Kansas Geological Survey

Ground-Water Recharge in the Upper Arkansas River Corridor in Southwest Kansas

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A supplemental report for
Technical Support for Ogallala Aquifer Assessment, Planning, and Management
(Kansas Geological Survey Open-File Report 2002-25)
for Fiscal Year 2002 activities by the Kansas Geological Survey supported by contracts with the Kansas Water Office and the Kansas Department of Agriculture

Kansas Geological Survey Open File Report 2002-30

July, 2002

GEOHYDROLOGY

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Introduction

Spatial and temporal variations in ground-water recharge are substantial across the Ogallala portion of the High Plains aquifer. Average annual recharge to the High Plains aquifer ranges from a fraction of an inch in non-irrigated upland to several inches underlying some flood-irrigated fields and to over one foot as leakage from the overlying alluvial aquifer of the upper Arkansas River. The year-to-year annual recharge for each of these different types of areas varies greatly depending on such factors as the amount and temporal distribution of rainfall, the temperature and humidity, the amount of irrigation water use and, in the case of the upper Arkansas River, the precipitation and water use in Colorado that affect the flow into Kansas. Long-term changes in climate, land and water use, and agricultural practices have caused increases or decreases in the average annual recharge rates. Research conducted during the Upper Arkansas River Corridor Study, a Kansas Water Plan project, gives some insight into these recharge variations at the regional scale. Information on recharge used in the study was based on previous investigations and publications, calculations using river flow and use data, and conceptual and numerical models of ground-water flow and river-aquifer interactions (Whittemore, 2000a; Whittemore et al., 2000a, 2001). Figure 1 shows the location of the High Plains aquifer within the boundary of the regional numerical model in the study area.

Recharge to the High Plains aquifer occurs from different sources in the upper Arkansas River corridor. Areal recharge from precipitation over non-irrigated land is the smallest of the recharge rates. Recharge over irrigated land is substantially greater than from precipitation over non-irrigated area because the water applied produces conditions of high soil moisture that can lead to drainage more frequently. For example, heavy rainfall falling on soils moist from irrigation can much more rapidly produce conditions that lead to effective recharge. Flood irrigation has greater recharge than center pivot because water must saturate the shallow soils underlying the furrows to flow completely across the field. Arkansas River water is diverted across portions of both the alluvial valley and the upland in Kearny and Finney counties and used for flood irrigation. Seepage from under the unlined canals used to carry the water from the river and ditches that distribute the water to fields provides substantial localized recharge. A small, shallow reservoir (Lake McKinney) used to store diverted river water in east-central Kearny County also provides localized recharge. The current condition of lower water levels in nearly all of the High Plains aquifer underlying and adjacent to the Arkansas River causes river water to seep into the alluvial aquifer and then recharge the underlying High Plains aquifer.

Surface Recharge from Precipitation in Non-Irrigated Land

Areal recharge to the High Plains aquifer from precipitation on non-irrigated land was estimated by Dunlap et al. (1985) to be less than 0.5 inch/yr (1.3 cm/yr) in the upper Arkansas River corridor. A slightly greater initial value of 0.6 inch (1.5 cm) of surface recharge over non-irrigated land was used in the numerical models of Whittemore et al. (2001) for ground-water flow in the upper Arkansas River corridor.

The values for surface recharge in both non-irrigated and irrigated land were adjusted in the models to refine the numerical solutions for ground-water flow for “predevelopment” (1940) conditions based on water-level and water-use data for 1938-1942 and simulations based on

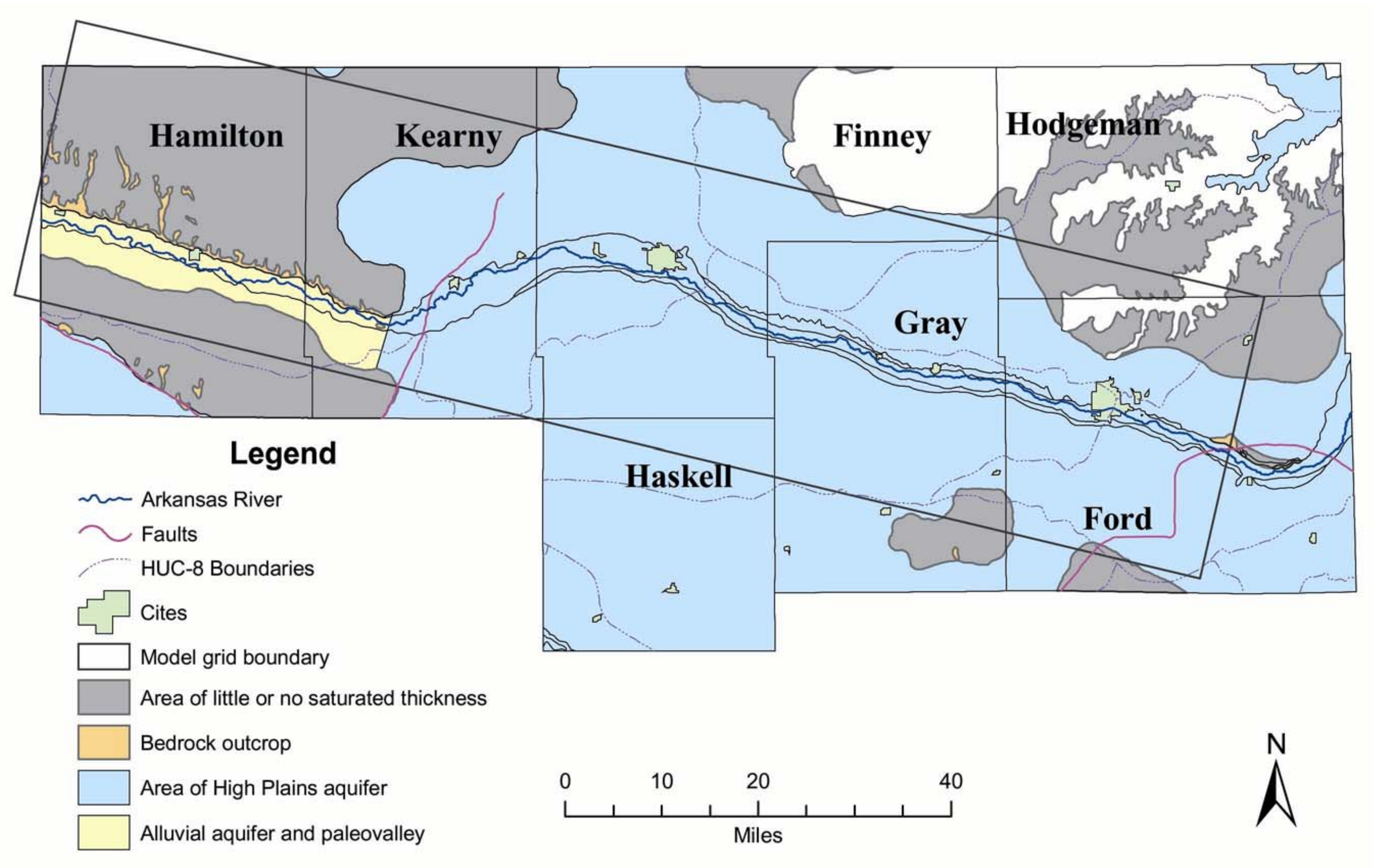


Figure 1. The location of the regional model of the upper Arkansas River corridor in southwest Kansas. The boundary of the model grid extends from the Colorado-Kansas border through parts of Hamilton, Kearny, Finney, Haskell, Gray, Hodgeman, and Ford counties to where the Crooked Creek–Fowler Fault zone crosses under the Arkansas River. The thin black lines on both sides of the Arkansas River delineate the boundaries of the alluvial valley and terrace deposits.

1990's conditions. The calibration for the 1940 model allowed adjustments in both the hydraulic conductivity and recharge. The initial hydraulic conductivity for the 1990's models was based on the final values for the 1940 simulation. The specific storage was estimated from lithologic logs. The 1990's period included substantial changes in ground-water levels that needed to be matched in the calibration. There is a possibility that both the hydraulic conductivity and the specific storage of the smaller saturated thickness of the High Plains aquifer in the 1990's were different from the values for the larger thickness in 1940 due to vertical hydrostratigraphic differences. Some areas of substantial water-level decline could lead to change in hydraulic conductivity and specific storage large enough to possibly introduce additional error into the recharge values during calibration. Thus, the error in the surface recharge values is much greater in the 1990's models than in the 1940 model. For surface recharge values to be more valid for the 1990's simulations, the models would need to be revised with the objective of achieving more accurate recharge.

Data for surface recharge was extracted from files used in the numerical models for the 1940 simulation and processed using ArcMap to produce a map (Figure 2) displaying values for the model cells. The grid used in the numerical simulations is a regular mesh of square cells that are 0.5 mile on a side, giving an area of ¼ square mile or a quarter section for each cell. The grid is composed of 58 rows, equivalent to a grid width of 29 mi, and 252 columns, equivalent to a grid length of 126 mi, resulting in a total of 14,616 cells in a grid layer. There are two layers in the model, one for the alluvial aquifer and the other for the High Plains aquifer and the older alluvial aquifer underlying the sand dunes south of the river floodplain in Hamilton and western Kearny counties. There are 1,421 active cells in layer one and 9,313 active cells in layer two. An active cell is one where the aquifer of interest actually exists within the model area.

Figure 2 displays the distribution of surface recharge to the High Plains and alluvial aquifers for the 1940 steady-state model. The map does not include the discharge or recharge between the river and the alluvial aquifer because this was handled by stream-aquifer simulation in the model. A description of the river-aquifer discharge and recharge in 1940 is included in Whittemore et al. (2001). The areas of low annual recharge in Figure 2 (less than 1 inch per year) represent non-irrigated land and cover most of the alluvial aquifer and the High Plains aquifer where it is not overlain by alluvium in the river valley. The cells with apparent high recharge along some of the edges of the High Plains aquifer extent in Hamilton and Kearny counties do not indicate surface recharge but are for boundary conditions entered into the model to represent lateral ground-water flow from thinly saturated portions of the aquifer into the main aquifer.

Surface Recharge in Irrigated Land

Water has been diverted for most of the twentieth century from the Arkansas River in Kearny and Finney counties into five ditch service areas. The initial value of water seeping underneath the main canals was estimated as 1% per mile of the diversion (based on discussion with the Kansas Department of Agriculture and a ditch area manager) for each ditch service area for the ground-water models. Recharge from surface-water diversions over the irrigated fields was specified in the models as a fraction of the diversions allocated for surface-water irrigation to each of the five ditch service areas. Within each ditch service area, the irrigation return flow

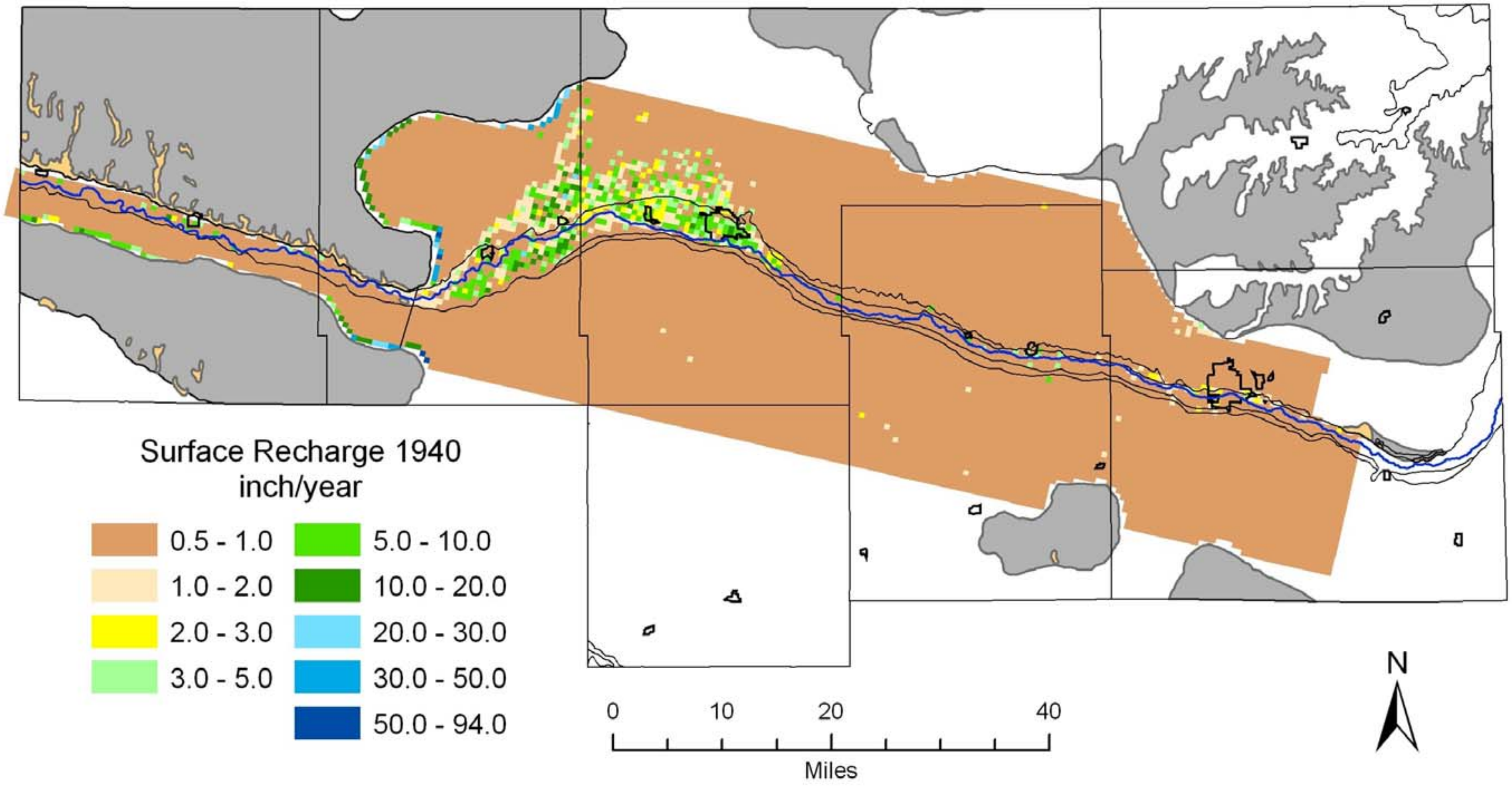


Figure 2. Distribution of surface recharge to the alluvial and High Plains aquifers in the upper Arkansas River valley. The boundaries of the alluvial aquifer and terrace deposits are shown as thin black lines on either side of the Arkansas River. See Figure 1 for explanation of other features. The apparent high recharge in the cells along parts of the High Plains aquifer extent in Hamilton and Kearny counties does not indicate surface recharge but represents lateral ground-water flow needed for model boundary conditions.

was distributed over the existing water rights in proportion to the irrigated area associated with each water right. The initial values of recharge for the water applied to fields for irrigation were calculated as 25% of the surface water spread by ditches and the ground water pumped from irrigation wells within the ditch service's area. The value of 25% was based on Meyer et al. (1970). The total amount of ditch water applied to fields that was used in the calculation was computed as the difference between the total water diverted from the Arkansas River and the water lost by seepage from the main irrigation canals. The calculations were made for each ditch service area. The recharge amounts were summed for each grid cell in the ground-water flow model.

Figure 2 shows the much higher amounts of surface recharge in the ditch service areas in eastern Kearny County and western Finney County than outside these areas for 1940. The irrigated areas in 1940 were within the current boundaries of the cities because the cities were substantially smaller in 1940 than today. Figure 2 indicates that the surface recharge was generally within the range 1-20 inch/yr, values much greater than those for areal precipitation recharge. The largest values generally represent cells in which a canal, ditches, and flood irrigation were present. The distribution of recharge in the ditch service areas in the 1990's is expected to have been somewhat similar to that in the circa 1940 period except that the amount within the city boundaries such as Garden City would be much less. The section in this report on the impact of recharge on water levels substantiates the high recharge in the ditch irrigation area north of the Arkansas River.

The overall surface recharge for the 1990's in the ditch service areas can be estimated from the amount of water diverted. The mean annual flow diverted from the Arkansas River for irrigation during 1989-1998 was approximately 63,000 acre-ft/yr. Most of the river water diverted for irrigation was lost to the atmosphere by evaporation and crop evapotranspiration. The amount consumed is estimated to be about 75% of the diversion flow or 47,000 acre-ft/yr. An estimated 25% (16,000 acre-ft/yr) of the diversions seeped from below canals, ditches, and fields irrigated with the river water and recharged the underlying aquifers. A small amount of this recharge appears to discharge to the alluvial aquifer and then to the Arkansas River based on the higher ground-water levels in the High Plains aquifer than the river surface in the area southeast of Lake McKinney.

The initial value for recharge from land irrigated by well water outside the ditch service areas that was used in the 1940 model was also based on 25% of the water use. The isolated, scattered cells in Figure 2 that generally have recharge values of 1-5 inch/year represent irrigated fields. The irrigation method in the circa 1940 period was flooding of furrows.

Recharge from the Arkansas River to the Alluvial Aquifer

Before wells began to pump substantial amounts of ground water from the alluvial and High Plains aquifers in the upper Arkansas River corridor, the river usually gained flow along nearly all of its length in southwest Kansas (based on USGS streamflow data and water-level data in Latta, 1944, McLaughlin, 1943, and Waite, 1942). The water levels in the High Plains aquifer were usually only slightly higher than in the adjacent alluvial aquifer, thus, the average amount of ground-water discharge per river mile was relatively small. However, the discharge generally increased baseflow downstream. These increases were shown in the numerical model of the "predevelopment" period and are also supported by river flow measurements (Whittemore et al., 2001). During high-flow periods, the river would have recharged the alluvial aquifer but this recharge would have returned to the river during low flow. In general, the river acted as the main discharge zone for the areal precipitation recharge to the High Plains and alluvial aquifers in the river corridor.

The installation and pumping of large-capacity wells in the alluvial aquifer of the Arkansas River after 1900 would have produced local, shallow cones of depression in the aquifer. This would have induced seepage of some river water into the alluvial aquifer where the consumptive loss of water from the aquifer reversed hydraulic gradients from baseflow to seepage conditions. As increased numbers of high-capacity wells were installed in the High Plains aquifer, especially from the 1950's through the mid-1980's, the local cones of depression in the water levels began to coalesce. During the 1970's, the amount of Arkansas River water available for ditch irrigation was low and the amount of pumping from the High Plains aquifer in the river corridor substantially increased. Ground-water levels declined in most areas of the High Plains aquifer across the corridor. The water-level declines became regional and dropped across most of the High Plains aquifer. The vertical head gradients that were generated caused a substantial increase in the downward movement of water from the alluvial aquifer into the underlying High Plains aquifer (Whittemore et al., 2001). The regional declines in water levels in the High Plains aquifer also changed the direction of ground-water flow in the river corridor. Ground water began not only to move from the river into the alluvial aquifer and down into the underlying High Plains aquifer but also to migrate away from the river and alluvial valley. The numerical simulation of ground-water flow indicates that flow directions have shifted from the general regional movement towards the east-southeast based on the 1940 "predevelopment" conditions to the southeast or south in the area south of the river from eastern Kearny County to western Gray County, and to the northeast from the river in portions of western Finney County. (See Whittemore et al., 2001, for additional details of the models.)

After the 1970's, increasing amounts of river water seeped into the alluvial and High Plains aquifers. The corridor changed progressively downstream from a system of average net increases in baseflow to net flow decreases even after accounting for the diversions for ditch irrigation. Today, the location where baseflow typically adds to the river flow is east of Dodge City.

Flow losses along the Arkansas River between the Colorado-Kansas line (represented by Coolidge or Syracuse) and Garden City are shown in Figure 3, and between Garden City and Dodge City are illustrated in Figure 4. The values in the Figure 3 have been adjusted for the river water diverted from the river, so both graphs represent losses that were caused by river seepage and evapotranspiration losses. There has been a substantial increase in the flow loss from the river channel between the state line and Garden City after 1980. Except for one year, the Arkansas River gained flow between Garden City and Dodge City up to the early 1970's based on the annual discharge difference (Figure 4). The single year of flow loss before the mid-1970's occurred during 1965 when very high river flows caused substantial bank storage in the alluvial aquifer. The general trend from the start of the records in the mid-1940's to the late 1970's was a steady decrease in the amount of flow gained between Garden City and Dodge

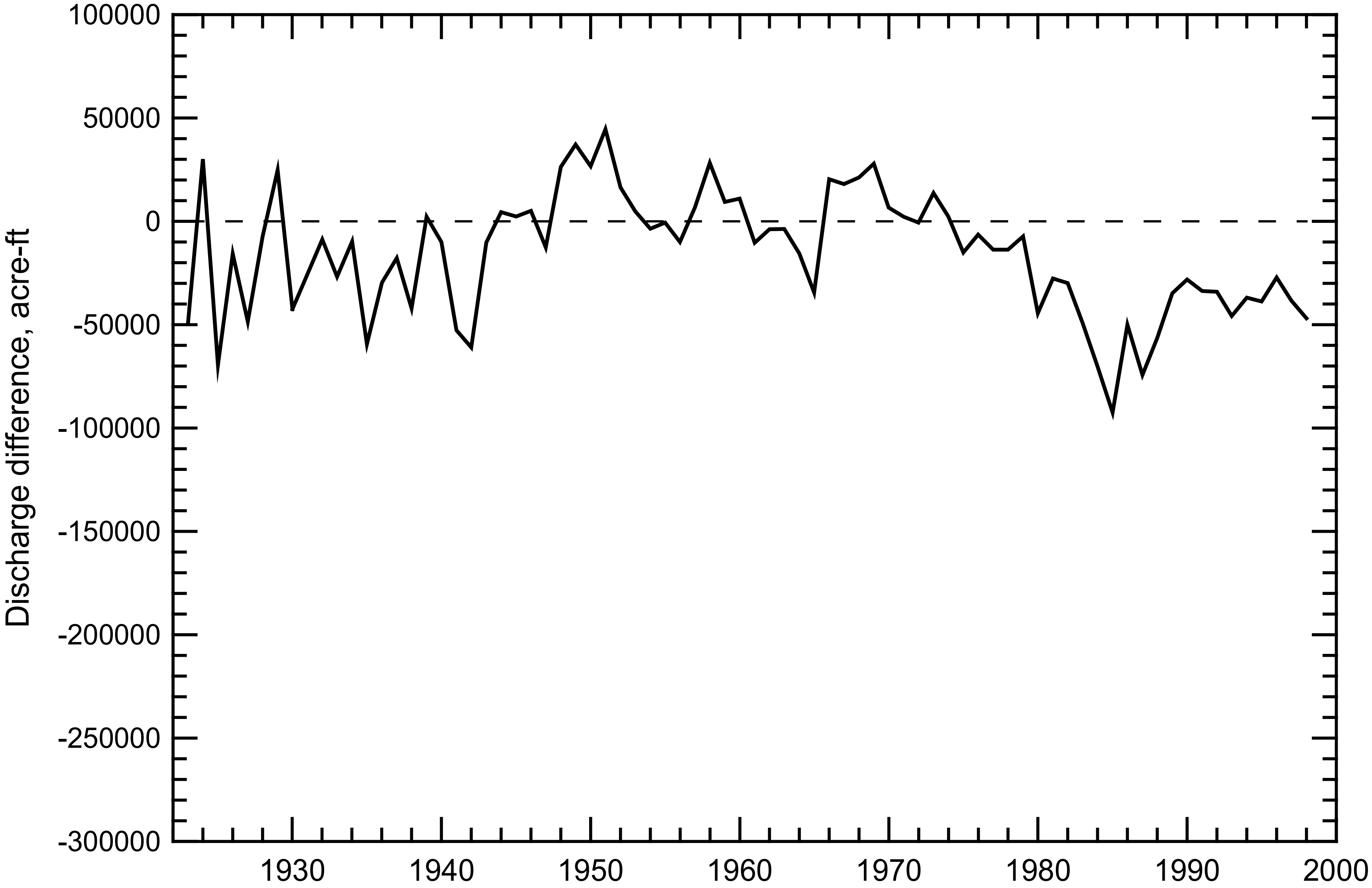


Figure 3. Net gain or loss from the Arkansas River channel computed from the annual river flow at Garden City plus total irrigation diversions in Kearny and Finney counties minus flow at Syracuse. Negative values indicate flow loss.

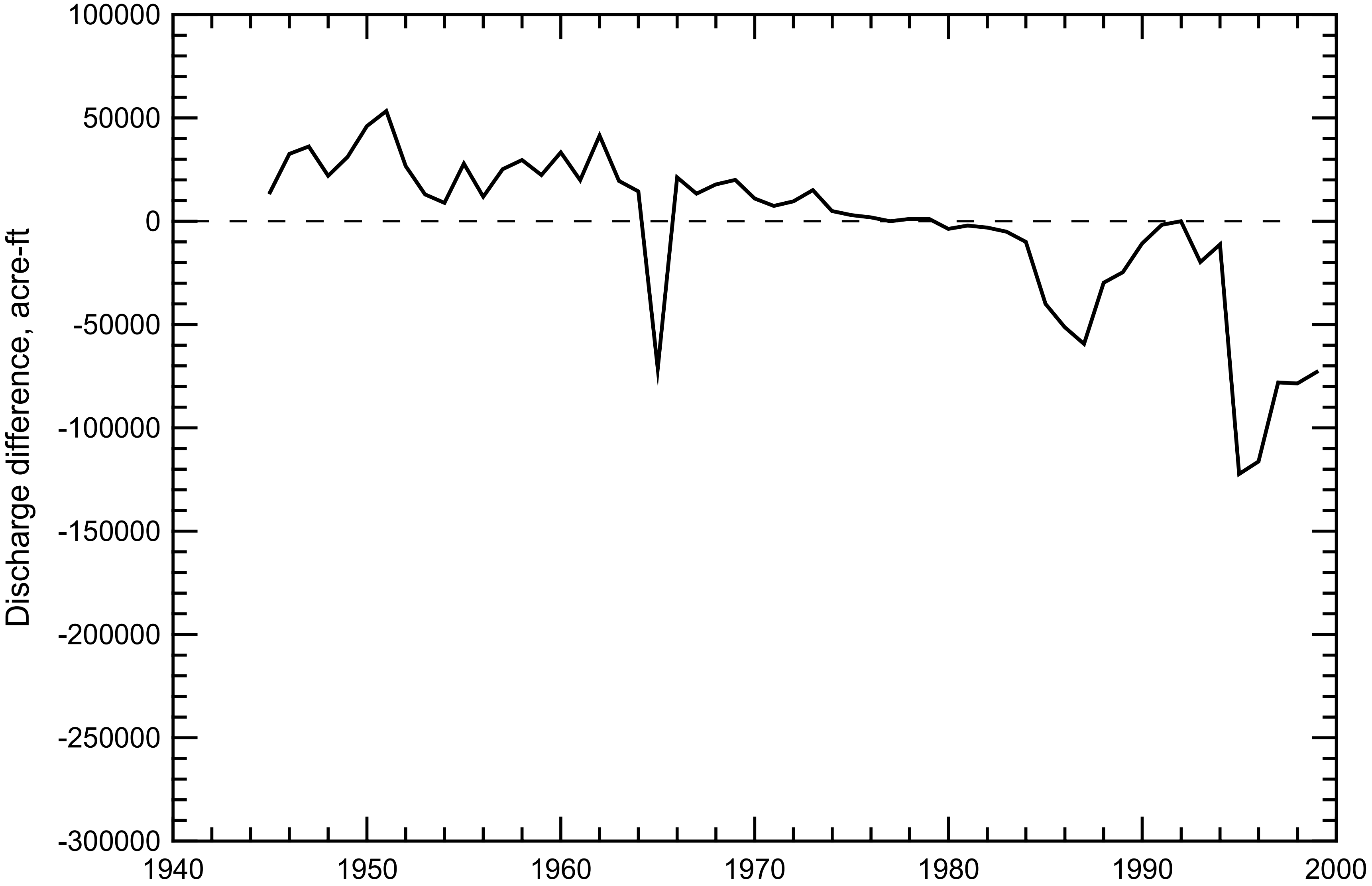


Figure 4. Difference in annual flow of the Arkansas River between Garden City and Dodge City. Negative values indicate flow loss.

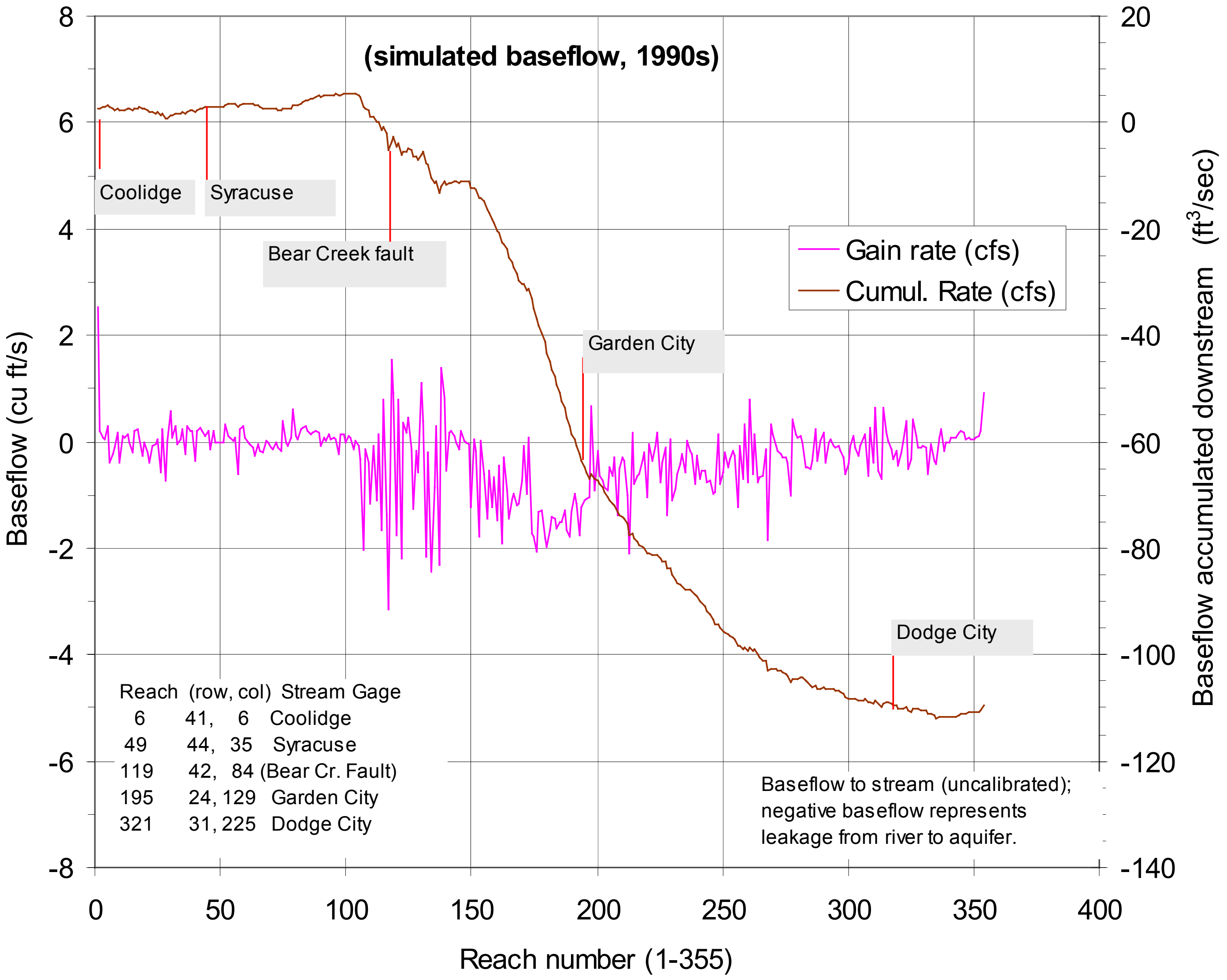
City. Starting in the early 1980's, the river began to lose flow after declines in ground-water levels farther along the river corridor stopped the discharge from the High Plains aquifer to the alluvium. The losses are particularly large when the river flows are greater than average, such as in 1987 and during the last several years. During periods of lower river discharges at the state line, there can be little or no water that flows past Garden City when water is being diverted for irrigation in Kearny and Finney counties. If the flow is low enough at the state line, the flow may not reach Dodge County even when there is no water diverted in Kearny and Finney counties. Thus, the absolute magnitude of the river flow losses between Garden City and Dodge City is smaller during periods of low flow at the state line than during moderate to high flows from Colorado because there is a smaller amount of river water available for recharge.

The average annual decrease in river flow from the Colorado-Kansas border (gaging station near Coolidge) to Dodge City was 152,000 acre-ft/year (210 acre-ft/day, 1.66×10^8 gal/day, 243 cfs) for the ten-year period of 1989-1998. The mean annual flow diverted from the river for irrigation during the same period was 63,000 acre-ft/yr. In comparison, ground-water withdrawals for irrigation were about 760,000 acre-ft/yr and the total pumped for municipal, industrial, and stock use (for wells with water rights) were approximately 42,000 acre-ft/yr during the last few years of the 1990's in the 5 counties of the river corridor (Whittemore et al., 2001).

The estimated amount of water lost from the surface of the river to evaporation was about 6,000 acre-ft/yr based on lake evaporation rates and an approximation of the average surface area of flow in the river from Coolidge to Dodge City (Whittemore et al., 2001). This comprises less than 4% of the total annual decrease in river flow along that distance. Up to 20,000 acre-ft/yr of water from the alluvium could be consumed by phreatophytes in the river valley based on water consumption data for a study in southwestern U.S. (Culler et al., 1982) and an investigation of phreatophyte density in the upper Arkansas River corridor (Tomelleri and Hulett, 1983). Some of this water would be derived from river flow and the rest of the phreatophyte consumption would be from infiltration of precipitation into the soil of the floodplain.

By difference, the amount of water that seeped from the river channel and recharged ground water during 1989-1998 averaged about 73,000 acre-ft/yr if approximately half of the phreatophyte consumption was from river flow. The total recharge from the ditch diversion system (about 16,000 acre-ft/yr) and the river channel is estimated to have averaged nearly 90,000 acre-ft/yr during the period. If ¾ of the phreatophyte water consumption along the river valley was derived from river flow, then the river-channel recharge was approximately 68,000 acre-ft/yr and the total recharge from the river and irrigation diversions was about 84,000 acre-ft/yr for 1989-1998. The amount of recharge during the high flow years of the late 1990's is greater than the 10-year average. Annual recharge of Arkansas River water into the alluvial aquifer in southwest Kansas substantially exceeded 100,000 acre-ft during 1995-2000 (Whittemore et al., 2001).

The interchange of water between the Arkansas River and the alluvial aquifer in the numerical simulation of the river corridor for 1990's conditions is shown in Figure 5. Data for the graph are based on a steady-state model in which the average 1990's ground-water levels were maintained as constant by reducing the water use from the aquifer. The approach used to



Reach	(row, col)	Stream Gage
6	41, 6	Coolidge
49	44, 35	Syracuse
119	42, 84	(Bear Cr. Fault)
195	24, 129	Garden City
321	31, 225	Dodge City

Baseflow to stream (uncalibrated); negative baseflow represents leakage from river to aquifer.

Figure 5. Baseflow gains and seepage losses along the Arkansas River from a 1990's steady-state simulation with water use reduced sufficiently to maintain average ground-water levels of the 1990's.

simulate the baseflow was independent of streamflow measurements (Whittemore et al., 2001). The results reflect what the ground-water flow and streambed leakage simulation produced in terms of river-aquifer interactions. The line in Figure 5 with the high-frequency oscillations is the simulated streamflow from grid cell to grid cell along the Arkansas River (successive river nodes). The scale for this line is the left-hand y-axis. The fluctuations in the baseflow from node to node are less than about ±3 cfs of a running average along the river in the corridor model. The smooth line in Figure 5 represents the cumulative baseflow gains from ground-water discharge or seepage losses along the river from the Colorado-Kansas line to the eastern end of the model past Dodge City. The right-hand y-axis applies to this line.

Figure 5 illustrates the cumulative flow losses along the Arkansas River from the state line to Dodge City for the 1990's. The cumulative flow changes are relatively small from the Colorado-Kansas line to the western portion of the Bear Creek fault zone. The cumulative flow losses become substantial near the fault zone where the High Plains aquifer begins and continue to the eastern end of the modeled area. The greatest rate of flow loss is through Finney and Gray counties. The flow loss rate then decreases in Ford County.

The pattern in measured flow losses along the Arkansas River is similar to the simulated losses for that period. The observed flow loss between the gaging stations at Coolidge (near the state line) and Syracuse averaged 10 cfs during 1990-1999. In comparison, the simulated accumulated change is a very small gain between Coolidge and Syracuse (Figure 5). The simulated model does not directly include evapotranspiration. Thus, the actual change in flow would be expected to be a small loss between Coolidge and Syracuse rather than the very small gain that was simulated. The average observed loss from the river between Syracuse and Garden City, adjusted by adding diversions for irrigation, was 52 cfs for 1991-1998, with a low of 37.4 cfs in 1992 and a high of 64.7 cfs in 1998. The simulated flow loss for river-aquifer interactions over the same reach is about 66 cfs (Figure 5). The average flow loss observed during 1991-1999 between Garden City and Dodge City was 77 cfs, with a low of about 1 cfs in 1992 and a high of 169 cfs in 1995. The simulated loss between the two gaging stations is approximately 47 cfs (Figure 5). Considering that evapotranspiration consumption of water would increase the simulated flow losses, the simulation is a relatively good representation of the average river-aquifer interactions during the 1990's.

Most of the flow losses between the state line and Garden City occur from the western edge of the High Plains aquifer underlying the river valley (near the former town of Hartland) to Garden City. The distances along the Arkansas River between Hartland and the stream gaging station at Garden City and between the stations at Garden City and Dodge City are approximately 22 miles and 53.3 miles, respectively. If the width of the active river channel where seepage occurs averages 0.05 mile, the areas of the channel between Hartland and Garden City and between Garden City and Dodge City are 1.1 sq miles and 2.7 sq miles, respectively. Mean flow losses of 52 cfs and 77 cfs for the two river reaches (see above) translate to annual recharge rates of 642 inch/yr (53.5 ft/yr, 1.8 inch/day) and 392 inch/yr (32.7 ft/yr, 1.1 inch/day), respectively, for these channel areas. Not all of this recharge seeps to the underlying High Plains aquifer due to evapotranspiration and pumping losses. The following section describes the leakage of the streambed recharge from the alluvial aquifer to the High Plains aquifer.

Leakage from the Alluvial Aquifer to the Underlying High Plains Aquifer

Under present and predicted average conditions of hydraulic head, ground water in the alluvial aquifer of the upper Arkansas River valley flows both laterally from the river and vertically into the underlying High Plains aquifer (Whittemore et al., 2001). Leakage from the alluvial aquifer to the underlying High Plains aquifer begins at the western extent of the High Plains aquifer in southwest Kansas near the former town of Hartland. The length of the alluvial valley from Hartland to the Kearny-Finney county line is about 16 miles; the width of the alluvial aquifer in this stretch ranges from 1.5 to 4 miles. The total areal surface of this part of the alluvial valley is approximately 50 square miles. The length, width range, and areal surface of the section of the alluvial valley from the Kearny-Finney county line to Garden City are about 12.5 miles, 2.5-3 miles, and 34 square miles, respectively. The length, width, and areal surface of the alluvial valley from the Garden City to Dodge City are approximately 40 miles, 2.5 miles, and 100 square miles, respectively. The total surface area of the alluvial valley from Hartland to Dodge City is about 184 square miles, which is equivalent to 118,000 acres.

An average net recharge of 73,000 acre-ft from the Arkansas River to the alluvium followed by leakage into the underlying High Plains aquifer during 1989-1998 is equivalent to a recharge rate of about 7.4 inches per year over the entire area of the alluvial valley. During 1995-2000 when the river flows and recharge were much greater, the recharge would have been over 100,000 acre-ft, meaning recharge rates of over one foot per year. Figures 3 and 4 show that the flow losses vary substantially and are not the same for the two river stretches represented by the graphs. Recharge rates could have averaged as great as 1.5 feet over the alluvial valley in 1995 and 1996 and even more in selected sections of the valley. These rates assume uniform recharge along each section of the alluvial valley. Substantial differences in the hydraulic connection between the alluvial and High Plains aquifers (Whittemore et al., 2000b) mean that local leakage rates from the alluvium to the underlying aquifer are expected to be both appreciably less than and greater than1.5 ft/year.

The recent seepage rate from the Arkansas River to the alluvium is controlled primarily by the amount of water in the river, the head gradient from the river into the alluvial aquifer, and the hydraulic conductivity of the riverbed. Much of the alluvial aquifer consists of coarse sands and gravels. A zone of low permeability clays and silty clays underlies much of the alluvium and slows the downward movement of shallow ground water into the High Plains aquifer. Thus, the hydraulic conductivity of the alluvium is generally greater than that of the sediments underlying the alluvium. This allows seepage from the river to move outward into the alluvial aquifer more readily than into the underlying High Plains aquifer. Consequently, the lower conductivity stratum typically underlying the alluvium appears to be a limiting control on the rate of river-water loss to the alluvial aquifer. Therefore, when the river flow is low, the rate of seepage from the alluvial aquifer to the High Plains aquifer is less of a limiting factor on the amount of seepage. A greater percentage of the low flows are lost to the ground-water system, resulting in dry riverbed conditions during many periods. When the river flow is high, the rate of infiltration from the alluvium to the High Plains aquifer probably limits the amount of river-water seepage. The river infiltration saturates the alluvium across the river valley and increases the seepage relative to low flow conditions but the flow can be great enough that the river flows through the entire corridor.

Impact of Recharge on Ground-Water Levels

The distribution of and changes in water levels in the High Plains and alluvial aquifers relative to the surface elevation of the Arkansas River illustrate the impact of recharge variations in the river corridor. Before diversion of Arkansas River water and development of ground-water resources in the river corridor, ground-water tables to the north and south of the river were, in general, slightly higher than in the river. After the substantial ground-water development, water levels in the High Plains aquifer dropped substantially in much of southwest Kansas. However, recharge from the ditch service area and the river valley has kept water levels from dropping as much as they have farther from these locations.

The effect of the interrelationships between ground-water recharge and withdrawal rates on aquifer water levels can be illustrated by well hydrographs across the river corridor. The hydrographs for wells along a cross section extending north and south of the Arkansas River in east-central Kearny County (within the column of townships in R. 35 W.) are a good representation of these relationships. The cross section includes part of the ditch service area, the Arkansas River valley, and the upland to the south of the river (Figure 6). The water-level records for wells with greater than a decade of water-level measurements were selected for displaying hydrographs.

Table 1 lists information for the 5 wells in Figure 6 that lie to the north of the Arkansas River valley and Table 2 includes data for the 6 wells south of the river. The wells are listed in order of decreasing (Table 1) and increasing (Table 2) distance from the Arkansas River, based on measurements from each well location directly north or south to the river on USGS topographic quadrangles. All 5 of the wells in Table 1 are screened in the High Plains aquifer. The first two wells lie to the northwest and outside of the irrigated area served by Arkansas River diversions. The third and fourth wells listed in Table 1 are within the boundaries of the Amazon ditch service area. The fifth well is in the southwest corner of an isolated section of the Great Eastern ditch service area and next to the Amazon service area. The land-surface elevation decreases from the west to the east and from the north to the south in the area of the 5 wells.

The first two of the 6 wells listed in Table 2 south of the river are within the South Side ditch service area and are screened in the Quaternary alluvial aquifer. The other 4 wells are outside the ditch irrigation boundary and are screened in the High Plains aquifer. The depths of these 4 wells increase with distance from the river. Although river surface elevation changes with river stage, the stage variations usually range within only a couple of feet for near normal flows. Information on the source and processing of the data listed in Tables 1 and 2 are in Whittemore et al. (2001).

Comparison of the ground-water levels to Arkansas River elevations illustrates the change in the water-level surface of the ground water in different parts of the river corridor relative to the river. Tables 1 and 2 list the height of the land surface at the wells above the river and the height of the water level at the well locations above the river in 1940. The 1940 water levels at the well locations directly north of the river ranged from 13 to 36 ft above the river-water surface. At the well locations directly south of the river, the water levels in the alluvium were the same as the river surface and in the High Plains aquifer were 2 to 9 ft above the river

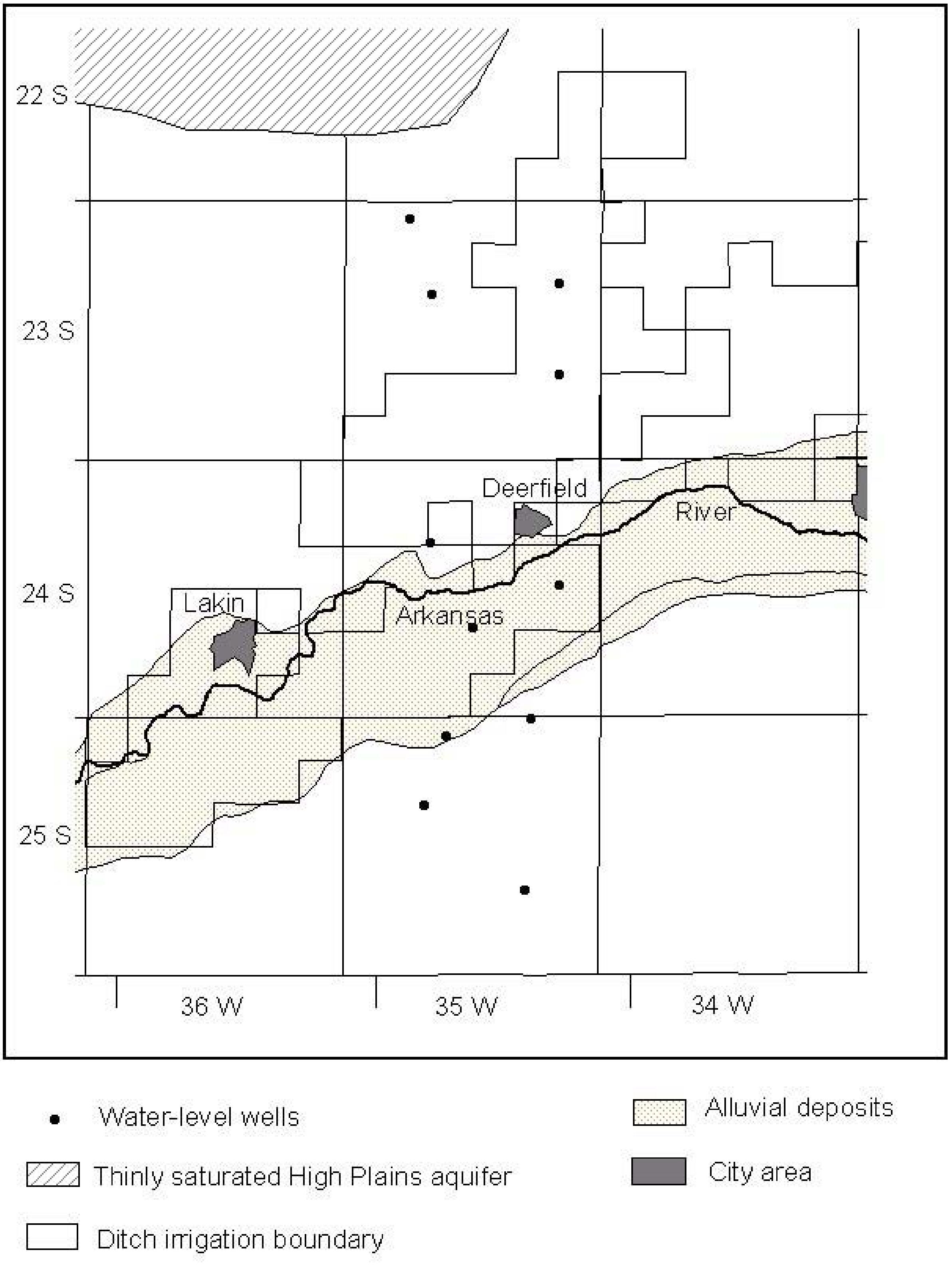


Figure 6. Location of wells with long-term water-level measurements along the eastern side of Kearny County and north and south of the Arkansas River.

Table 1. Water Levels and Associated Information for Wells in the High Plains Aquifer North of the Arkansas River in East-Central Kearny County.

Well location, well number, and period of record	Well depth, ft	Land surface elevation, ft	Well use	1940 water-level depth, ft	Distance from river, miles	Location relative to ditch irrigation area and Arkansas River floodplain	Land surface elevation above river, ft*	1940 water-level elevation above river, ft*
23S 35W 05ACC 01 1/17/66 – 1/4/99	180	3096	Irrigation	114	8.2 N	2.8 miles west of Amazon Ditch. Above floodplain	144	30
23S 35W 16BBC 01 8/29/84 – 1/4/99	263	3038	Irrigation	55	6.8 N	1.9 miles west of Amazon Ditch. Above floodplain	91	36
23S 35W 12CCC					6.1 N	In Amazon area		13
01 5/1/58 – 4/20/93	378	3009	Irrigation	67		Above floodplain	80	
02 1/15/92 – 1/4/99		3010	Irrigation	68			81	
23S 35W 25BBB					4.0 N	In Amazon area		30
02 4/1/58 – 1/11/94	320	3005	Irrigation	46		Above floodplain	76	
03 11/17/93 – 1/22/99		3000	Irrigation	41			71	
24S 35W 09CCC 01 5/1/58 – 1/5/99	253	2998	Observation	30	1.1 N	In Great Eastern area, near main canal Above floodplain	50	20

* Elevation of river directly south of well taken from USGS 7.5 minute topographic quadrangle.

Table 2. Water Levels and Associated Information for Wells in the High Plains Aquifer or Alluvium South of the Arkansas River in East-Central Kearny County.

Well location, well number, and period of record	Well depth, ft	Land surface elevation, ft	Well use	1940 water-level depth, ft	Distance from river, miles	Location relative to ditch irrigation area and Arkansas River floodplain	Land surface elevation above river, ft*	1940 water-level elevation above river, ft*
24S 35W 13CCC 02 1/1/62 – 9/6/94	50	2941	Unused	12	0.9 S	End of Southside area In floodplain	12	0
24S 35W 22CCC 02 5/1/58 – 4/26/99	65	2962	Irrigation	20	0.9 S	In Southside area In floodplain	20	0
25S 35W 04BDD 01 1/21/85 – 1/4/99	299	2990	Irrigation	40	3.5 S	0.5 mile south of Southside boundary Above floodplain	44	4
25S 35W 02BAA 01 4/1/75 – 1/22/99	300	2990	Observation	52	3.7 S	Over 1 mile southeast of Southside boundary Above floodplain	58	6
25S 35W 17AAA 01 3/1/75 – 1/4/99	320	2995	Irrigation	37	4.9 S	2 miles south of Southside boundary Above floodplain	46	9
25S 35W 26BAB 01 6/1/75 – 1/4/99	367	3005	Irrigation	70	7.6 S	Over 6 miles south of Southside boundary Above floodplain	72	2

* Elevation of river directly north of well taken from USGS 7.5 minute topographic quadrangle.

surface in 1940. This indicates that there would have been a component of ground-water flow from the High Plains aquifer towards the river both north and south of the river in combination with the predominant easterly direction of regional flow. The head gradient towards the river would have been greater on the north side than on the south side of the river in 1940.

Figures 7-9 show the hydrographs for the wells in Tables 1 and 2 relative to the Arkansas River level. The hydrographs for the two wells outside the ditch-irrigation area north of the river are in Figure 7 and for the 3 wells within the ditch boundaries north of the river are in Figure 8. The depth to water becomes shallower the closer to the river for these three wells (Figure 8). The hydrographs for the 6 wells south of the river are graphed in Figure 9.

The earliest water levels for all of the wells with records that begin before 1970 were above the river surface. Pumping from the aquifers caused the ground-water levels to drop below the river surface at all of the wells during the mid-1970's to the early 1980's. Extrapolation of the hydrograph trends for the two wells in High Plains aquifer farthest south of the river indicates that the water levels probably declined below the river level in the early 1970's at these locations. During 1974 through 1979, the flow in the Arkansas River and, thus, the amount of water available for surface-water irrigation diversion were particularly low. Substantial amounts of ground water were pumped from the aquifers within the ditch service areas because the amount of diverted river water was substantially smaller than the long-term mean. Except for the well closest to the north side of the river valley, the water levels in all the wells in the High Plains aquifer have remained below the river surface after 1979. The water level at the well in the Great Eastern ditch area north of the river (24S-35W-09CCC) has remained above the river surface since 1984 (Figure 8). The well is sited close to the Great Eastern canal and near Lake McKinney, thus, the High Plains aquifer receives substantial local recharge. The January 2000 measurement for a well farther to the north of the river (located at 23S-35W-25) is 10 ft below the river surface as interpreted from the USGS topographic map.

Arkansas River flows at the state line increased during 1980 through 1982 but were still below the long-term average. Ground-water levels continued to drop in all of the wells in Figures 7-9 with records for this period. River flows were above average for 1983 through 1988 and exceeded three times the mean in 1987. The quantity of water diverted from the river for irrigation also was above the long-term mean for 1983-1988. The water levels for wells within the ditch service areas began to increase during this period, reflecting substantial recharge from the river water diverted in canals and spread over fields and a decline in the amount of ground water needed for irrigation (Figure 8). Water levels also rose within the alluvial aquifer reflecting the higher river levels and greater amounts of flow available for recharge (Figure 9). However, water levels in the High Plains aquifer south of the river continued to decline.

From 1990 through 1993, the river flow and diversion volumes dropped to lower than the long-term mean, resulting in less recharge and a slight drop in water levels for the High Plains and alluvial aquifer wells in the ditch service areas (Figures 8 and 9). From 1995-1999, river flow and diversion volumes were above average. The recharge for this period is reflected as appreciable water-level rises in the two hydrographs for the High Plains aquifer wells in the Amazon ditch area (Figure 8). Water levels for the High Plains aquifer well north of and near the river valley and for the alluvial wells stabilized during 1995-1999. The higher water levels

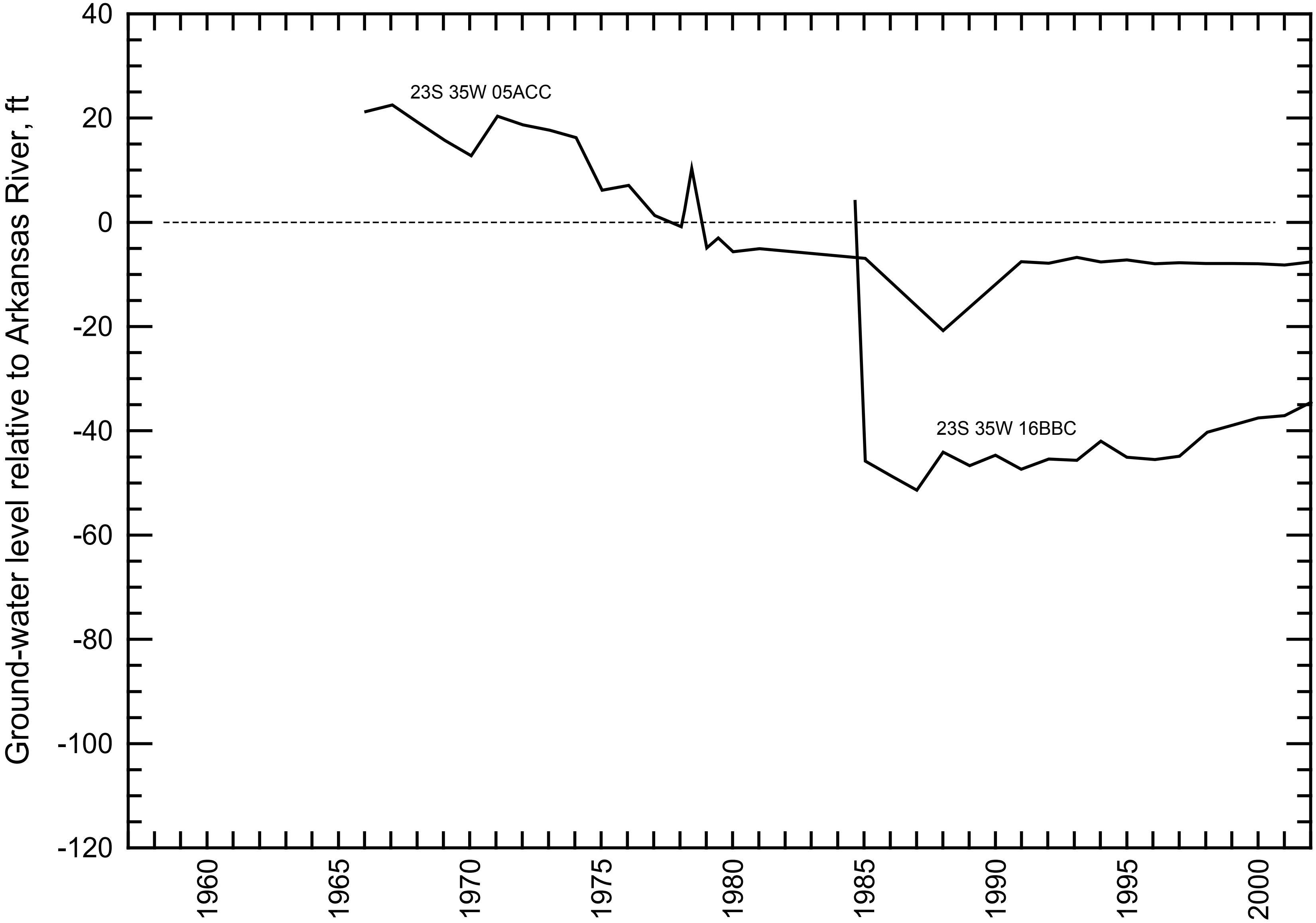


Figure 7. Hydrographs for wells in Table 1 outside the ditch irrigation area represented as water levels relative to the elevation of the Arkansas River.

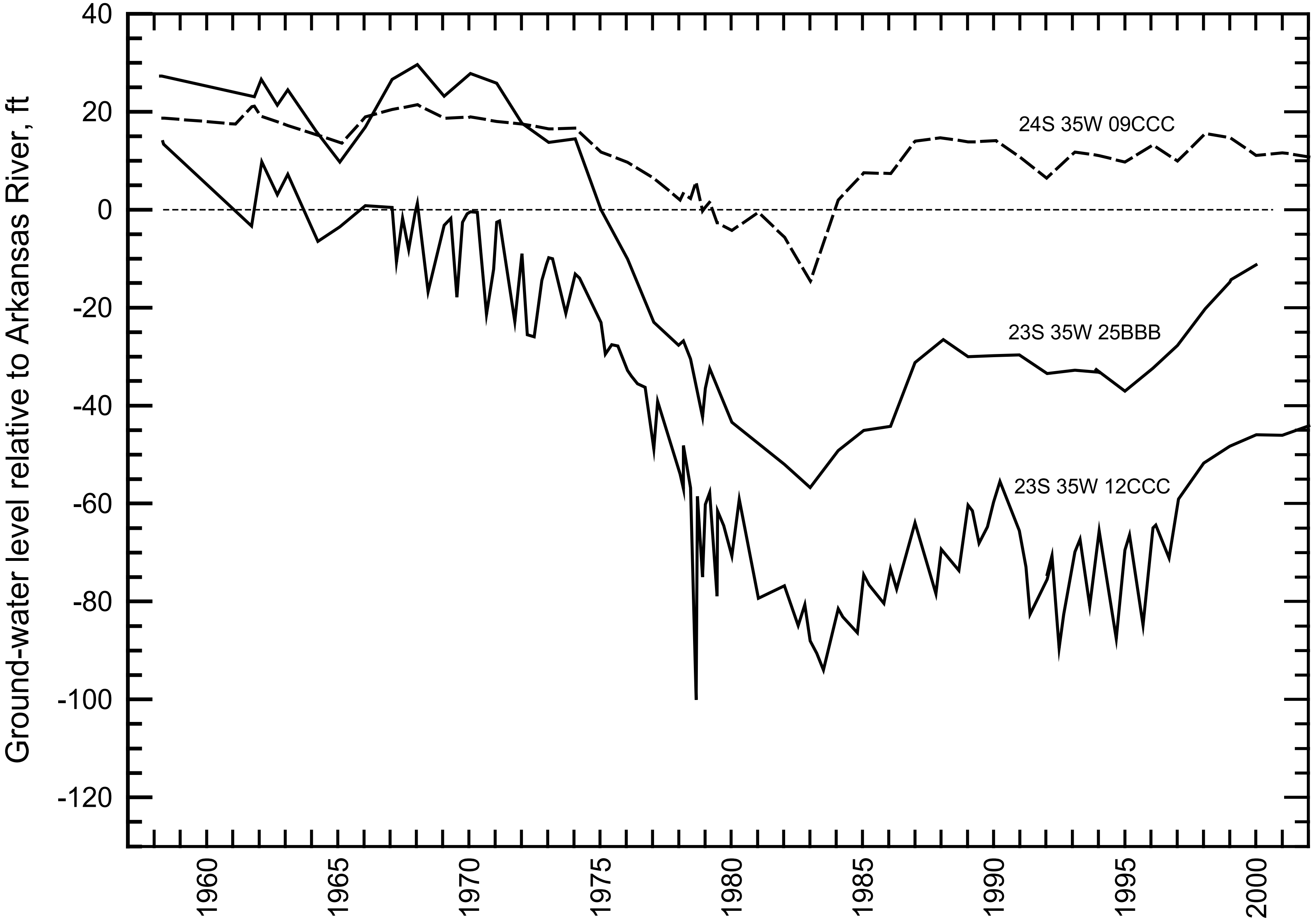


Figure 8. Hydrographs for wells in Table 1 within the ditch irrigation area represented as water levels relative to the elevation of the Arkansas River.

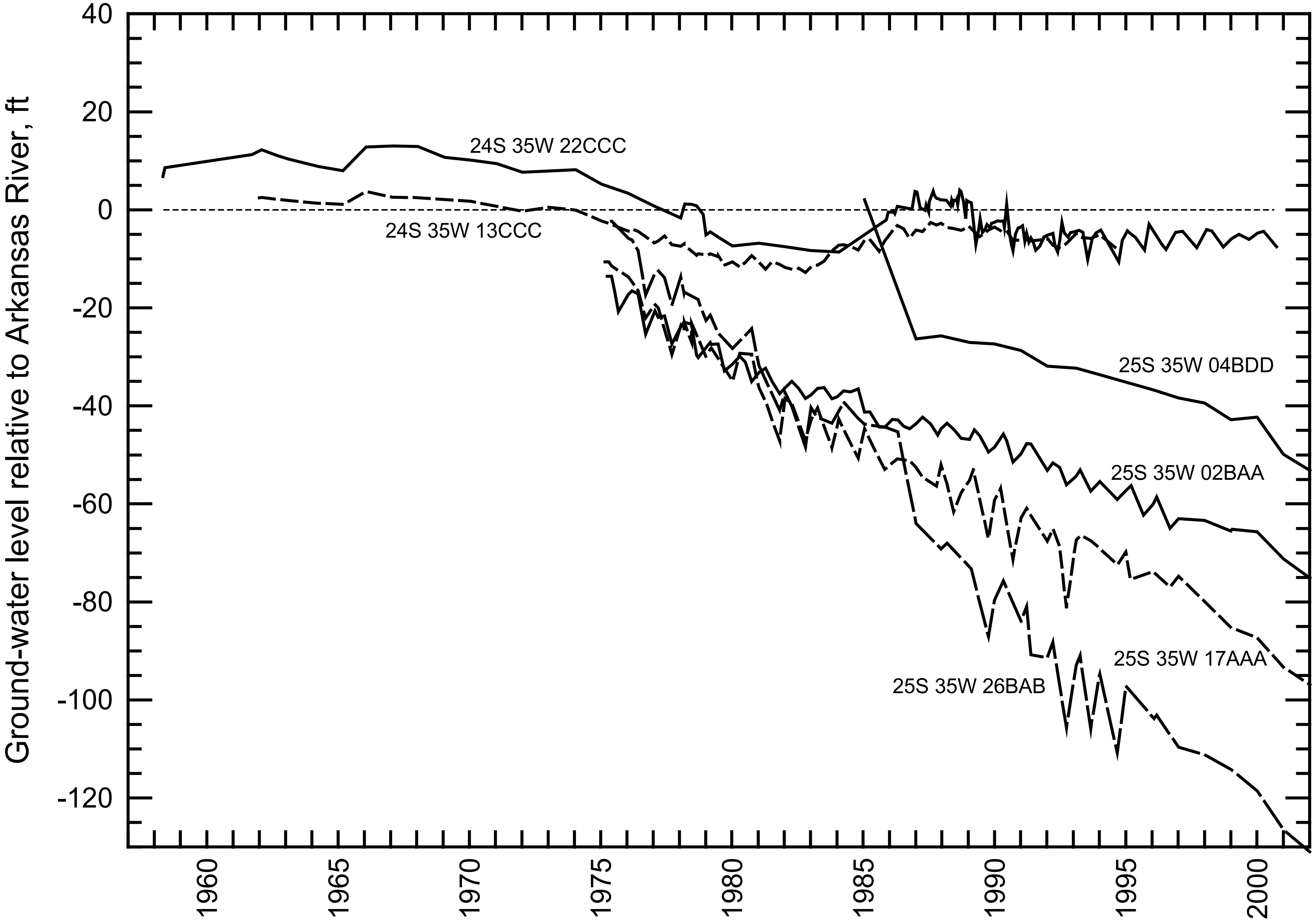


Figure 9. Hydrographs for wells in Table 2 represented as water levels relative to the elevation of the Arkansas River .

for the wells within the ditch service areas north of the river after the mid-1980's than during the early 1980's are probably responsible for the stable or slight rise in the water levels of the two wells outside the ditch-irrigated area after the mid-1980's (Figure 7). The reason is that the rising water levels under the ditch area would have decreased the head gradient towards the east and southeast near the western boundary of the ditch service area.

Water levels in the High Plains aquifer wells south of the river continued to drop at a substantial rate during the 1990's (Figure 9). In general, the farther is the distance of the well location from the river, the steeper was the rate of decline. The farther a well is from the river and alluvial aquifer, the smaller is the recharge water volume that flows in the subsurface to the well. The hydrographs display no large variations with time that are correlated with river flow and irrigation diversions as do those for the alluvial wells and wells north of the river in the ditch-irrigation area. However, there are some changes in the general rate of decline that may correspond to annual variations in river flows and diversions. In addition, the decline rate changes are affected by the amount of pumping that correspond to annual rainfall variations over the field locations.

Figure 10 displays the distribution of water-level changes in the High Plains aquifer between 1991 and 2000 across the area of the regional model of the upper Arkansas River corridor. The water-level rises to the north of the Arkansas River in east-central Kearny County and west-central Finney County represent the effect of the surface recharge from much of the area irrigated by diverted river water. The lower two hydrographs in Figure 8 are for wells in the water-level rise area. The south-central part of the model area in Figure 10 shows that there are substantial water-level declines across a large region and that the declines increase to the south. The Arkansas River valley lies between the water-level rise and decline areas. The water levels in the High Plains aquifer underlying the valley do not vary much from year to year because leakage of water from the alluvial aquifer maintains the levels.

The long-term trend in the hydrographs for the two alluvial wells in Figure 9 is a declining water level. However, Arkansas River flow was generally smaller during the late 1950's and early 1960's than in the mid-1980's and late 1990's. Therefore, a change in the average annual flow of the river could not account for this drop. Two factors are responsible for the trend. The main factor is the change in the morphology of the Arkansas River channel. Since the start of ditch irrigation in the late 1800's and later regulation of the river flow by reservoirs in Colorado, the river channel has narrowed and become more entrenched (Spray, 1986). This is reflected in the changes at the USGS gaging stations where the datum for the water-stage recorders has been lowered. For example, since October 1986, the stage datum at the Garden City station has been 9 ft lower than for the period 1957-1964 (USGS, 1999). The date of the contours in the USGS topographic maps used to estimate the river surface elevations is 1958-1960. The topographic maps were photo-revised for selected features in 1978 but the river surface shown in the map represents a 1958 interpretation of aerial photographs with a 1960 field check. Although the scour of the river channel could be somewhat greater near the stage recorder at Garden City due to the proximity to the bridge supports, it is clear that the river channel has deepened substantially since 1960. The lower river level results in lower ground-water levels in the alluvium near the river. The other factor explaining part of the long-term downward trend in the alluvial water levels is the water-level decline in the High Plains aquifer

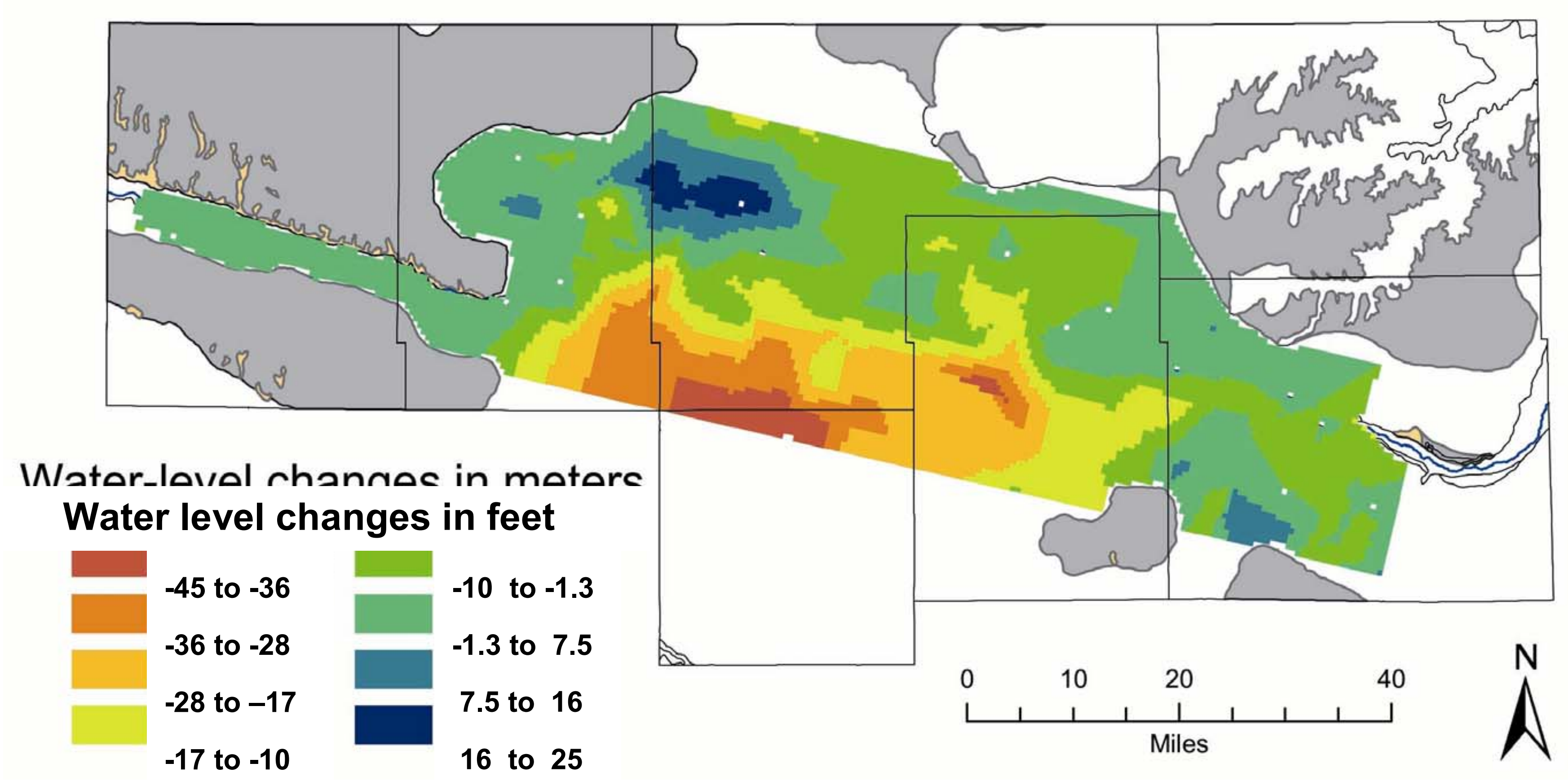


Figure 10. Change in the water-level surface between 1991 and 2000 represented as color-shaded intervals in the area of the regional model of the upper Arkansas River corridor. The intervals range from a maximum water-level decline of 45 ft to a maximum water-level rise of 25 ft.

underlying and to the south of the river. The vertical hydraulic gradient from the alluvium to the underlying aquifer caused seepage from the alluvium to the underlying High Plains aquifer, thereby slightly lowering the water table in the alluvial aquifer. The magnitude of this effect is expected to be greater the farther the distance from the river.

Since 1990, the higher water levels at the alluvial wells have been about 5 ft below and the lower water levels approximately 8 ft below the river level based on the river surface estimates from the USGS topographic maps (Figure 9). The lower water levels for the well at 24S-35W-22 during the 1990's occurred at the end of the irrigation season and reflect pumping within the alluvial aquifer and in the underlying High Plains aquifer. The difference in elevation between the river surface and the ground-water levels in the alluvial wells 0.9 miles to the south is expected to be less than one ft during the non-irrigation season when the water levels in the alluvial aquifer are higher. Thus, the estimated deepening of the Arkansas River channel is approximately 5 ft in eastern Kearny County since 1960.

Impact of Recharge on Ground-Water Quality

The salinity of ground waters in the High Plains aquifer has increased substantially during the last half of the 20th Century in the Arkansas River corridor as a result of saline recharge derived from the river. The recharge occurs along the river channel and moves into the alluvial aquifer and then into the underlying High Plains aquifer, and also from irrigation canals, ditches, and fields irrigated with the river water. The migration of saline recharge from the river into the High Plains aquifer could be considered as a depletion of water usable (without treatment) for such uses as public water supply, drinking water for young stock, and industrial supplies requiring low dissolved solids. This would be a different type of depletion from the actual loss of water but one that is appropriate to consider in evaluating the various management considerations and the impacts of human activities on the aquifer resources.

Dissolved solids contents in low flows of the Arkansas River water can exceed 4,000 mg/L at the Colorado-Kansas state line. The major dissolved constituents in Arkansas River water, in the order of decreasing mass concentrations that usually occur, are sulfate, sodium, bicarbonate, calcium, magnesium, and chloride. Sulfate concentration has ranged from 700 to 2,600 mg/L and averaged between 1,900 and 2,000 mg/L during the last couple of decades. The range in chloride content has been about 40-200 mg/L during that period (Whittemore, 2000b).

Dissolved solids contents in ground waters unaffected by the river water are as low as less than 300 mg/L. The TDS concentration ranges to over 4,000 mg/L in ground water affected by saline river water and ditch irrigation recharge. Sulfate concentration ranges from less than 30 mg/L in the freshest ground waters to over 2,700 mg/L in the most saline ground waters in the river corridor. The chloride concentration is less than 10 mg/L in the freshest ground water and is usually less than 300 mg/L in the most saline water affected only by saline river water and ditch irrigation (Whittemore, 2000a).

The recommended maximum concentration for dissolved sulfate and chloride in drinking is 250 mg/L sulfate. A few years ago, the US EPA proposed a maximum contaminant level of

500 mg/L dissolved sulfate for drinking water. However, investigations conducted for the US EPA indicated that adults can tolerate over 500 mg/L without noticeable short-term effects. Studies have not been concluded on what maximum level of sulfate content is recommended for infants. In the absence of a more conclusive standard, 500 mg/L can serve as a useful upper limit for designating whether the water is usable or unusable without treatment for a drinking-water supply. Sulfate concentrations of several hundred mg/L have been found to cause problems for many young livestock. Thus, the 500 mg/L sulfate level might also be considered appropriate as a recommended upper limit for young livestock.

The distribution of sulfate concentration in the High Plains aquifer has been mapped based on analyses of water samples collected primarily from 1990 to 2000 (Whittemore, 2000a). Figure 11 displays the area with greater than 500 mg/L sulfate content in the High Plains aquifer in the river corridor. The figure also shows the area where the saline ground water is predicted to flow during the next 40 years in the High Plains aquifer based on flow pathlines generated from the results of a transient flow simulation assuming average 1990's water use remains constant. The 500 mg/L isoline for sulfate concentration for 2040 was drawn along the ends of pathlines for 40 years of flow with origins in the numerical model cells along the 500 mg/L sulfate isolines for 2000. Figure 12 also illustrates the same current area with greater than 500 mg/L sulfate concentration as in Figure 11 but with an area where the saline water is expected to flow based on a different prediction approach. The 500 mg/L sulfate isoline for 2040 was drawn along the ends of pathlines for 40-years flow generated using the results of a steady-state simulation based on reduced irrigation pumping to maintain average 1990's water levels in the High Plains aquifer. Description of the numerical methods and model assumptions used to produce the pathlines are included with figures showing the pathlines in Whittemore et al. (2001).

The additional area of the High Plains aquifer into which the saline water derived from Arkansas River water recharge will move by 2040 is located mainly to the south of the river valley from south-central Kearny County to western Ford County, and to the east of the high sulfate area north of the river in western Finney County (Figures 11 and 12). The width of the additional saline area south of the river is up to a few miles in Figure 11 and up to 1-2 miles in Figure 12. If ground-water pumping continues for the next few decades in the corridor at about the same rate as during the 1990's, the future salinized area will be closer to that depicted in Figure 11 than in Figure 12. The conditions for the numerical simulation used to produce Figure 12 involved reducing the ground-water use by about 80% to maintain average 1990's water levels. Thus, substantial reductions in pumping would be necessary in the near future to substantially decrease the future salinized area of the High Plains aquifer predicted in Figure 11.

The pathlines of ground-water flow generated from numerical simulations are for the travel of water particles. The travel of generally conservative constituents in water such as sulfate can be considered the same as for water particles except for dispersion that causes dilution during flow. Thus, the actual movement of the 500 mg/L isoline for sulfate concentration will not be as far as predicted in Figures 11 and 12 due to dilution. However, the difference in the distance due to dilution is not expected to be substantial in most areas of the corridor for two reasons. First, the High Plains aquifer contains water with over 1,000 mg/L sulfate content within much of the area with greater than 500 mg/L. Second, water in front of the 500 mg/L isoline already has increased sulfate concentration due to the migration of the salinity front.

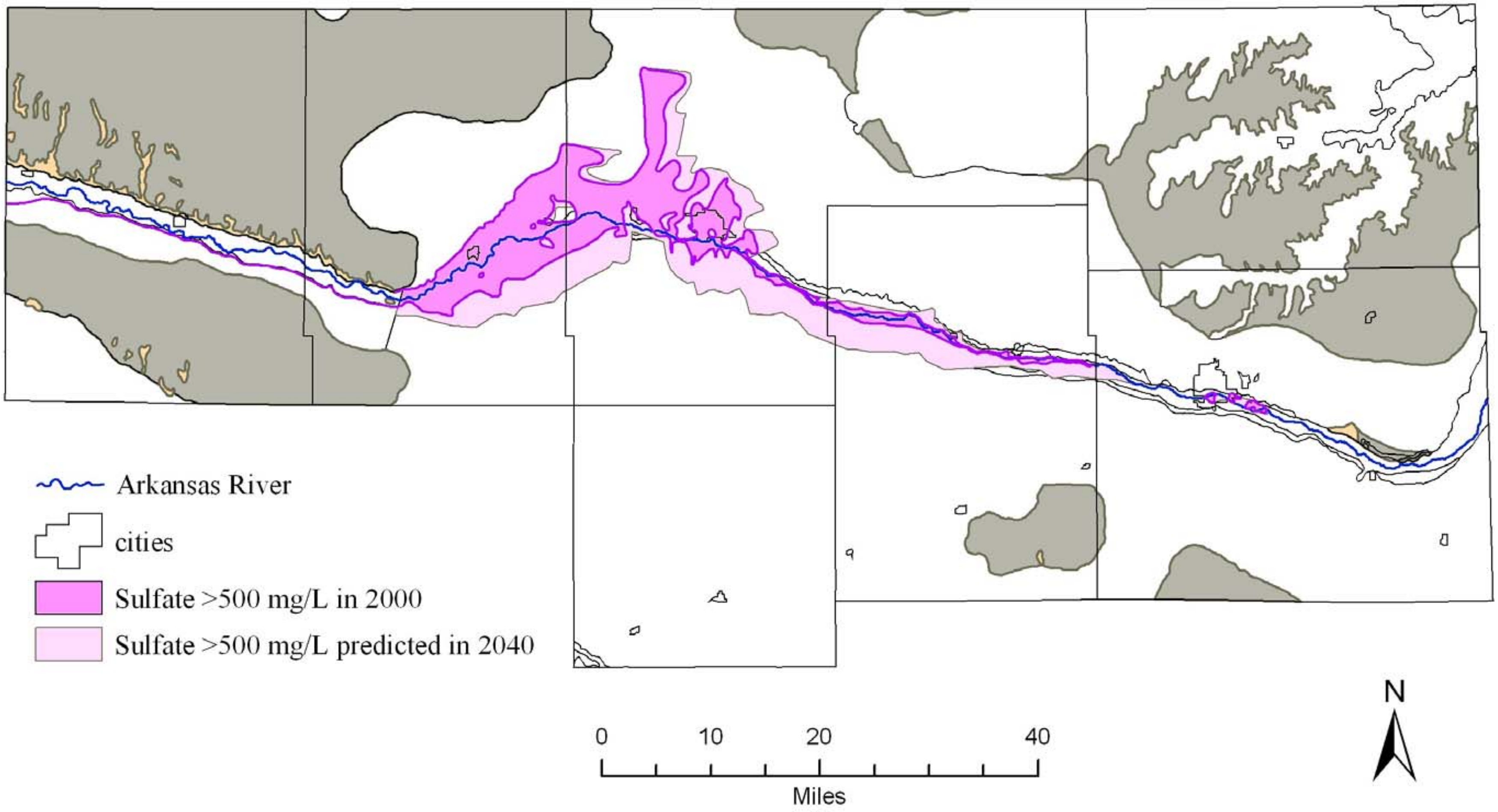


Figure 11. Distribution of high sulfate concentration (>500 mg/L) in 2000 from observations and predicted in 2040 from a 40-year transient simulation of ground-water flow based on average 1990's water use in the High Plains aquifer. See Figure 1 for explanation of additional features of the map.

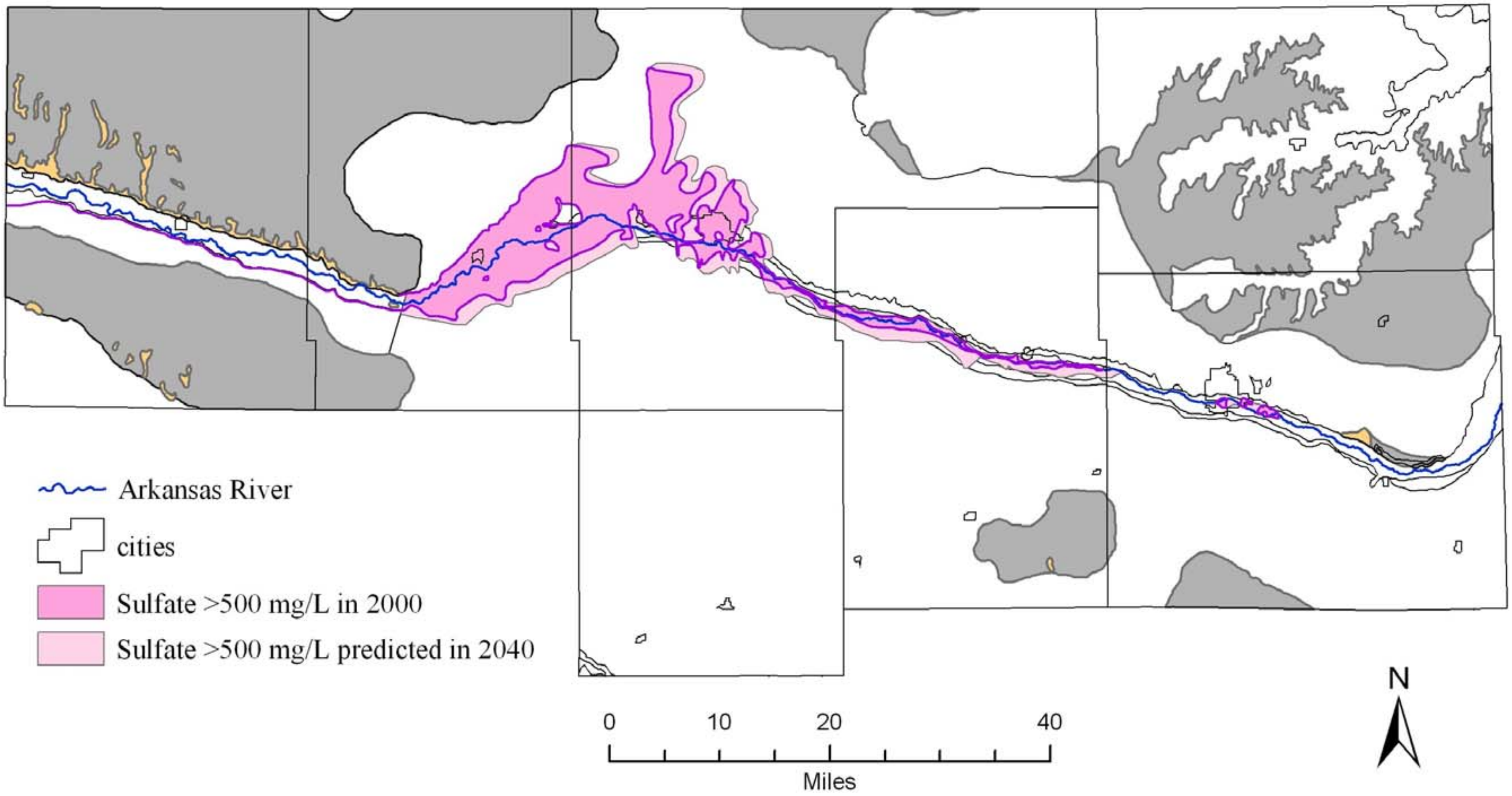


Figure 12. Distribution of high sulfate concentration (>500 mg/L) in 2000 from observations and predicted in 2040 for a 40-year travel time for ground-water flow from a steady-state simulation based on reduced irrigation water use to maintain average 1990's water levels in the High Plains aquifer. See Figure 1 for explanation of additional features of the map.

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