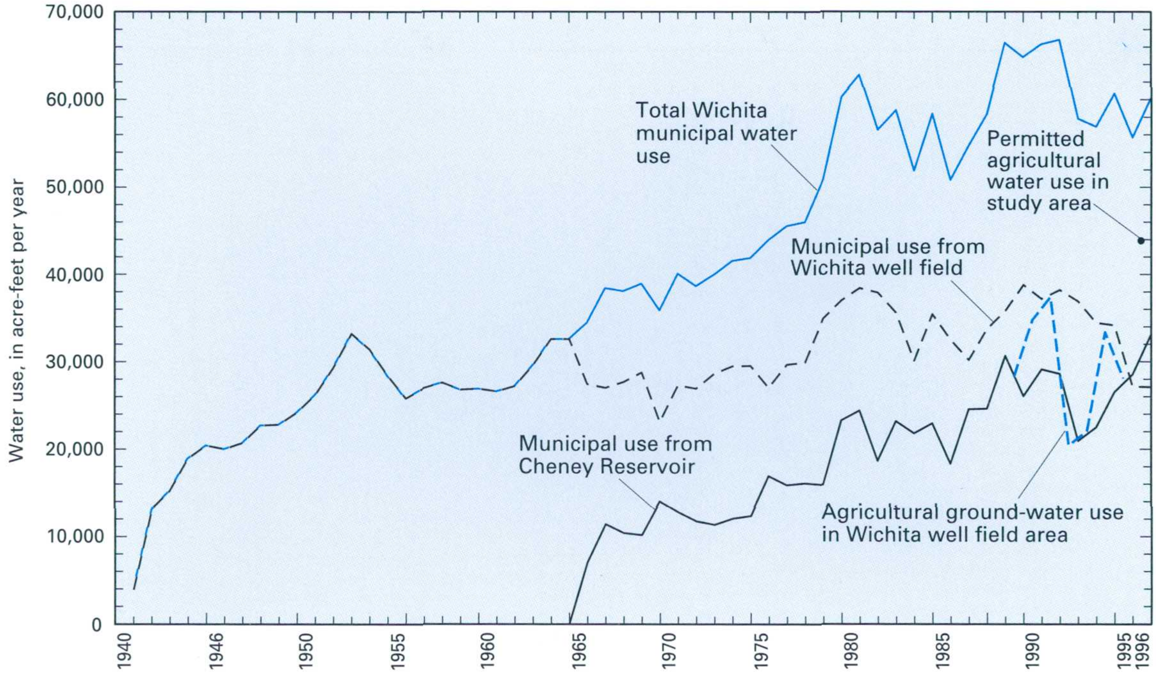


Figure 5. Municipal water use by the city of Wichita from the Wichita well field and Cheney Reservoir and agricultural ground-water use in study area, 1940–96. Data obtained from Gerald T. Blain (City of Wichita, written commun., 1997) and the Kansas Department of Agriculture, Division of Water Resources, and the Kansas Water Office (1990–96).

city personnel. Data are stored by the city in paper and electronic form and by the USGS in electronic form.

The available water-level data were used to plot hydrographs for selected wells for 1938–97 and to map water levels and water-level changes for a variety of time periods. The wells selected (fig. 6) are distributed throughout the study area as indicated in figure 7. The hydrographs for these selected wells reflect a history of hydrologic conditions and responses to ground-water withdrawals within the well field and in surrounding areas. The hydrograph for well 886 is a representative descriptor of water-level changes near the historic center of the city's well field pumpage, whereas the hydrograph for well 307 presents a view of the effects in the southern part of the well field. Hydrographs for wells P29, 104, 810, 3004, and 3039 present hydrologic conditions in areas away from the city well field. The hydrograph for well 104 is particularly noteworthy in its depiction of the effects of irrigation withdrawals.

Water-level altitude maps were constructed for January 1957, 1970, 1993, and 1998 (figs. 7–10). Water-level change maps were constructed to describe changes between August 1940 (predevelopment) and each of these times (figs. 11–14) and for the period January 1993 to January 1998 (fig. 15). These years were selected as representative of broader time periods and trends as depicted in the hydrograph for well 886 (fig. 6) and as discussed later in this report. The month of January was selected for each year to provide comparable conditions with a minimal effect from seasonal factors. The water-level change maps were constructed using August 1940 measurements where they existed, primarily near city wells 1–25, and a few measurements from September 1940 for some wells in the western part of the study area. Where no 1940 measurements existed, values were interpolated from the August 1940 water-level contour map (fig. 4).

Table 1 indicates changes in aquifer storage volume between August 1940 and January 1957, 1970, 1993, and 1998 and between January 1993 and January 1998. Changes in storage were determined from areas inside water-level-change contours for these selected time periods and were computed as changes in storage volume inside the study area boundary and inside the well field boundary. Storage changes were computed using the specific-yield value (0.2) used by Stramel (1956). Water-level declines at individual wells such as observation well 886 are important for indicating changes at a specific time and are suggestive of the effects at that point, such as dewatered shal-

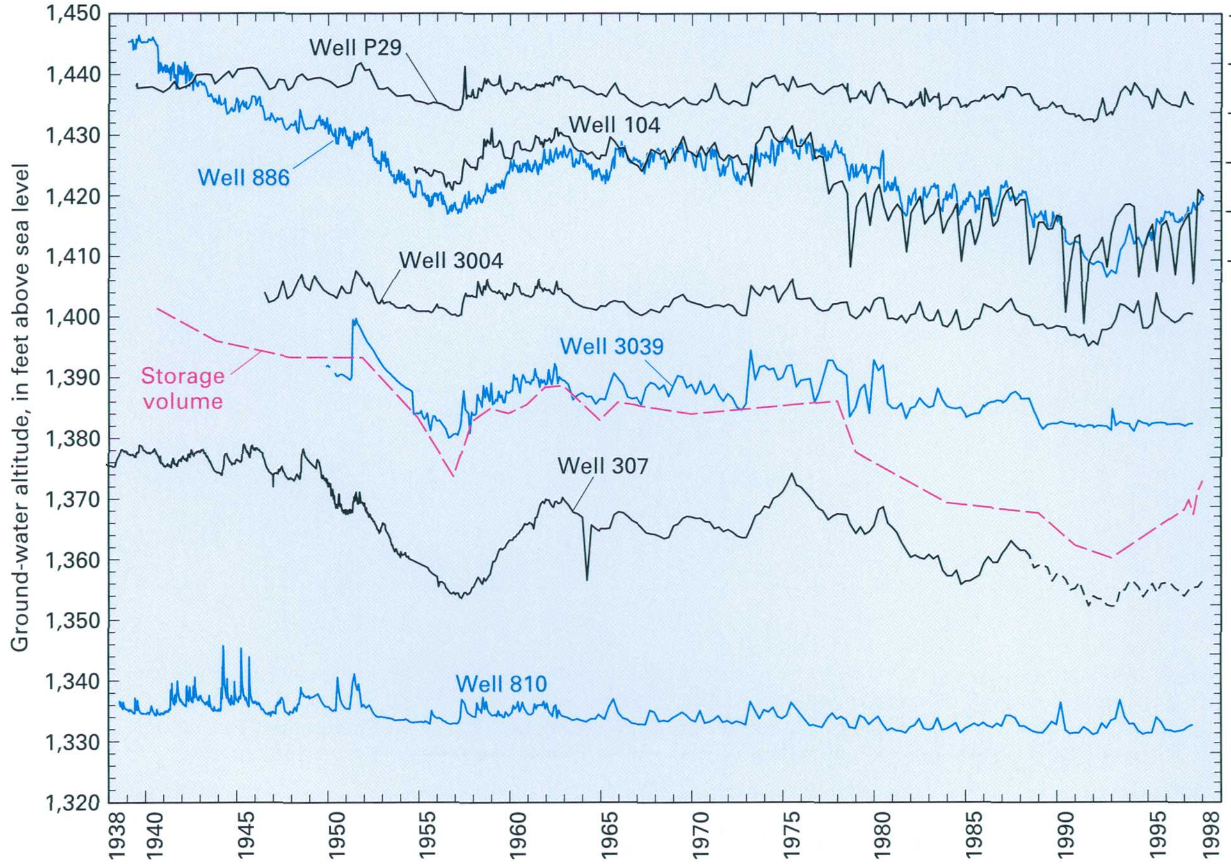
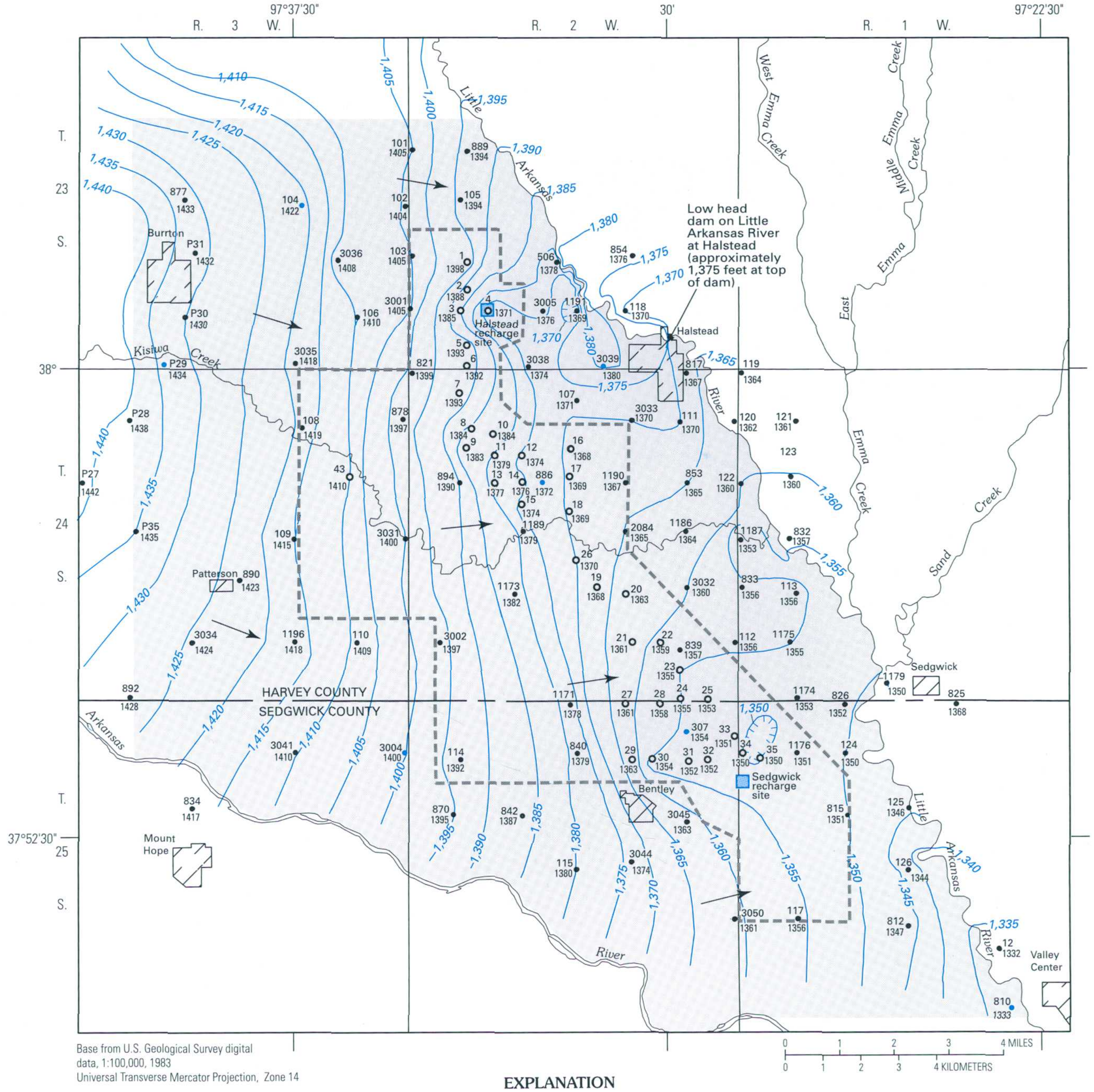


Figure 6. Hydrographs for selected wells and *Equus* Beds aquifer storage-volume depletions in study area, 1938–97 (source of data: water levels collected by city of Wichita personnel; data on file with U.S. Geological Survey in Lawrence, Kansas.) Location of wells shown in figure 7.

low wells or increased pumping costs to lift water from greater depths. Changes in storage are a better measure of the overall effect on the aquifer and represent a decrease in the ground-water resource available for use.

The period from September 1940 to early 1957 was a time of water-level decline resulting from the beginning of withdrawals from the city well field and culminating in the drought of the mid-1950's (fig. 2). City well field withdrawals increased throughout most of this period. Water levels had declined by more than 20 ft by 1957 in large parts of the well field as indicated by figure 11 and hydrographs for wells 886 and 307 in figure 6. The elongated northwest-southeast shape of the area of water-level declines generally encompasses the locations of the city pumping wells. The maximum water-level decline of 30.48 ft was noted in the observation well near city well 4 (fig. 11). Some water-level declines, generally less than 5 ft, even occurred in areas far from the city withdrawals toward the end of the drought as indicated by figure 11 and hydrographs of wells P29, 104, 810, and 3004 (fig. 6). By January 1957, a loss of 171,000 acre-ft of water in storage in the *Equus* Beds aquifer had occurred within the study area since August 1940 (table 1). The general flow direction in the *Equus* Beds aquifer in the study area at the culmination of the 1950's drought, however, remained generally west to east as it had been prior to development (August 1940) (fig. 7).

The period from 1958 to 1977 was generally characterized by relatively constant ground-water withdrawals, near-normal precipitation, and stable water levels with some recovery of water levels from the lows reached during the mid-1950's drought (wells 886 and 307, fig. 6), at least partly due to wetter than normal years immediately following the drought (fig. 2). The water-level change map for August 1940 to January 1970 (fig. 12) indicates again larger water-level declines in the east-central (older) part of the



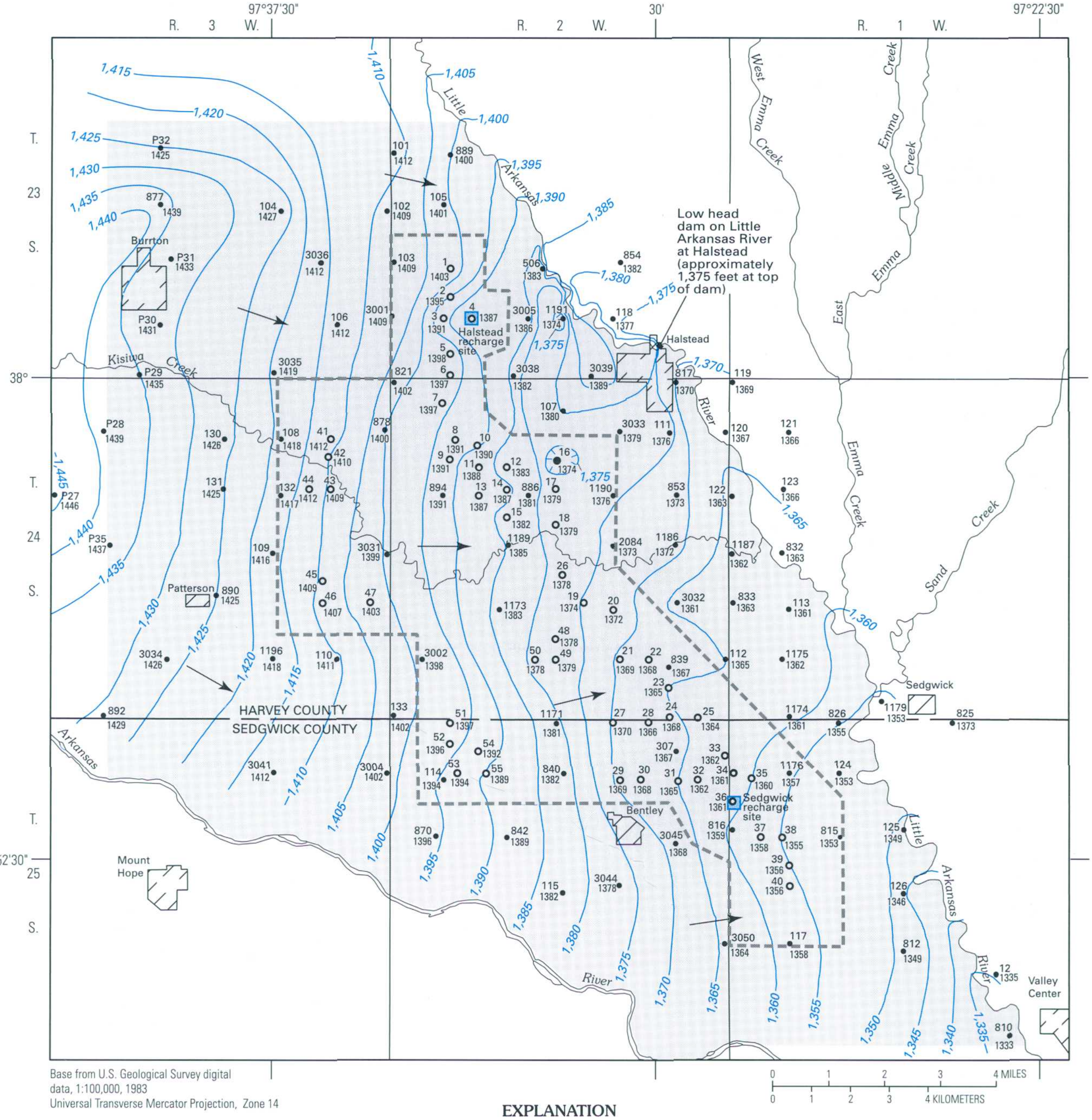
EXPLANATION

- Study area
- 1,375 — Water-level contour—Shows altitude of water level, January 1957. Contour interval 5 feet. Datum is sea level
- Approximate areal extent of Wichita well field
- Drainage ditch
- Approximate direction of ground-water flow
- Artificial recharge demonstration site
- Observation well in vicinity of city of Wichita supply well
- Other observation well
- Well with hydrograph in figure 6

Well number shown above symbol; water-level altitude, in feet above sea level, shown below.

Water-level measurements are made by city of Wichita personnel.

Figure 7. Water-level altitudes for January 1957 in the *Equus* Beds aquifer in the vicinity of the Wichita well field.



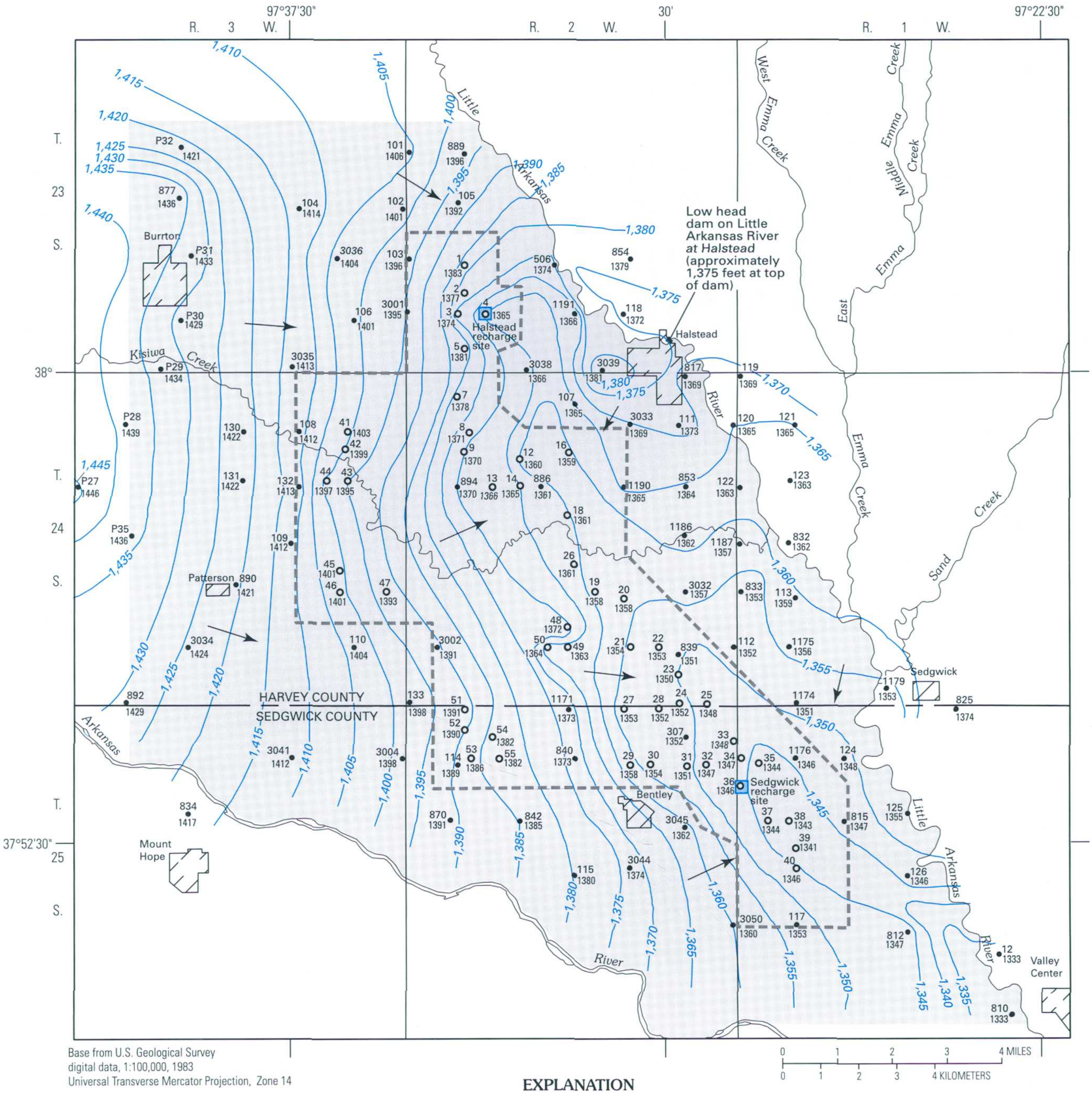
EXPLANATION

- Study area
- —1,375— Water-level contour—Shows altitude of water level, January 1970. Contour interval 5 feet. Datum is sea level
- Approximate areal extent of Wichita well field
- Drainage ditch
- Approximate direction of ground-water flow
- Artificial recharge demonstration site
- 1 / 1403 o Observation well in vicinity of city of Wichita supply well
- 854 / 1382 • Other observation well

Well number shown above symbol; water-level altitude, in feet above sea level, shown below.

Water-level measurements are made by city of Wichita personnel.

Figure 8. Water-level altitudes for January 1970 in the *Equus* Beds aquifer in the vicinity of the Wichita well field.



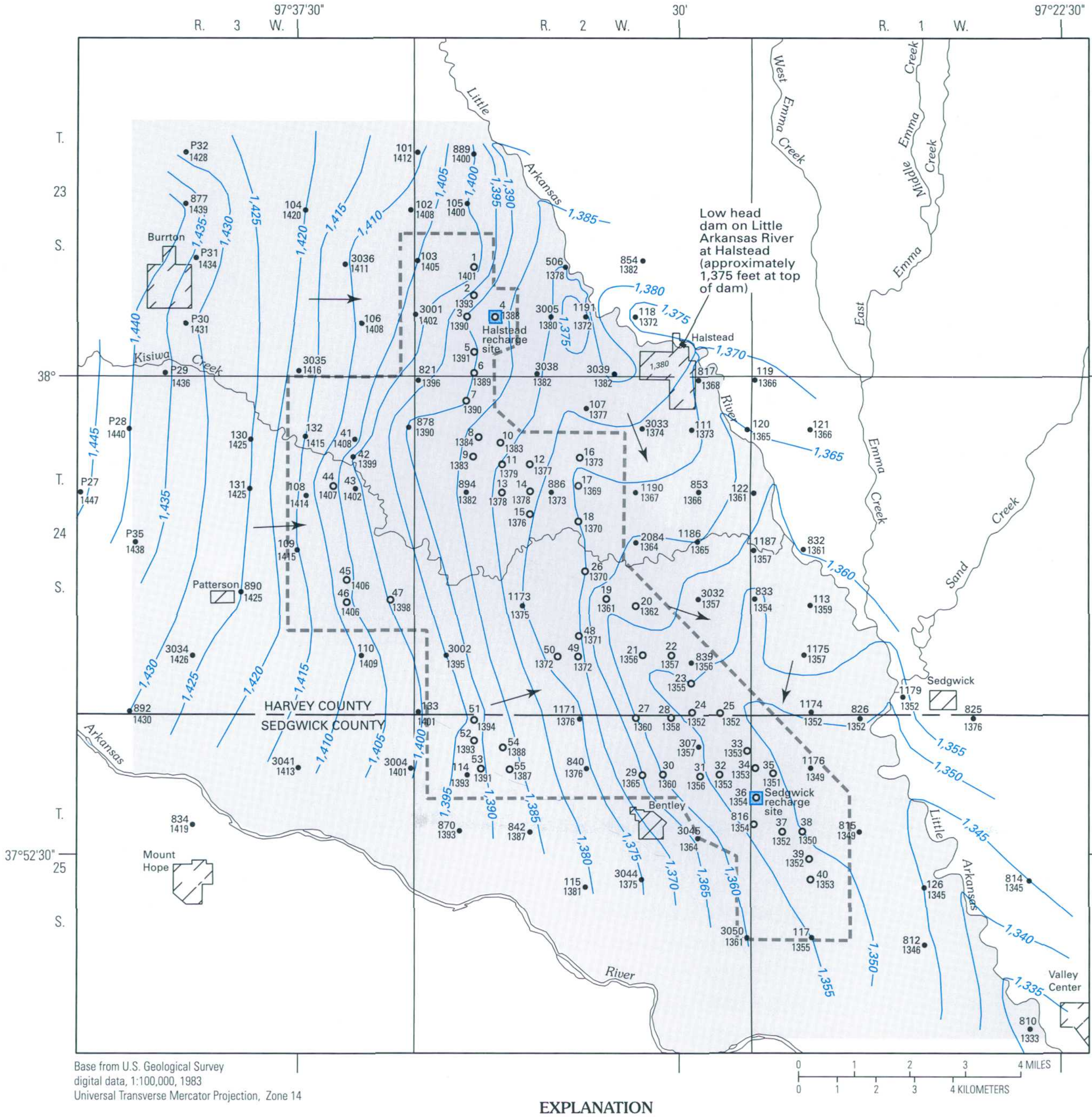
EXPLANATION

- Study area
- 1,375 — Water-level contour—Shows altitude of water level, January 1993. Contour interval 5 feet. Datum is sea level
- Approximate areal extent of Wichita well field
- Drainage ditch
- Approximate direction of ground-water flow
- Artificial recharge demonstration site
- 1 / 1383 — Observation well in vicinity of city of Wichita supply well
- 854 / 1379 — Other observation well

Well number shown above symbol; water-level altitude, in feet above sea level, shown below.

Water-level measurements are made by city of Wichita personnel.

Figure 9. Water-level altitudes for January 1993 in the *Equus* Beds aquifer in the vicinity of the Wichita well field.



EXPLANATION

Study area

—1,375— Water-level contour—Shows altitude of water level, January 1998. Contour interval 5 feet. Datum is sea level

Approximate areal extent of Wichita well field

Drainage ditch

Approximate direction of ground-water flow

Artificial recharge demonstration site

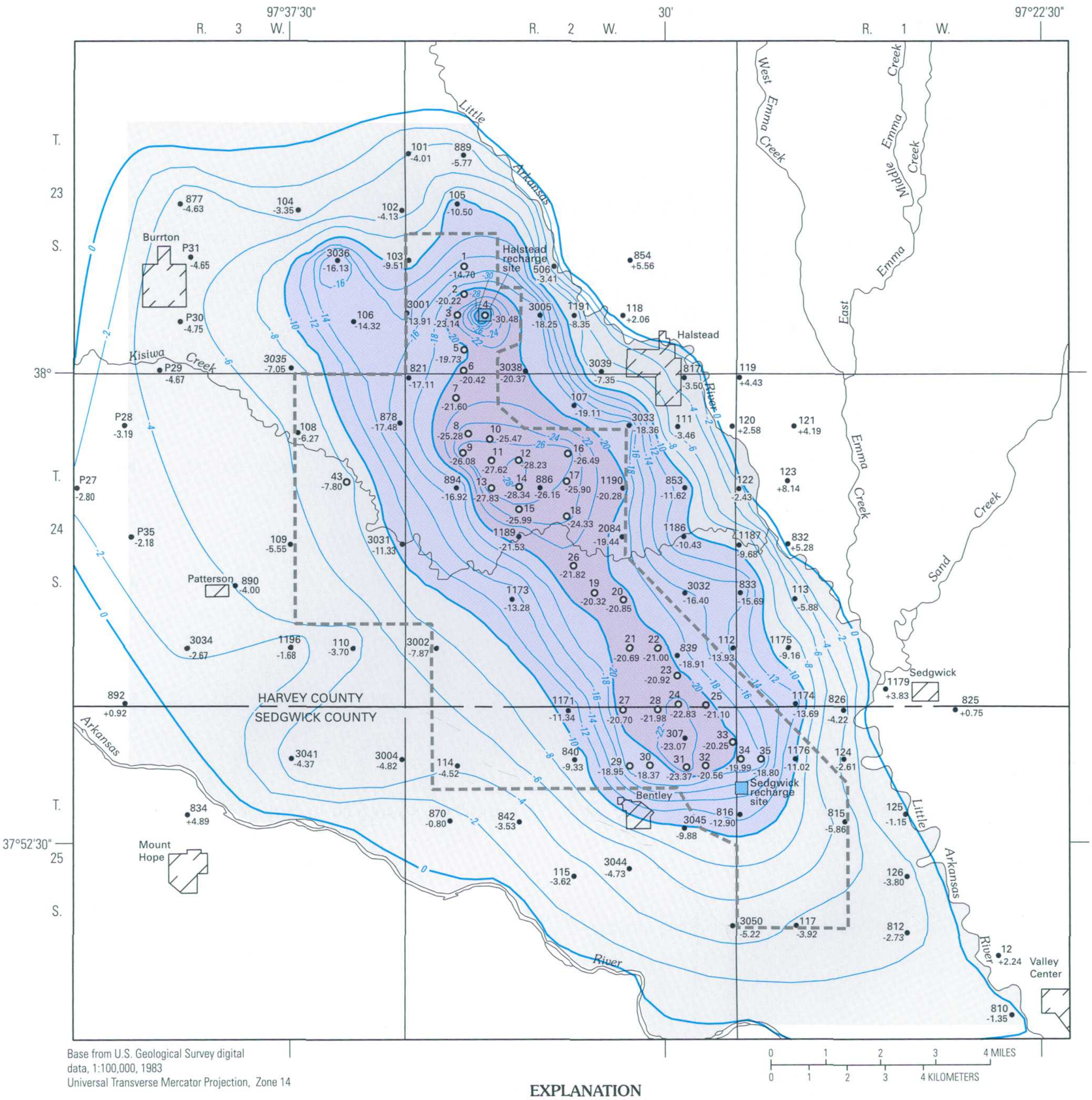
1 / 1401 o Observation well in vicinity of city of Wichita supply well

854 / 1382 • Other observation well

Well number shown above symbol; water-level altitude, in feet above sea level, shown below.

Water-level measurements are made by city of Wichita personnel.

Figure 10. Water-level altitudes for January 1998 in the *Equus* Beds aquifer in the vicinity of the Wichita well field.



EXPLANATION

Area of water-level declines between:

10 and 20 feet

20 and 30 feet

Study area

—-2— Line of equal water-level change—Interval 2 feet

- - - - Approximate areal extent of Wichita well field

— — — Drainage ditch

Artificial recharge demonstration site

1 / -14.70 o Observation well in vicinity of city of Wichita supply well

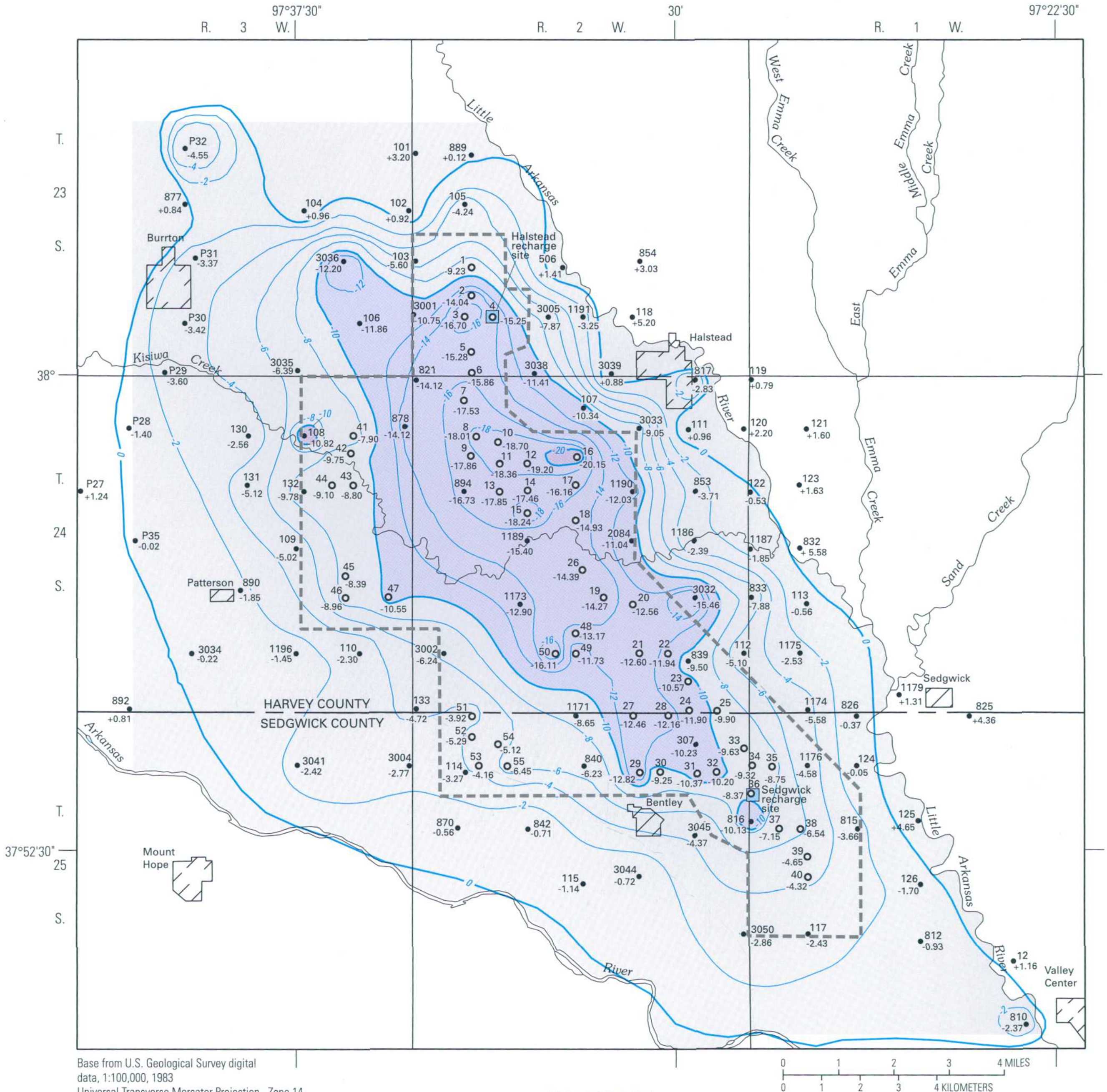
854 / +5.56 • Other observation well

Well number shown above symbol; water-level change, in feet, shown below. Negative number indicates water level is less than in August 1940.

Water-level measurements are made by city of Wichita personnel.

Depletion of storage volume in study area between August 1940 and January 1957 is -171,000 acre-feet.

Figure 11. Water-level change from August 1940 to January 1957 in the *Equus* Beds aquifer in the vicinity of the Wichita well field.



EXPLANATION

Area of water-level declines between:

- 10 and 20 feet
- 20 and 30 feet

Study area

-2 — Line of equal water-level change—Interval 2 feet

- - - - Approximate areal extent of Wichita well field

— — — Drainage ditch

Artificial recharge demonstration site

1 / -9.23 ○ Observation well in vicinity of city of Wichita supply well

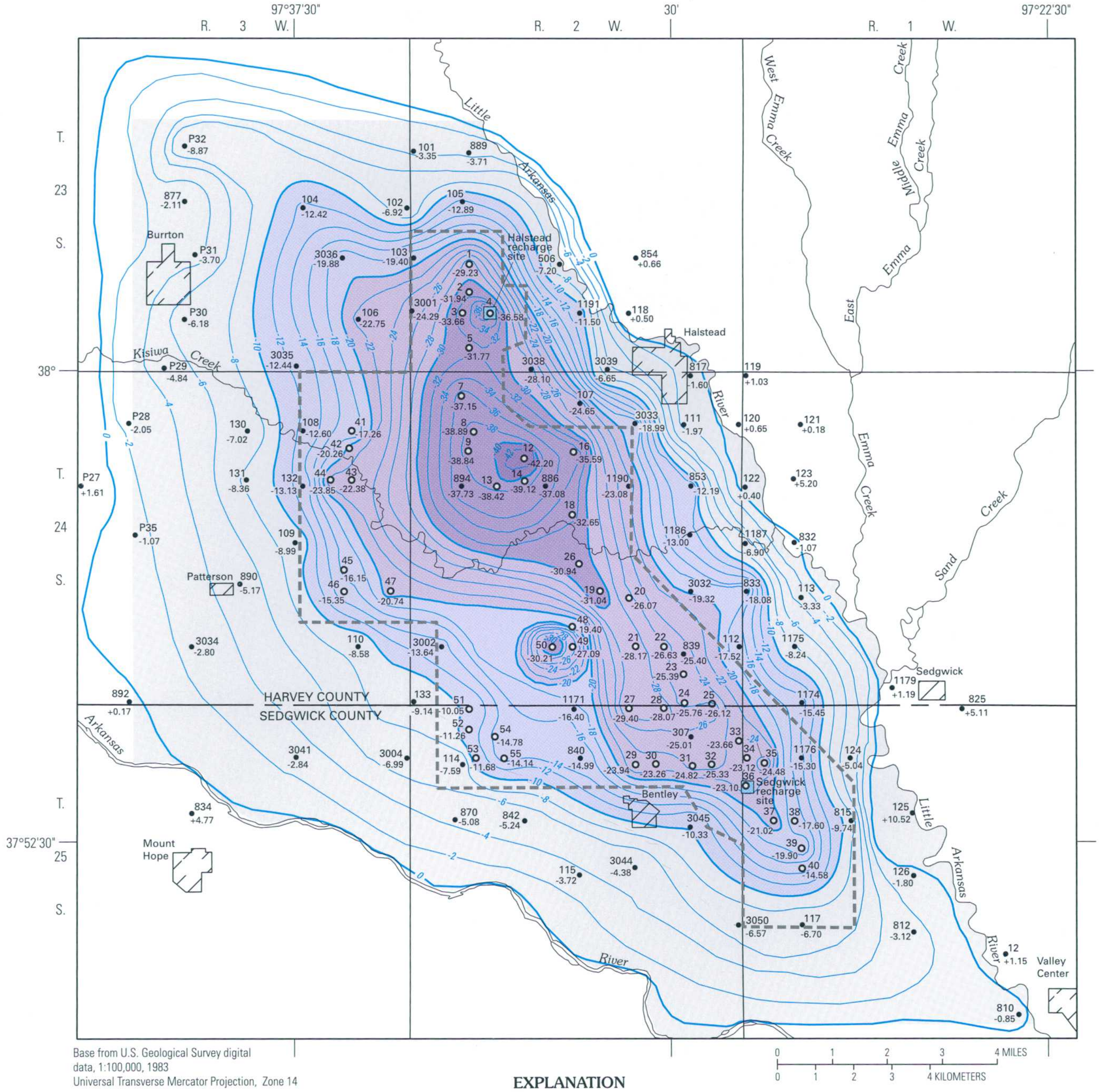
854 / +3.03 ● Other observation well

Well number shown above symbol; water-level change, in feet, shown below. Negative number indicates water level is less than in August 1940.

Water-level measurements are made by city of Wichita personnel.

Depletion of storage volume in study area between August 1940 and January 1970 is -108,000 acre-feet.

Figure 12. Water-level change from August 1940 to January 1970 in the *Equus* Beds aquifer in the vicinity of the Wichita well field.



EXPLANATION

Area of water-level declines between:

- 10 and 20 feet
- 20 and 30 feet
- 30 and 40 feet
- 40 and 50 feet

Study area

-2 Line of equal water-level change—Interval 2 feet

Approximate areal extent of Wichita well field

Drainage ditch

Artificial recharge demonstration site

1 / -29.23 Observation well in vicinity of city of Wichita supply well

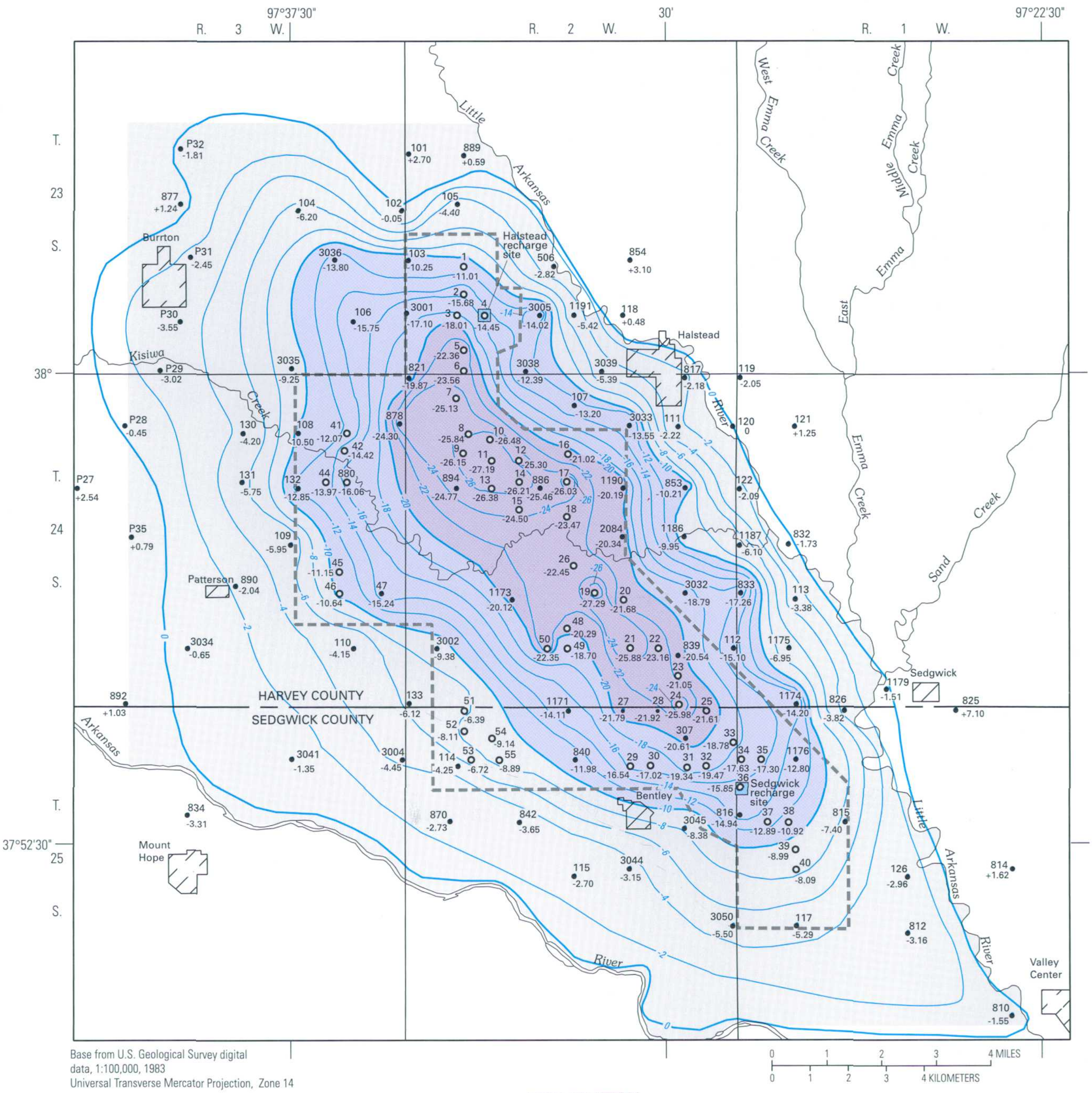
854 / +0.66 Other observation well

Well number shown above symbol; water-level change, in feet, shown below. Negative number indicates water level is less than in August 1940.

Water-level measurements are made by city of Wichita personnel.

Depletion of storage volume in study area between August 1940 and January 1993 is -255,000 acre-feet.

Figure 13. Water-level change from August 1940 to January 1993 in the *Equus* Beds aquifer in the vicinity of the Wichita well field.



EXPLANATION

Area of water-level declines between:

10 and 20 feet

20 and 30 feet

Study area

—-2— Line of equal water-level change—Interval 2 feet

- - - - Approximate areal extent of Wichita well field

— — — Drainage ditch

Artificial recharge demonstration site

1 -11.01 o Observation well in vicinity of city of Wichita supply well

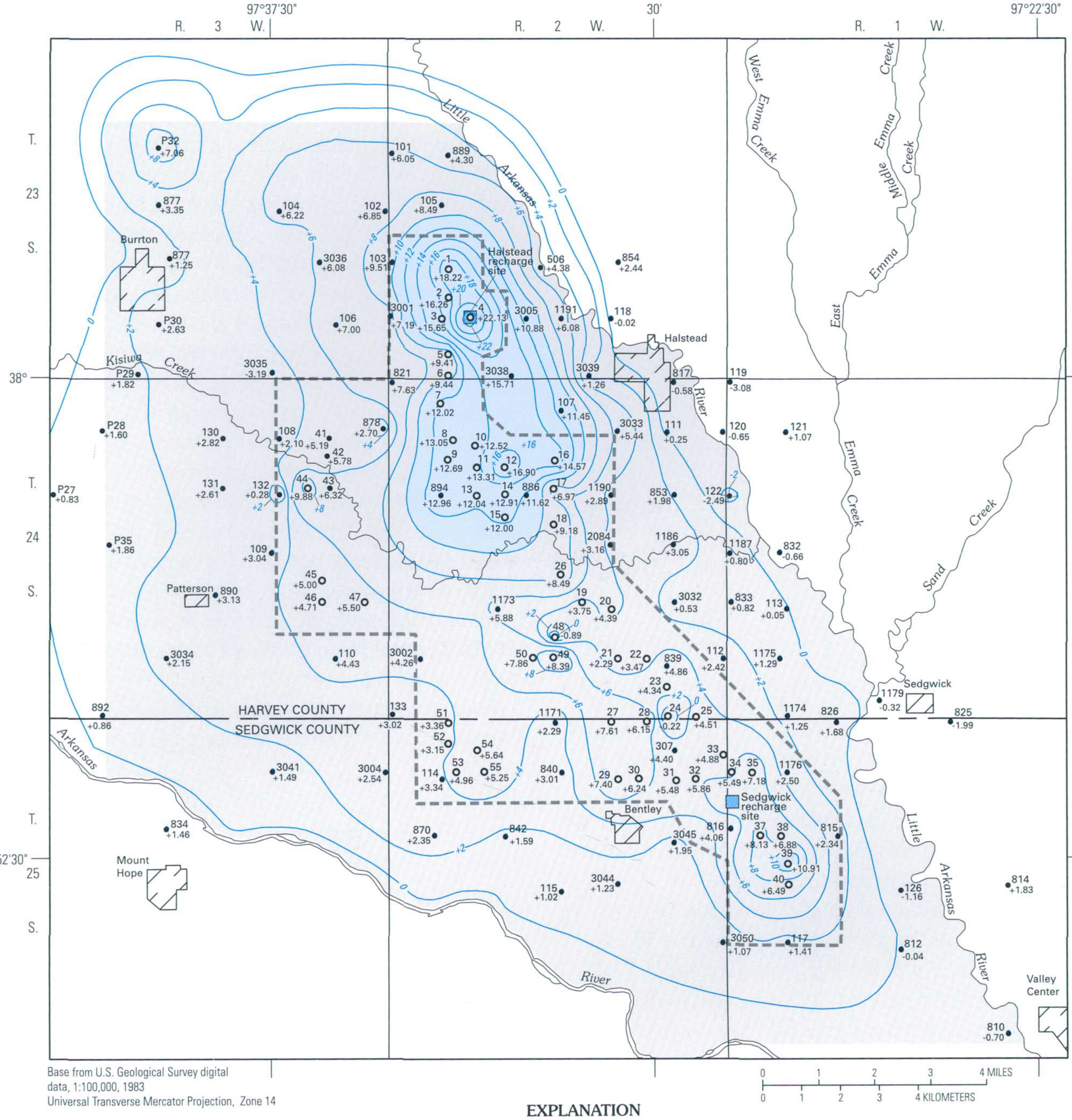
854 +3.10 • Other observation well

Well number shown above symbol; water-level change, in feet, shown below. Negative number indicates water level is less than in August 1940.

Water-level measurements are made by city of Wichita personnel.

Depletion of storage volume in study area between August 1940 and January 1998 is -176,000 acre-feet.

Figure 14. Water-level change from August 1940 to January 1998 in the *Equus* Beds aquifer in the vicinity of the Wichita well field.



EXPLANATION

- Area of water-level recovery greater than 10 feet
- Study area
- +2 Line of equal water-level change—Interval 2 feet
- Approximate areal extent of Wichita well field
- Drainage ditch
- Artificial recharge demonstration site
- 1, +18.22 Observation well in vicinity of city of Wichita supply well
- 854, +2.44 Other observation well

Well number shown above symbol; water-level change, in feet, shown below. Negative number indicates water level is less than in January 1993.

Water-level measurements are made by city of Wichita personnel.

Replenishment of storage volume in study area between January 1993 and January 1998 is 79,000 acre-feet.

Figure 15. Water-level change from the January 1993 to January 1998 in the *Equus* Beds aquifer in the vicinity of the Wichita well field.

Table 1. Storage-volume changes in the *Equus* Beds aquifer in the Wichita well field area, August 1940 to January 1998

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

Time period	Storage-volume change within study area, in acre-feet	Storage-volume change within well field area, in acre-feet
From August 1940 to January 1957	-171,000	- 93,700
From August 1940 to January 1970	-108,000	- 68,500
From August 1940 to January 1993	-255,000	-154,000
From August 1940 to January 1998	-176,000	-110,000
From January 1993 to January 1998	+ 79,000	+ 44,000

well field but lesser declines in most areas than in 1957. The maximum water-level decline from predevelopment to January 1970 was 20.15 ft near city well 16, which was the only well on the 1970 map where water-level declines exceeded 20 ft, whereas on the 1957 map (fig. 11), 34 wells had declines of more than 20 ft. The loss in aquifer storage of 108,000 acre-ft between August 1940 and January 1970 for the study area represents a 37-percent replenishment of storage from January 1957 lows. In 1970, the general flow direction in the *Equus* Beds aquifer in the study area (fig. 8) remained generally west to east as it had been in 1957 and prior to development.

The period from 1978 to 1993 produced another phase of ground-water-level declines (fig. 6) resulting from increased city well field withdrawals, greatly increased agricultural withdrawals (fig. 5), and the drought of 1988–92 (fig. 2). Many wells in the study area had their lowest water levels of record between 1991–93 at the climax of the drought. The largest water-level declines again occurred in the east-central part of the well field, particularly near city well 12 where a maximum water-level decline between August 1940 and January 1993 of 42.20 ft (fig. 13) was determined. Water-level declines also became more pronounced in areas farther from the original pumping wells in the east-central part of the well field. This was due to increased pumping in the western parts of the well field and increased agricultural withdrawals in the study area that by the early 1990's were similar in magnitude to city withdrawals from the well field (fig. 5). The effects of increased agricultural withdrawals during the late 1970's is apparent in the water-level declines and increased annual variations in water levels in well 104 (fig. 6). At their lowest in January 1993, water-level declines resulting from city and agricultural withdrawals encompassed an area of about 190 mi^2, extending from the Arkansas River to the Little Arkansas River in the vicinity of Halstead and Sedgwick. The largest ground-water-storage depletion recorded for the study area occurred in January 1993 at 255,000 acre-ft (table 1). By January 1993, water-level declines in the east-central part of the well field area had altered the water-level surface sufficiently between that area and the Little Arkansas River to change the water-level gradient and direction of flow from west to east prior to the 1988–92 drought, to northeast to southwest from the river toward the well field in that area (fig. 9). The drought was ended by greater-than-average precipitation and flooding during the spring and summer of 1993.

The period from of 1993 to 1998 has been characterized by near-average precipitation since the 1993 flooding (fig. 2), accompanied by decreased city well field withdrawals from the *Equus* Beds aquifer (fig. 5), and variable but near-average agricultural withdrawals compared to the previous years (fig. 5). These factors have resulted in some recovery in water levels from the record lows related to the drought of 1988–92. Water-level recoveries have been greatest in the east-central part of the well field and exceeded 10 ft in many places (figs. 6 and 15) where water-level declines had been largest. Even with the 1988–92 drought and the greatest recoveries occurring in the older pumping areas in the east-central part of the well field, the largest water-level declines since August 1940 remain in the older pumping areas (fig. 14). An observation well near city well 19 had the largest water-level decline, 27.29 ft, between August 1940 and January 1998. The loss of aquifer storage of 176,000 acre-ft between August 1940 and January 1998 in the study area represents a 31-percent replenishment of storage from the January 1993 low of record and is similar to the loss of storage at the low point of the 1950's drought. Water-level gradients and direction of flow in the area between the east-central part of the well field and the Little Arkansas River (fig. 10) are no longer from the river to the well field, as was the case during January 1993, but the gradients and direction present prior to development and up through at least the mid-1970's also have not been reestablished. In other parts of the study area, the direction of flow remained generally from west to east as had been the case since predevelopment.

The city of Wichita is investigating the potential for artificial recharge at two sites near Halstead and Sedgwick (fig. 1). Operation of the Halstead recharge demonstration site (fig. 1) began in September 1997. Water levels in a well near the Halstead recharge site (observation well near city supply well 4) increased more than 2 ft between July and October 1997 measurements, whereas water levels in near wells declined, indicating some effects from the recharge site (Aucott and others, 1998). A 20-ft rise in water level was noted in an observation well closer to the recharge site shortly after recharge began (David Stous, Burns and McDonnell Engineering Consultants, written commun., 1997).

The future of ground-water-level changes and the availability of water from the *Equus* Beds aquifer in the study area is dependent on the wise management of the resource. The historical record demonstrates the effects of city and agricultural withdrawals, artificial recharge, and droughts on water levels and the availability of ground water in storage. These factors need to be balanced and managed efficiently to optimize use of this resource and preserve it for future generations. The Equus Beds Groundwater Management District No. 2 was formed in 1975 to manage ground-water supplies in the study area. The District works with municipal and agricultural users to manage the aquifer using the "aquifer safe-yield principle," which limits ground-water withdrawals to annual ground-water recharge, and a "ground-water quality principle" as noted in Equus Beds Groundwater Management District No. 2 (1995).

SUMMARY

Quaternary alluvial deposits, known as the *Equus* beds, are as much as 250 ft thick in the study area northwest of Wichita, Kansas, and consist primarily of sand and gravel interbedded with clay or silt. The Wellington Formation underlies the Quaternary deposits, forming the bedrock confining unit below these deposits. Dissolution of the Hutchinson Salt Member, the middle member of the Wellington Formation, has resulted in subsidence of the overlying upper shale member of the Wellington Formation, the formation of low areas in the bedrock surface, and the accumulation of the alluvial deposits that now comprise the *Equus* beds.

The Wichita well field was developed in the *Equus* Beds aquifer northwest of Wichita, Kansas, to supply water to the city. In August 1940, ground-water levels in the study area were in a near-predevelopment condition. On September 1, 1940, the city began pumping from 25 wells in the well field, and by 1959 there were 55 wells in use in the well field. City ground-water withdrawals from the *Equus* Beds aquifer increased steadily from the beginning of pumpage until the early 1950's. Agricultural withdrawals were relatively small until the 1970's. Water levels declined by more than 20 ft in much of the city well field area between August 1940 and January 1957 in response to the increasing city withdrawals and the mid-1950's drought. During the late 1950's, water levels recovered somewhat from their mid-1950's lows and were relatively stable through the mid-1970's in response to relatively constant city withdrawals and normal climatic conditions. City withdrawals increased sporadically from the late 1970's through the early 1990's in response to increased demand and the 1988–92 drought. Agricultural withdrawals in the study area increased substantially beginning in the late 1970's, and by the end of the 1988–92 drought, were nearly equal to city withdrawals from the well field. In response to increased withdrawals and drought conditions, water levels in most wells declined to lows of record during 1991–93, declining as much as 40 ft or more. Ground-water storage depletion reached a maximum of record of 255,000 acre-ft in January 1993. Water-level declines encompassed an area of about 190 mi^2 at their maximum in January 1993 and extended from the Arkansas River to the Little Arkansas River in the vicinity of Halstead and Sedgwick. Since flooding in 1993, city withdrawals have decreased due to the increasing reliance of the city on Cheney Reservoir as a water-supply source, while average agricultural withdrawals were similar to withdrawals in the early 1990's, and precipitation was near average. Ground-water levels have since recovered more than 10 ft in some areas and aquifer storage replenished by 79,000 acre-ft between 1993 and 1998 primarily as a result of decreased city withdrawals.

The future availability of water from the *Equus* Beds aquifer in the study area is dependent on the wise management and long-term balance of city and agricultural withdrawals and artificial recharge especially during droughts. The Equus Beds Groundwater Management District No. 2 manages the *Equus* Beds aquifer in part by limiting ground-water withdrawals to annual ground-water recharge.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1998–657-657

W.R. Aucott and N.C. Myers—Changes in Ground-Water Levels and Storage in the Wichita Well Field Area, South-Central Kansas, 1940–98—USGS/WRIR 98–4141