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Kansas Geological Survey

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**CONCEPTUAL MODEL AND NUMERICAL  
SIMULATION OF GROUND-WATER  
SALINIZATION IN THE ARKANSAS RIVER  
CORRIDOR, SOUTHWEST KANSAS**

A Report to the Kansas Water Office

Contract No. 00-113

**Upper Arkansas River Corridor Study**

A Kansas Water Plan Project

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and

David P. Young

2001

Kansas Geological Survey Open-File Report 2001-2

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by

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## ACKNOWLEDGMENTS

This project was funded (in part) by the Kansas Water Plan. Susan Stover, Gerald Hargadine, and Thomas Stiles of the Kansas Water Office assisted in coordination of activities related to the study contracts and review of documents that led up to this report.

Appreciation is expressed to Julie Grauer (now head of the Subbasin Program), Eric Hargett, Kari Eck, and Jeff Lanterman (now in the Stafford Office of the Division of Water Resources) of the Upper Arkansas River Subbasin Water Resources Management Program and Mark Rude, Commissioner of the Garden City Office, Division of Water Resources, Kansas Department of Agriculture for cooperative work and review for the project. Brownie Wilson of the Kansas Water Office provided an electronic dataset from WIMAS and Jeff Schloss assisted in the use of the database. Marios Sophocleous and Li Zheng gave very helpful suggestions for modeling approaches during the project. Jinwu Ma assisted in the development of the GIS interface. Eric Hargett of the DWR provided a review of the report. The comments of the Associated Ditches and Wright Water Engineers, Inc. on various aspects of the Upper Arkansas River Corridor Study were considered during the writing of the report; responses to many of their questions were incorporated in the text.

## EXECUTIVE SUMMARY

This report describes the conceptual model and numerical simulation of ground-water salinization in the upper Arkansas River corridor in southwest Kansas. The study is a Kansas Water Plan project conducted for the Kansas Water Office during 1995-2000. The study area comprises the Arkansas River corridor in Hamilton, Kearny, Finney, Gray, and Ford counties. The main problem addressed is the contamination of ground waters in the alluvial and High Plains aquifers by saline water of the Arkansas River that enters Kansas from Colorado.

The salinity of ground water in the alluvial aquifer of the upper Arkansas River corridor in southwest Kansas has greatly increased since the beginning of irrigation diversions in Colorado and Kansas in the late 1800's. The salinity of the High Plains aquifer along the river corridor has also greatly increased starting at locations of pumping wells after 1900 and then becoming more regional as a result of wide-spread declines in ground-water levels in the aquifer after 1970. The source of the saline water is flow in the Arkansas River that enters Kansas from Colorado. Ground water in the upper Dakota aquifer underlying the river corridor is fresh and is not a source of salinity. The saline river water will continue to enter the High Plains aquifer in substantial amounts in the future and impact an ever-increasing area of the aquifer.

Before irrigation diversions and large declines in ground-water levels, the Arkansas River gained flow along nearly all of its length in southwest Kansas. The ground-water discharge to the river was fresh and decreased the natural levels of dissolved solids in the river water by dilution. The baseflow increased downstream and thus decreased the dissolved solids concentration progressively downstream. After irrigation started in Colorado in the 1870's, Arkansas River flow entering Kansas decreased in quantity and became more saline. After diversions began in the 1880's in Kansas, the salinity of ground water in the alluvial aquifer would have increased in areas affected by seepage from the canals and recharge from the fields irrigated with the saline river water. The increased salinity of water in the alluvial aquifer would have decreased the dilution capacity of discharge from the alluvium to the river.

The installation and pumping of large-capacity wells in the alluvial aquifer and then the High Plains aquifer after 1900 would have produced local, shallow cones of depression in the aquifers. Cones of depression close to the river would have induced the seepage of some river water into the alluvial aquifer. The cones of depression could have resulted in saline alluvial water moving down into the upper parts of well screens in the High Plains aquifer in areas where there are no thick clays underlying the alluvium. In areas where thick clays are present, the increase in salinity in the High Plains aquifer is expected to have been primarily from flow down the gravel packs of wells with annular spaces not sealed through the alluvial aquifer.

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 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 levels in the main portion of the High Plains aquifer dropped below the water levels in the alluvial aquifer and the shallow zones of the High Plains aquifer. The vertical head gradients that were generated caused a substantial increase in the movement of saline water from the alluvial aquifer into the underlying High Plains aquifer, and an increase in the movement of shallow saline water in the High Plains aquifer into the deeper aquifer. The movement occurred both as areal migration where there was no substantial thickness of clay layers to appreciably retard the vertical movement, and as gravel-pack flow in the annular space of large-diameter wells that were not sealed through the alluvial aquifer or the upper part of the High Plains aquifer. The regional declines in water levels in the High Plains aquifer also changed the direction of ground-water flow in the river corridor. Saline 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. Ground-water levels in 1940 indicated that regional flow directions were general towards the east-southeast. The water-level surface for the 1990's indicates that the regional flow direction has shifted 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.

After the 1970's, increasing amounts of river water seeped into the aquifers. The net baseflow additions to the river changed 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. Thus, the salinity of the river water entering Kansas is no longer normally diluted by baseflow except soon after large flow events when bank storage of less saline water returns to the river. The result is that the salinity of river water passing the Colorado-Kansas border on a given day does not usually change appreciably as it flows downstream to Dodge City. The river seepage is much greater downstream or east of the Bear Creek Fault zone (where the High Plains aquifer underlies the alluvial aquifer) than in the alluvial valley from the Colorado-Kansas border to western Kearny County.

During the 1980's and 1990's, recharge from the ditch service areas, coupled with decreased pumping of ground water when ample supplies of river water were available for irrigation, increased ground-water levels in eastern Kearny and western Finney counties underlying the ditch irrigation areas north of the Arkansas River. However, the large water-level declines in the High Plains aquifer south of the river have produced an even greater hydraulic gradient from the river valley to the south than was generated in the 1970's. The simulation of flow based on 1990's conditions indicates that saline water will move at substantial rates from the river into the alluvium and thence into the High Plains aquifer south of the river. The migration of saline water from the river and alluvial aquifer could reach as far as 3-4 miles south of the alluvial valley after 40 years and pass completely through the sand hills well field of Garden City if current conditions continue. Even if the ground-water pumping were reduced to maintain the average 1990's water levels, the saline water would continue to migrate from the alluvial valley into the High Plains aquifer south of the valley from eastern Kearny County to western Gray County. However, the rate of movement would be substantially slowed and the flow direction in Finney County and western Gray County

would shift somewhat towards the southeast. Thus, saline water would take longer to affect all of the sand hills well field of Garden City.

Ground-water flow simulations based on 1990's conditions indicate that most of the fresh ground water in the alluvial trough underlying the sand dunes south of the alluvial valley in Hamilton and western Kearny counties should not be significantly affected by saline river or alluvial aquifer water. The recharge in the sand dune area is large enough and the pumping small enough that ground water generally flows parallel to the river valley rather than from the Quaternary alluvial aquifer into the sand dune area. This assumes no substantial further development of ground water in the alluvial trough that would lower ground-water levels and induce flow of saline ground water from the alluvial valley into the area of freshwater.

The simulations also show that the area of the High Plains aquifer affected by the leakage of saline water from the overlying alluvial aquifer from central Gray County to east of Dodge City should remain under the alluvial valley during the next 40 years. This conclusion also assumes that water levels will not be substantially different from the 1990's in the High Plains aquifer along this section of the river corridor. If pumping in the High Plains aquifer north and south of this part of the alluvial valley causes water-level declines that are appreciably greater than in the 1990's, then some saline water could start to move outward from the edge of the river valley.

The observed salinity distribution in the High Plains aquifer in the river corridor indicates that local pumping effects are enough to cause a substantial increase in the travel rate of saline ground water. Thus, the simulation results in this report should only be used to show the patterns of saline water migration in terms of general direction and distance and not for detailed predictions on a smaller scale.

A predominant result of the evaluation of water-level declines in the High Plains aquifer and the numerical simulations of ground-water flow based on 1990's conditions is the contrast in conditions north and south of the Arkansas River in eastern Kearny and western Finney counties. North of the river, the recharge from the ditch service area produces conditions in which the water levels and the ground-water flow directions often do not change substantially with time. South of the river, the high rate of ground-water declines has shifted ground-water flow directions to the south and increased flow rates in that direction. Continued declines at the current rate will result in complete depletion of the saturated thickness at distances of more than several miles south of the river. Numerical simulations suggest that recharge from the river and the alluvial aquifer could maintain a west-east band of sustainable saturated thickness that would be several miles wide from the river to the south. The saturated thickness would rapidly decrease in a southward direction. The recharge from the river channel and the ditch irrigation system to the underlying alluvial and High Plains aquifers exceeded 100,000 acre-ft/yr during the late 1990's when the river flows were greater than average. Although the river water recharging the aquifers is saline, it is a valuable resource if viewed in terms of quantity.

A scenario of altered water use was simulated to show the effects of a no-pumping zone in the High Plains aquifer south of the alluvial valley. Stopping all pumping along a 3-mile band just south of the alluvial valley from eastern Kearny County through western Finney County decreased the southerly component of ground-water flow direction and shortened the flow paths during the 40-year simulation. However, the ground water still migrated at substantial rates towards the freshwater in the aquifer and past the Garden City well field in the sand hills. The implications are that it would take a very large amount of added fresh recharge along the river valley margin to protect the well field. The economic impact of no pumping and the difficulty of obtaining enough freshwater to provide recharge along the corridor would be expected to be substantial. Treatment of saline ground water could be evaluated to determine whether it would be more feasible and economically possible. The no-pumping scenario should not be interpreted as a recommendation by this study to conduct the action. Planning and management activities should be conducted by the appropriate local and state agencies and associations.

## **INTRODUCTION**

### **Problem**

The Arkansas River in southeastern Colorado and westernmost Kansas is one of the most saline rivers in the United States. Diversion of water for irrigation and evapotranspiration in Colorado have substantially decreased the flow and greatly increased the salinity of the river waters entering Kansas. In addition to salinity, the concentrations of many other dissolved constituents in the river water are high.

Ground-water levels have declined in the High Plains aquifer in southwest Kansas due to decreased recharge from the Arkansas River and pumpage from the aquifer. Arkansas River flow that enters Kansas from Colorado is lost between the state line and Dodge City because of infiltration through the streambed, diversion from the river for irrigation, and evapotranspiration by phreatophytes. Saline water from the river and from irrigated fields is infiltrating to and contaminating the ground water in the alluvial and High Plains aquifers in the upper Arkansas River corridor. Ground-water declines in the High Plains aquifer have also decreased the amount of fresh subsurface flow to the alluvium that diluted salinity and other constituent concentrations in the past. Municipal ground-water supplies that are or may be impacted by salinity and nitrate contamination include those for Syracuse, Lakin, Deerfield, Holcomb, Garden City, Cimarron, and Dodge City.

The distribution of salinity and the mechanisms for its entrance into and movement within the High Plains aquifer were not well known before this study. An assessment of the sources, migration, present distribution, and possible future extent of the ground water contamination is critical for developing plans for minimizing or mitigating ground-water quality problems in the river corridor. The Upper Arkansas River Corridor Study was developed to provide information regarding salinity in the Arkansas River and associated aquifers within the study area to enable agencies, municipalities, agriculture, and industries in the region to better manage water resources in order to minimize or mitigate water-quality problems.

### **Objectives and Scope of Work**

The basic objectives of the study comprise major parts of the objectives listed under the water-quality and ground-water decline issues in the subsection on the Arkansas River Corridor Subbasin in the Upper Arkansas Basin section of the Kansas Water Plan:

- A. Water-Quality Issue: Document the fate and effects of contaminated Arkansas River flows on the alluvial, Ogallala, and Dakota aquifers in the river valley.
- B. Ground-Water Decline Issue: Clearly establish the links among decreased flow in the Arkansas River, increased levels of water contamination in the alluvial, Ogallala, and Dakota aquifers, and lowered ground-water tables.

The study was proposed as a 5-year plan in which the Kansas Geological Survey (KGS) would design and conduct hydrogeological and geochemical investigations in cooperation with several local and state agencies. This report addresses objectives related to the quality of ground water within the study area. The major objectives discussed within this report include:

1. Characterization of the ground-water quality in the aquifers of the upper Arkansas River corridor in southwest Kansas.
2. Determination of the factors controlling contamination of the ground water by saline Arkansas River water, including the links among river water-quality changes, variations in river flow, and lowered ground-water tables in the aquifers in the river corridor.

Knowledge of the chemical characteristics of the ground water and spatial distribution of dissolved constituents is necessary for determining the impact on water use in the corridor. Information on the spatial changes and temporal variations in the ground-water quality salinity are needed to compare to changes in water levels and ground-water flow so that conceptual models of the fate and transport of the river water can be developed. The findings on ground-water quality form the basis, along with the results from other reports of this study on the aquifer hydrogeology and river-water quality, for developing and interpreting a numerical model of salinity movement.

## **Location and Description of Study Area**

The study area includes the Arkansas River corridor from the Colorado state line through Hamilton, Kearny, Finney, Gray, and Ford counties (Figure 1). The area includes the Intensive Groundwater Use Control Area (IGUCA) of the upper Arkansas River valley, the portions of Hamilton, Kearny, and Finney counties that use ditch irrigation, and a buffer zone outside of these areas. The buffer zone was selected to include freshwaters in the High Plains aquifer just outside of the area affected by salinity. The study area lies within the High Plains region of the Great Plains physiographic province. There are no substantial tributaries to the Arkansas River from Hamilton County eastward to the middle of Ford County. Mulberry Creek joins the Arkansas River in eastern Ford County near the town of Ford. In addition to the High Plains and overlying alluvial aquifers, the study area includes the alluvial aquifer in the bedrock trough underlying and to the south of the Arkansas River in Hamilton and western Kearny counties. Ground water is also obtained for water supplies within the study area from the Cretaceous bedrock (primarily the Dakota Formation) underlying the High Plains aquifer or present where the High Plains aquifer is not present or its saturated thickness is too thin to supply water to wells.

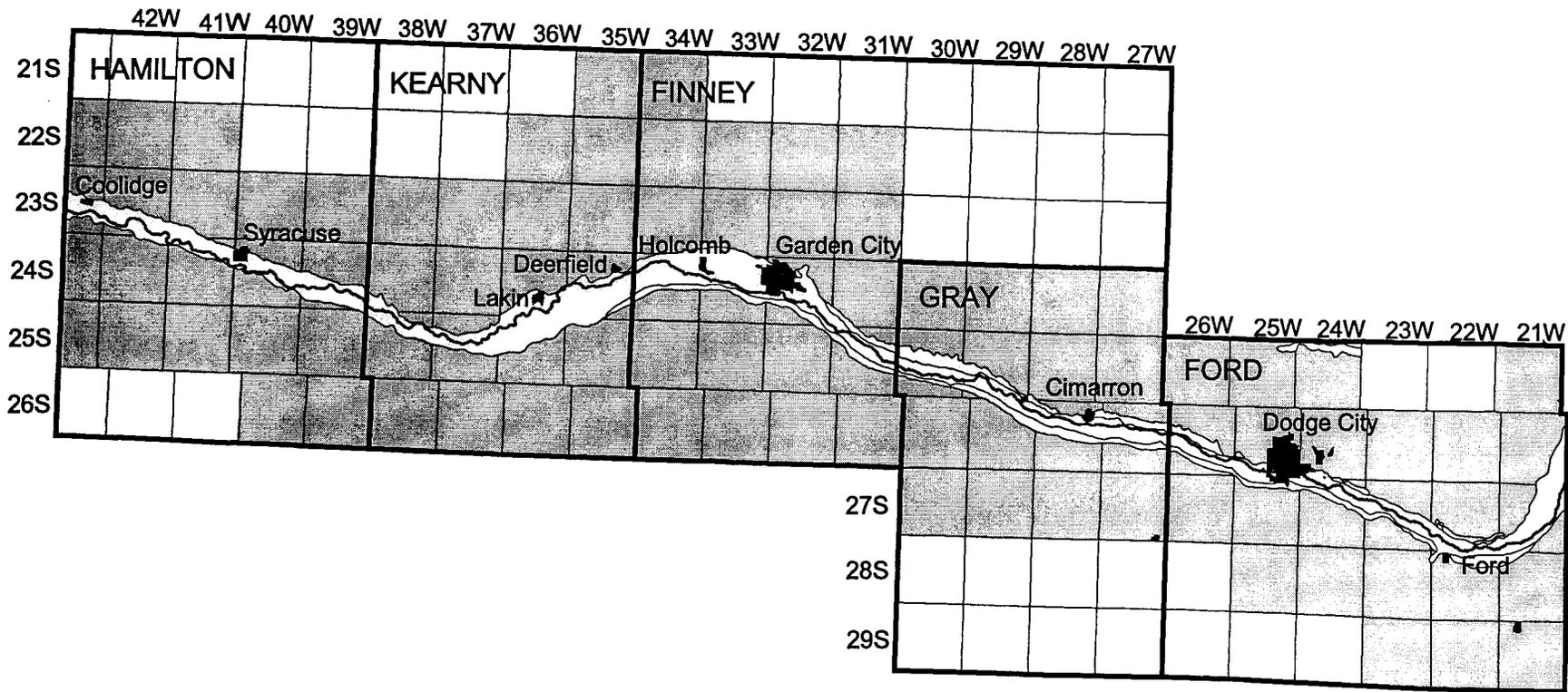


Figure 1. Location of the area of the Upper Arkansas River Corridor Study within the 5-county region. The study area is shaded.

# CONCEPTUAL MODEL OF SALINIZATION OF THE GROUND WATER

## Spatial and Temporal Variations in River-Water Quality

Arkansas River water in southwest Kansas is saline during both low and high flows. An evaluation of the water quality data for the river was presented in Whittemore (2000a). The report included a discussion of the spatial and temporal variations in and the sources of the salinity.

The salinity of Arkansas River water entering Kansas derives from substantial concentration of natural sources of dissolved solids in the river water and alluvial ground waters by consumptive loss of water to evapotranspiration in Colorado. 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, chloride, and silica. 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. The water is extremely hard. Nitrate concentrations are always relatively low (usually 1-3 mg/L as nitrate-nitrogen). The relationships between specific conductance and dissolved solids, sulfate, sodium, calcium, magnesium, chloride, nitrate, fluoride, and boron concentrations are all highly significant and can be used to estimate the concentrations of these substances to varying degrees of accuracy.

The dissolved solids and sulfate concentrations of Arkansas River water entering Kansas often reach a maximum of 4,200-4,500 mg/L and 2,500-2,600 mg/L, respectively, at flows near 100 cfs and below. The precipitation of gypsum in soils from saline river water used for irrigation in Colorado limits the sulfate and dissolved solids contents of the irrigation return flows that contribute to the high salinities. The chloride concentration is not generally limited by mineral precipitation in the return flows and is a better indicator of the extent of concentration of the river waters by evapotranspiration losses. The salinity of river water at the state line decreases with increasing river discharge at flows greater than 200 cfs. However, even the highest flows that have occurred during the last decade have been saline.

The salinity of the Arkansas River in eastern Colorado began to increase soon after the start of substantial irrigation diversions. Since the start of continuous records of both water quality and discharge at the state line in 1963, the salinity of Arkansas River water has continued to increase. The increases are reflected both as more frequent occurrences of dissolved solids and sulfate concentrations near the maximum limitation by gypsum precipitation in flows less than about 150 cfs, and by higher salinities in flows greater than this discharge. The past increases were caused mainly by the increased consumption of water leaving the residual salts in a smaller water volume. More recent salinity increases are probably mainly the result of flushing salts accumulated over decades in soils and shallow ground waters in the area irrigated by river water in Colorado. Assuming consumption remains nearly constant in the future, future salinity changes will depend on climatic changes

and on whether the mass flow rate of dissolved solids into Kansas has increased to the level of the salt accumulation rate in Colorado.

After entering Kansas, the salinity of Arkansas River water does not change significantly as it passes through southwest Kansas. Most of the current spatial variations in the salinity within southwest Kansas are due to the differences in quality at the state line that are transferred downstream. The average river salinity in southwest Kansas prior to surface-water and ground-water irrigation in Colorado and Kansas is expected to have decreased downstream because of dilution by freshwater discharge from the High Plains aquifer. Substantial declines in the water levels of the High Plains aquifer, particularly since the 1970's, changed the average flow condition from one of ground water discharging to the river to one in which river water recharges the aquifer. As ground-water level declines in the High Plains aquifer extended from the Kearny-Finney counties area eastward along the river corridor in southwest Kansas, the location where the dilution was significant slowly moved farther downstream. Today, the dilution point is east of Dodge City.

### **Spatial and Temporal Variations in Ground-Water Quality**

Ground waters have become saline in most of the Quaternary alluvial aquifer and in a substantial part of the High Plains aquifer along the upper Arkansas River corridor in southwest Kansas. The increase in ground-water salinity in the river corridor derives primarily from infiltration of saline waters from the Arkansas River. The seepage occurs from the river channel into the alluvial aquifer and then into the underlying High Plains aquifer, and also from below irrigation canals, ditches and fields irrigated with the river water. An evaluation of water-quality data for the aquifers was presented in Whittemore (2000b). The report included a discussion of the spatial and temporal variations in and the sources of the salinity.

Dissolved solids contents in ground waters unaffected by Arkansas River water are as low as less than 300 mg/L. These waters are primarily calcium-bicarbonate in chemical type. With increasing salinity, the water type changes to calcium-sulfate to calcium, sodium-sulfate to sodium, calcium-sulfate and finally to sodium-sulfate. The total dissolved solids (TDS) concentration ranges to over 4,000 mg/L in ground waters affected by saline river water and ditch irrigation. Sulfate concentration ranges from less than 30 mg/L in the freshest waters to over 2,700 mg/L in the most saline ground waters. 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 that is affected only by saline river water and ditch irrigation. Sulfate/chloride ratios range from as low as near one for some freshwaters to over 16 for some saline ground waters. Saline waters with chloride levels substantially greater than 300 mg/L or with relatively low sulfate/chloride ratios in comparison with other ground waters impacted by river water derive additional chloride from waste sources. These include saltwater discharge from conventional water softeners. The high calcium and magnesium contents of the ground waters made saline by river water seepage make the waters extremely hard. Hardness (as CaCO<sub>3</sub>) substantially exceeds 1,000 mg/L in much of the saline ground water. Nitrate-nitrogen concentrations range from less than one mg/L to over 30 mg/L. There are both fresh and saline ground

waters with nitrate-nitrogen levels exceeding the drinking water standard of 10 mg/L. The source of high nitrate in the ground waters is not the Arkansas River, which has nitrogen-nitrate contents that are nearly always less than 3 mg/L. The relationships between specific conductance and dissolved solids, sulfate, sodium, calcium, magnesium, chloride, potassium, boron, and hardness concentrations and also sodium adsorption ratio and soluble sodium percentage are all highly significant and can be used to estimate the concentrations of these substances or level of sodium hazard at varying degrees of accuracy.

Water-quality data indicate that the dissolved solids contents of the alluvial and High Plains aquifers were much smaller before the start of ditch irrigation and ground-water pumping. Ground water in the High Plains aquifer is expected to have been fresh (less than 1,000 mg/L TDS content) throughout the entire corridor of the upper Arkansas River before the late 1800's. However, the dissolved solids concentration was generally greater north of the Arkansas River in eastern Kearny, northern Finney, and northwest Gray counties than south of the river. The area with the highest natural background of dissolved solids is the Scott-Finney depression that extends from southern Scott County through part of Finney County to the Arkansas River. The TDS and sulfate concentrations are just over 1,000 and around 500 mg/L, respectively, in a small area of northern Finney County near the Scott County line. The background dissolved solids decrease towards the Arkansas River. Ground waters in the High Plains aquifer before ditch irrigation and ground-water development were fresh, with less than 50 mg/L sulfate concentration at Lakin, less than 120 mg/L at Deerfield, less than 80 mg/L at Holcomb and Garden City, and less than 60 mg/L at Cimarron and Dodge City.

In general, current sulfate contents of the alluvial aquifer decrease eastward from Hamilton County through Ford County. The sulfate values typically exceed 2,000 mg/L in the ground water in Hamilton County. Sulfate concentrations in most of the alluvial aquifer from Kearny County through Finney County range between 1,500 and 2,000 mg/L. In Gray County, the area with 1,500-2,000 mg/L sulfate content narrows within the alluvial valley to be mainly near the Arkansas River. The band of 1,500-2,000 mg/L sulfate concentration in the alluvium along the river extends to near Dodge City. A zone of ground water with 1,000 to 1,500 mg/L sulfate concentration follows the alluvium near the river past Dodge City. In general, ground water salinity in the alluvial aquifer near the edges of the alluvium in Gray and Ford counties is substantially less than near the river.

The present sulfate concentration in the High Plains aquifer is greater than 1,000 mg/L in the ground water underlying most of the Quaternary alluvium in Kearny County and under substantial parts of the alluvial aquifer in Finney County. The area with ground waters containing over 1,000 mg/L sulfate extends into part of the ditch irrigation service area to the north of the alluvial valley and east of the Amazon canal in Kearny and Finney counties. South of the Arkansas River in eastern Kearny and western Finney counties, an area of elevated sulfate concentrations (greater than 100 mg/L) extends south of the alluvial aquifer boundary. Essentially all the saline water in the High Plains aquifer in the Arkansas River corridor in Gray and Ford counties underlies the Quaternary alluvium. A band of ground water with greater than 500 mg/L sulfate content extends under the alluvial aquifer from

southeast of Garden City through most of Gray County. In Ford County, only isolated areas of the High Plains aquifer under the alluvium (primarily in the Dodge City area) contain greater than 500 mg/L sulfate concentration. The ground water in the High Plains aquifer south of areas affected by the river water is fresh along the river corridor, with sulfate concentrations less than 50 mg/L. Ground waters in the upper Dakota aquifer underlying the upper Arkansas River corridor are fresh.

The salinity of municipal well waters pumped from the High Plains aquifer has substantially increased along the upper Arkansas River corridor since the early 1900's. The sulfate concentration exceeds 1,000 mg/L in the High Plains aquifer around Lakin, which now obtains fresh ground water for its public supply from a couple miles northwest of the city. The sulfate concentration has increased to appreciably over 250 mg/L in water pumped from the main wells at Deerfield and the high capacity wells of Holcomb. Sulfate values have increased greatly in the ground water pumped from the High Plains aquifer for supplies within Garden City. There is a large range in the water quality under the city, with a few wells that pump water with over 1,000 mg/L sulfate content when operating. The spatial and temporal variations in the salinity are both large. The two most northerly wells in the group of 7 sand hills wells of Garden City located a few miles south of the Arkansas River recently began to draw in saline ground water. Sand hills well 5 yielded water with a sulfate content exceeding 700 mg/L when sampled in 2000. Although some ground waters in the High Plains aquifer in Gray County have increased substantially in salinity, the water supply of Cimarron, located at the edge and to the north of the alluvial aquifer, has only been affected by a small amount. The salinity has increased greatly in the municipal well waters of Dodge City pumped from the High Plains aquifer underlying the river alluvium. Three of these wells produce water with over 500 mg/L sulfate content. In comparison, the water from city wells in the High Plains aquifer located at the edge of the alluvial valley has either changed little or has only increased a small amount in sulfate concentration. Dodge City wells to the north of the alluvial valley yield freshwater that is unaffected by the saline water in the alluvial aquifer.

Clay layers of substantial thickness underlying parts of the alluvial aquifer and within much of the High Plains aquifer retard the downward movement of saline water from the alluvium and irrigated areas. However, gravel packs of large capacity wells (mainly irrigation wells) without grout seals or in which the grout seals are not deep enough to seal off shallow saline water can allow flow across the clay layers. The wells allowing gravel-pack flow include actively used, plugged, and abandoned wells. The usual method of plugging an abandoned well involves sealing the inside of the casing and not the gravel pack in the annular space outside the casing. Abandoned, unplugged wells with corroded casing could allow direct flow down the casing opening to the water table. Cross flow of shallow aquifer water to deeper zones can explain the substantial variations in salinity and nitrate concentrations observed for the High Plains aquifer. Although expensive, sealing of the gravel pack in abandoned wells is an important approach to preventing shallow contamination in the wellhead protection area of a municipal well in the river corridor.

## Changes in Ground-Water Levels

The distribution of and changes in water levels in the High Plains and alluvial aquifers relative to Arkansas River and ditch diversion flows illustrate the hydrologic conditions under which saline river water can infiltrate into the ground water. Just as surface water flows to lower elevation, ground water moves from an area of higher hydraulic head to an area of lower hydraulic head. Regional ground-water flow in the upper Arkansas River basin is generally in a west to east direction that reflects the regional topography sloping downward to the east. Before diversion of Arkansas River water and development of ground-water resources in the river corridor, ground-water tables were, on the average, slightly higher in the alluvial and High Plains aquifers than in the river. Thus, there was a small component of ground-water flow towards the river in addition to the regional flow direction. This resulted in net ground-water discharge from the High Plains and alluvial aquifers to the Arkansas River along nearly all of its length in southwest Kansas.

Substantial historical changes in the hydrologic conditions of the Arkansas River corridor first started with large-scale ditch irrigation in Colorado in the 1870's and then in Kansas during the 1880's. Consumptive losses of water in Colorado reduced the amount of river flow to Kansas. Distribution of the ditch water to portions of the river floodplain and to uplands in Kansas increased recharge to the alluvial and High Plains aquifers underlying the irrigated areas. The recharge increased when combined rainfall and flood irrigation lengthened the periods of water saturation in soils during which infiltration below the root zone could occur. The removal of the long-rooted prairie grasses for cropland could also have decreased the amount of soil moisture removed by the grasses in the deeper soil zone, thereby allowing more soil moisture to reach the water table.

Variations in Arkansas River flow resulted in changes in the amount of water available for ditch irrigation. In turn, the variation in diversions affected the amount of recharge from flood irrigation in the ditch service areas. Much of the early ground-water development in the river corridor included irrigation wells that supplemented water from river diversions, especially when Arkansas River flows were low. As more irrigation wells were installed in the ditch irrigation area, the average amount of recharge to the water table over periods of several years increased where river diversions were not used for irrigation or were not sufficient to supply irrigation needs. However, the greater pumping of ground water also caused declines in water levels.

Some wells were installed for irrigation in southwest Kansas starting from the early 1900's. Most of those wells constructed by 1940 were in the ditch irrigation areas along the river corridor. A substantial increase in the number of large capacity wells began during the 1950's. The installation of many new irrigation wells continued through the 1970's and into the early 1980's. At first, individual wells produced local cones of depression in the water-level surface around each well. The local depression in the water level of the High Plains aquifer caused saline water in the alluvial aquifer or shallow zone of the High Plains aquifer underlying ditch irrigation to move down towards the well screen during pumping. As the pumping continued and more wells were installed, eventually the cones of depression from

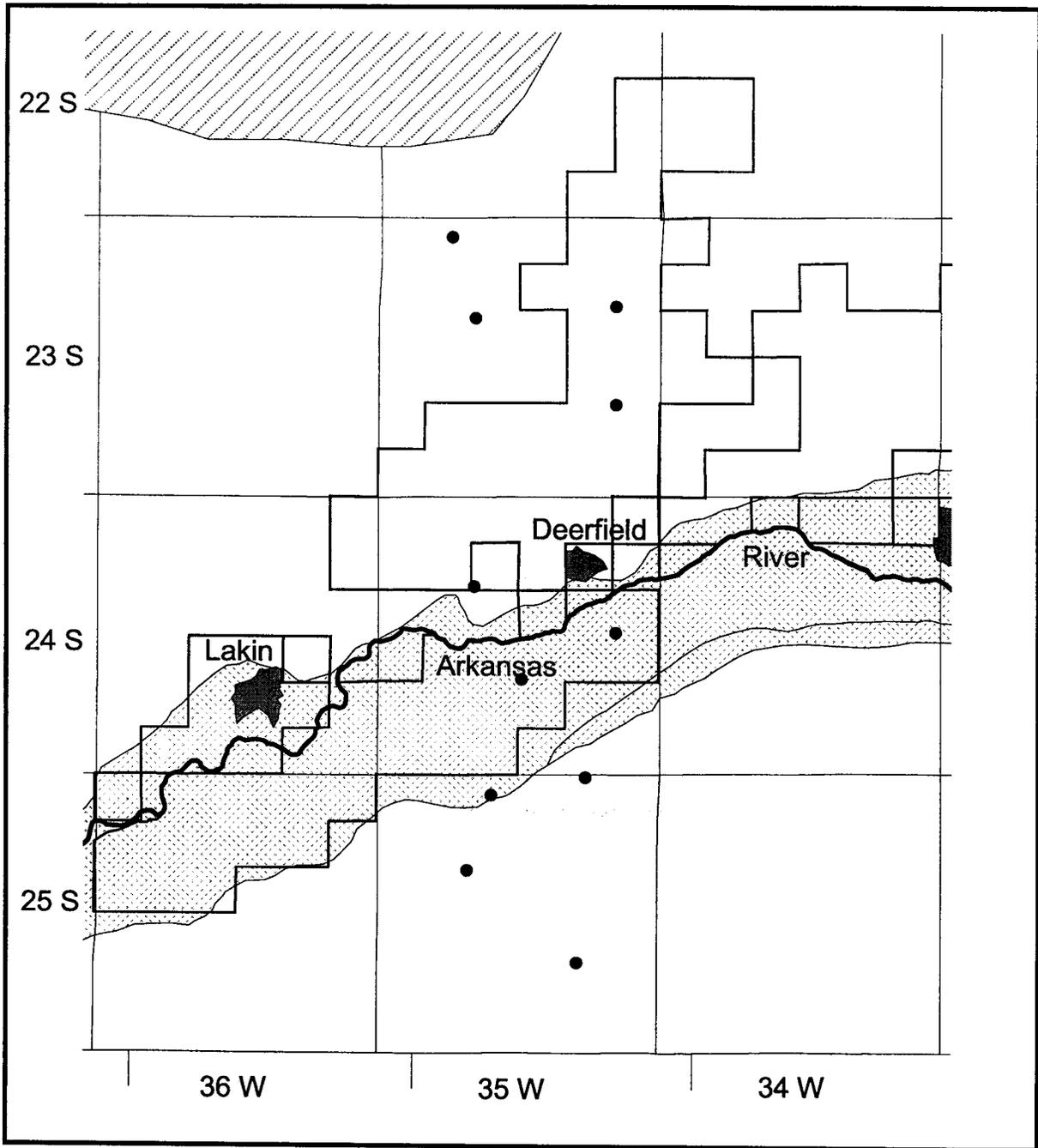
nearby wells expanded to intersect with one another. The overall result of pumping at an average annual rate that was substantially greater than recharge produced a regional decline in the water level of the High Plains aquifer. The water-level declines changed the hydraulic gradients, thereby reducing the component of ground-water flow to the river and finally reversing the gradient in many areas. The result was induced infiltration of saline river water to the alluvium and then to the High Plains aquifer along much of the Arkansas River valley.

The effect of the interrelationships among river flow, ditch diversions, recharge, and ground-water withdrawals on aquifer water levels for the Arkansas River corridor can be illustrated by well hydrographs. The column of townships in R. 35 W. extending north and south of the Arkansas River in east-central Kearny County was selected for display of hydrographs representing a cross section of water-level changes in different conditions. The township column crosses the Arkansas River valley, and part of the ditch service area (Figure 2). Wells for which greater than a decade of water-level measurements exist in the township column are located to the north and south of and within the ditch irrigation area. The hydrologic conditions represented by the wells range from the alluvial aquifer within the ditch service area to the High Plains aquifer to the north and south of the Arkansas River, both within and outside the ditch-irrigated area. The columnar rectangle within which the wells lie measures approximately 16 miles in a north-south direction and 4 miles east-west.

Table 1 lists information for the 5 wells in Figure 2 that lie to the north of the Arkansas River valley. The wells are listed in order of decreasing distance from the Arkansas River, based on measurements from each well location directly south to the river on USGS 1:24,000 (7.5 minute) topographic quadrangles. The water-level data for this table and Table 2 are from records in the KGS WIZARD database available at the web site

<http://magellan.kgs.ukans.edu/WaterLevels/index.html>

All 5 of the wells in Table 1 are screened in the High Plains aquifer. Four of the wells are used for irrigation; the other is an observation well. The first two wells lie to the northwest and outside of the irrigated area served by Arkansas River diversions. The other 3 wells are located within the ditch-irrigation area. The well depths range from 180 ft for the well in the northwest corner of the group, to over 300 ft for the two most eastern wells, to 253 ft for the most southern well. 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. There were changes at two of the wells that resulted in small differences in the land surface elevations that serve as a reference for the water-level depths. The water level of the first record in each well pair was adjusted by the difference in surface elevation to make the data consistent with a single surface elevation for each pair. The 1940 water-level depths in Tables 1 and 2 were taken from a map based on water-level measurements in McLaughlin (1943). The land surface and 1940 water-level elevations above the Arkansas River were computed using the river elevation directly south of each well as estimated from the USGS 1:24,000 topographic quadrangles. Although river surface elevation changes with river stage, the stage variations usually range within only a couple of feet for near normal flows.



- Water-level wells
- ▨ Thinly saturated High Plains aquifer
- ▭ Ditch irrigation boundary
- ▨ Alluvial deposits
- City area

Figure 2. 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 01 5/1/58 – 4/20/93 02 1/15/92 – 1/4/99	378	3009 3010	Irrigation Irrigation	67 68	6.1 N	In Amazon area Above floodplain	80 81	13
23S 35W 25BBB 02 4/1/58 – 1/11/94 03 11/17/93 – 1/22/99	320	3005 3000	Irrigation Irrigation	46 41	4.0 N	In Amazon area Above floodplain	76 71	30
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.

The hydrographs for the two wells outside the ditch-irrigation area are in Figure 3 and for the 3 wells within the ditch boundaries are in Figure 4. The x-axis for these and other figures in the water-level discussion are all for the same period. The y-axis range for depth to water is the same for Figures 3-5. The same axis dimensions allow direct visual comparison of relative changes in the water levels with time. The tick marks for the years represent the start of the labeled year. The record for the most northerly well (23S-35W-05) listed in Table 1 indicates that the water level dropped from the mid-1960's to the mid-1980's and then stabilized at the location. After a pronounced drop at the beginning of measurement, the water level in the other well outside the ditch-irrigation area (23S-35W-16) rose slightly from the mid-1980's to the present.

The third and fourth wells listed in Table 1 are within the boundaries of the Amazon ditch service area. The last 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 depth to water becomes shallower the closer to the river for these three wells (Figure 4). Water levels fluctuated but showed no pronounced upward or downward trend in the two wells with the shallower water levels (24S-35W-09 and 23S-35W-25) from the late 1950's to about 1970. The water levels then began an increasing rate of decline in these two wells after 1970 until reaching a minimum by early 1983. The hydrograph for the third well (23S-35W-12) in Figure 4 shows a water-level decline starting from the first measurements in the late 1950's that increased in rate until also reaching a minimum in 1983. The hydrograph for this well shows more short-term variation than for the other two wells because measurements were collected more frequently. Thus, there are water-level data for the irrigation season, during which the water levels were lower than in the non-pumping period. After 1983, the water levels rose in all three wells until reaching a plateau or maximum in the late 1980's to 1990. Since the late 1980's, the water level in the shallowest and most southerly well has fluctuated but shown no significant upward or downward trend. After the water levels in wells 24S-35W-25 and 23S-35W-12 reached maxima in 1988 and 1990, respectively, the levels declined during the early 1990's and then rose during the late 1990's.

The changes in water levels for the wells in Table 1 can be explained by a combination of ground-water development and recharge from Arkansas River water diverted for irrigation. The pumping of ground water for irrigation caused the declines in the water levels, whereas variations in the amount of ditch irrigation produced changes in recharge and water-level rises. Figure 6 illustrates the variations in the amount of water diverted from the Arkansas River and used for ditch irrigation in the Amazon and Great Eastern service areas. The annual amount of diversion was calculated from the monthly totals and represents the calendar year total. The annual diversion volumes are significantly correlated with the annual flow in the Arkansas River (Figure 7). The distance per year for the x-axes in Figures 6 and 7 are the same as for the hydrograph figures. The points for the annual diversions and river flows are plotted as July 1 for each year in the two figures. The variations in the amounts of water diverted are appreciable and reflect the large fluctuations in flows of the Arkansas River available for diversion during the irrigation season. The large declines in ground-water levels underlying the ditch-irrigated area during 1970 to the early 1980's (Figure 4) correspond to the period of decreasing ditch diversions to the late 1970's and the generally smaller than

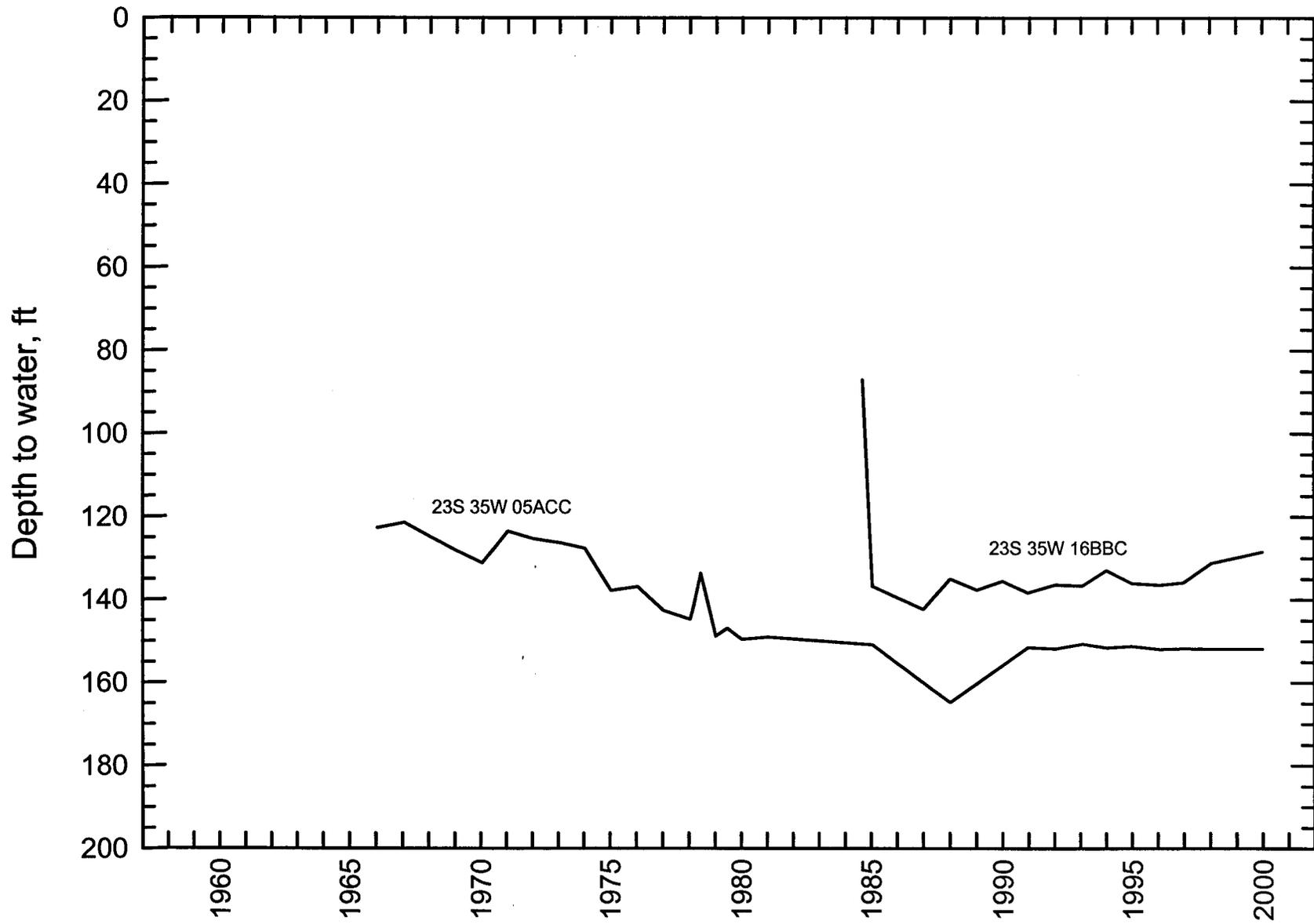


Figure 3. Hydrographs for wells in R. 35 W. north of the Arkansas River and outside the ditch-irrigation service area.

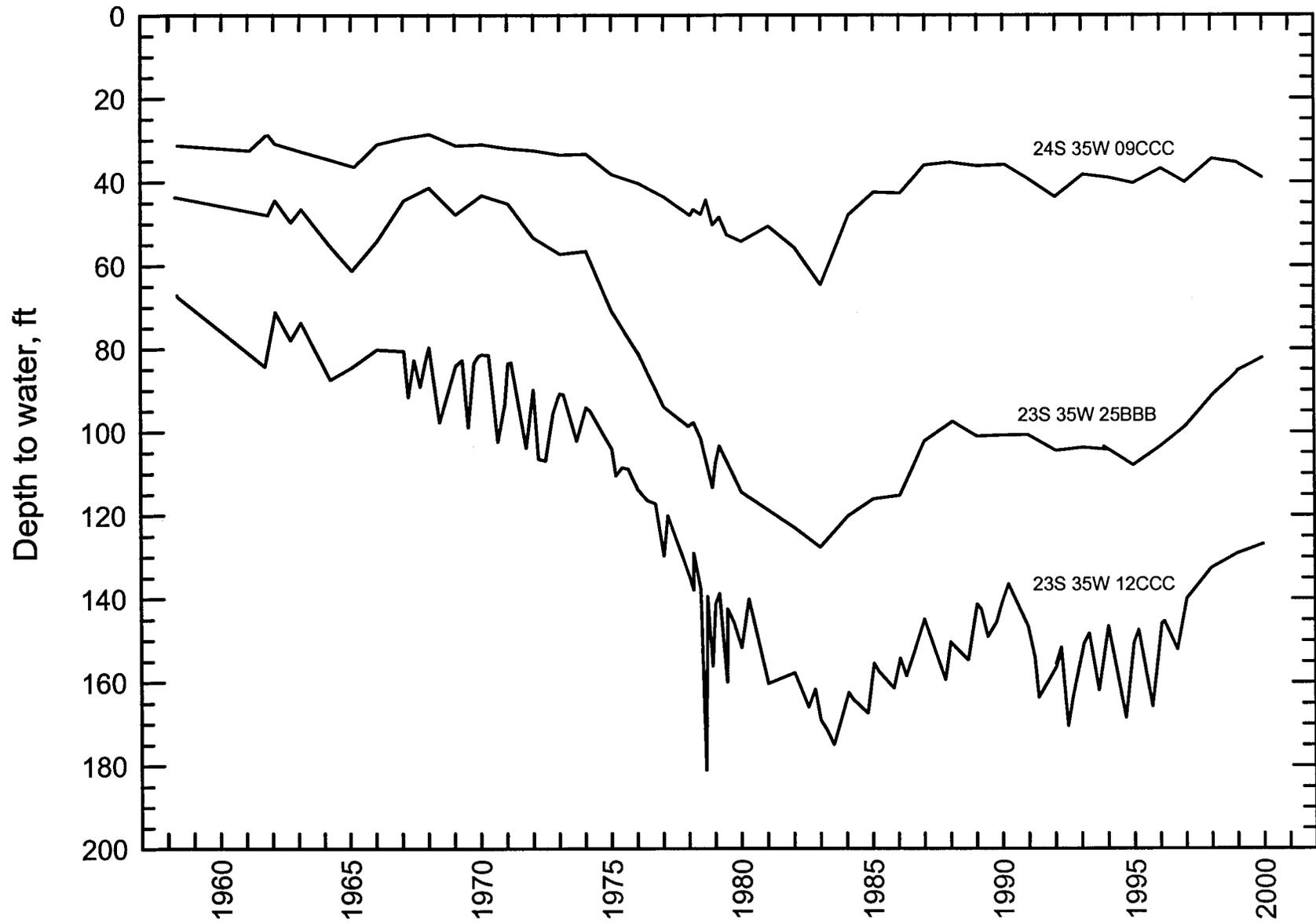


Figure 4. Hydrographs for wells in R. 35 W. north of the Arkansas River and inside the ditch-irrigation service area.

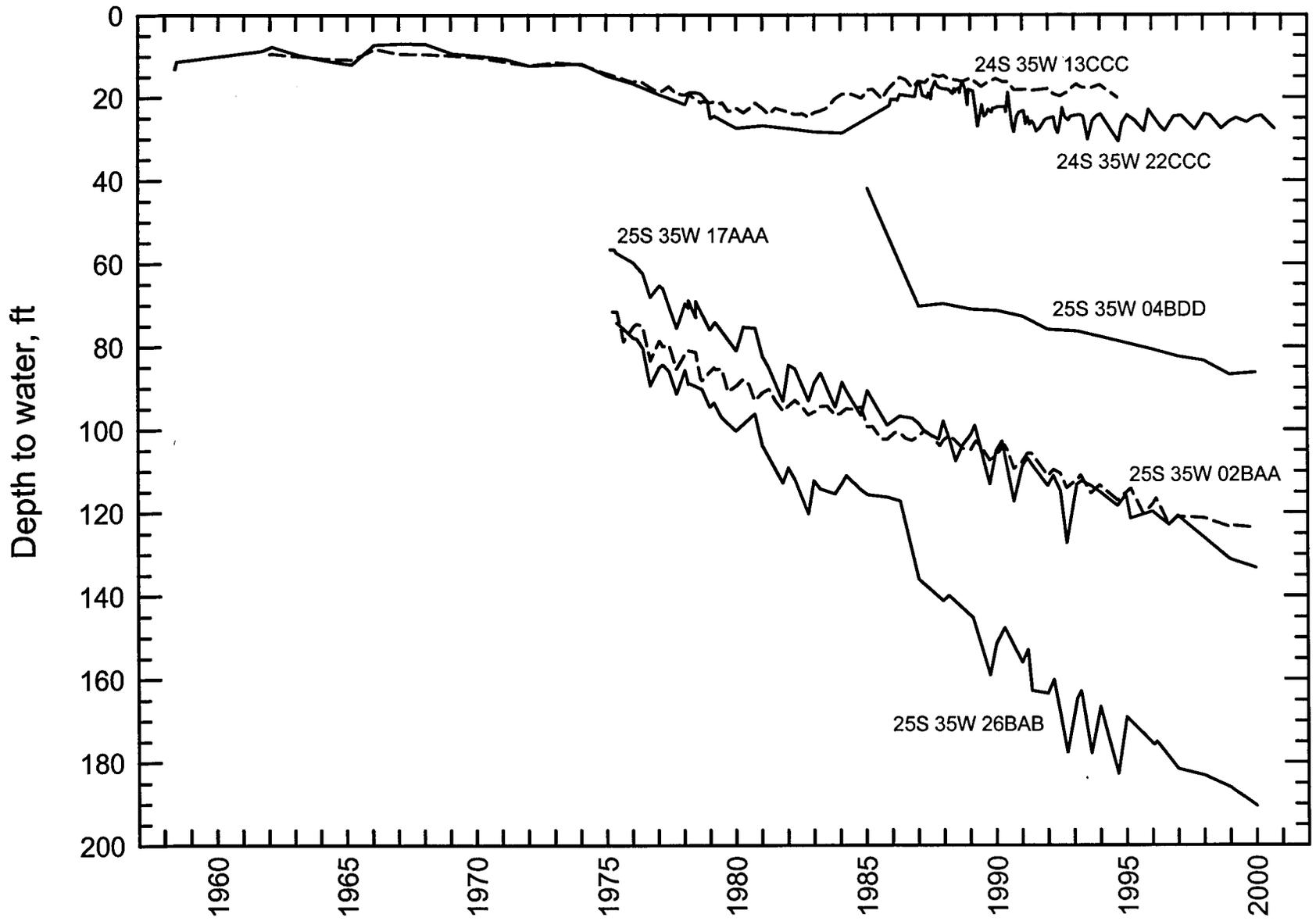


Figure 5. Hydrographs for wells in R. 35 W. south of the Arkansas River.

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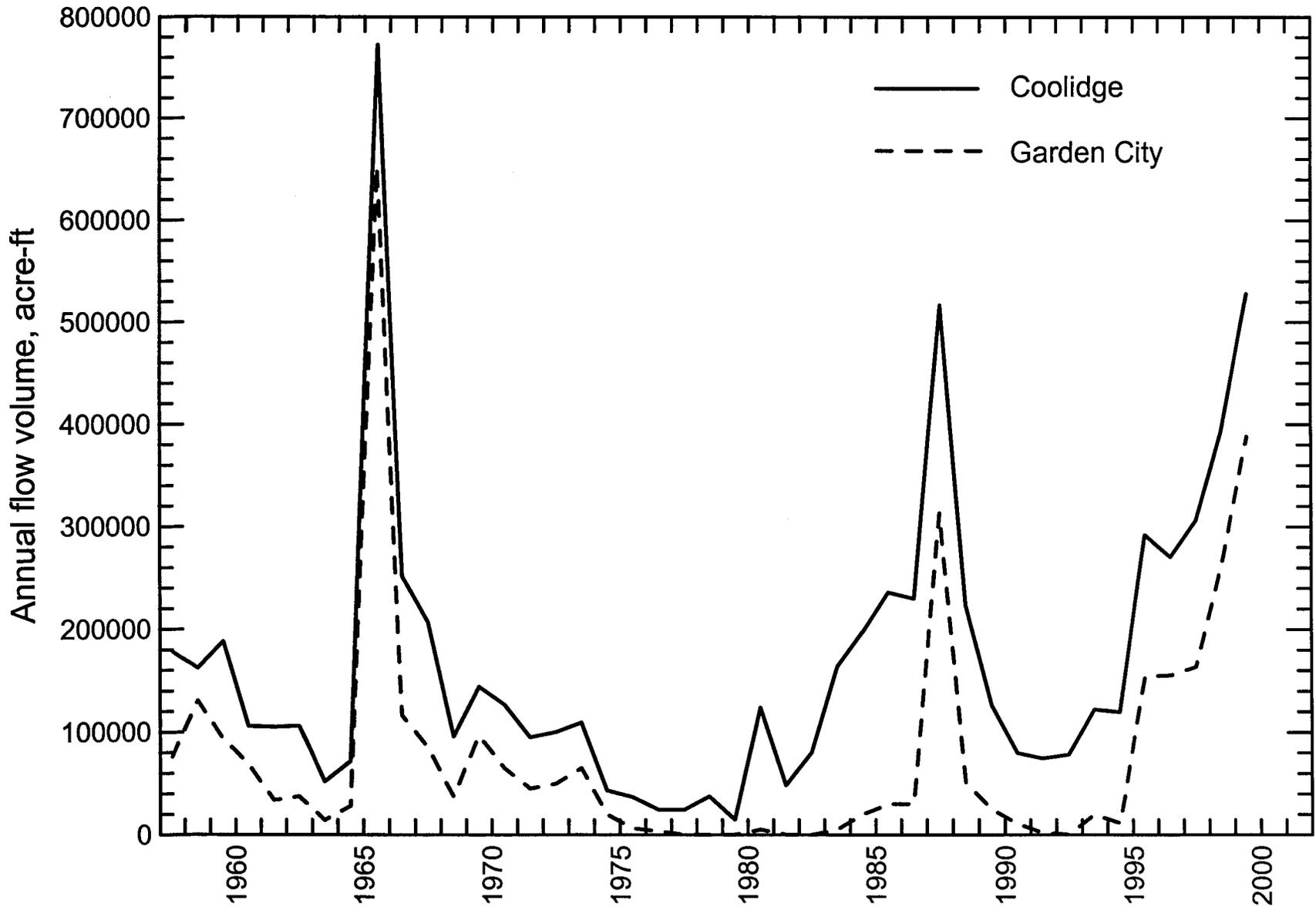


Figure 6. Annual volume of Arkansas River flow near Coolidge and at Garden City.

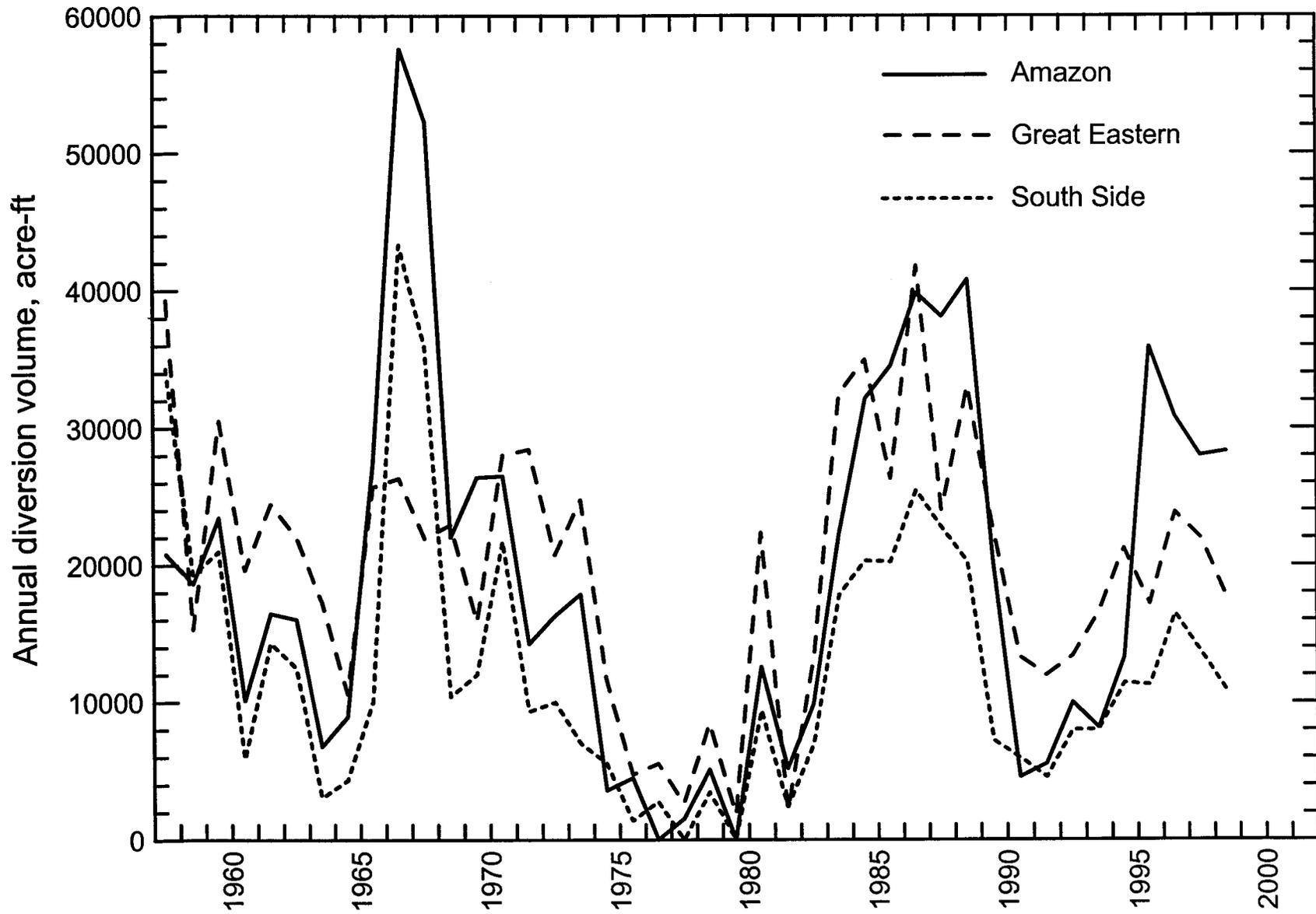


Figure 7. Annual diversions from the Arkansas River to the Amazon, Great Eastern, and South Side ditch systems.

average diversions in the early 1980's. During this period, the amount of ground water needed to supplement the river-water irrigation was substantial. Therefore, the large ground-water withdrawals produced substantial water-level declines during a period with only a relatively small amount of recharge from diversion canals and surface-water irrigation. The spike in the Great Eastern diversion for 1980 is reflected in a small rise in the water level of the well (24S-35W-09) within this ditch area; the well is located near the main canal.

Starting in 1983, the river diversions increased substantially and remained relatively high until 1989 (Figure 6). The ground-water recharge from the increased ditch irrigation during this period corresponds to a general rise in water levels for the 3 wells within the Amazon and Great Eastern ditch areas. From 1990 to 1994, the diversion volumes dropped to lower than average values, resulting in less recharge and a slight drop in water levels for the two wells in the Amazon ditch area. The drop in the diversion flow was not as great for the Great Eastern as for the Amazon ditch system, which may be part of the reason why the water level for the well in the Great Eastern area did not change much during 1990-1994. Starting in 1995, the diversion volume was high in the Amazon ditch system, and the resulting recharge corresponds to the increase in water levels after 1995-for the two wells in this ditch area. The increase in the water diverted to the Great Eastern ditch area was not as great for the latest period as for the Amazon system. This may explain the relatively constant water level in well 24S-35W-09 in comparison to the rises for the two wells in the Amazon service area. The higher water levels for the wells within the ditch service areas 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. 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.

Table 2 lists information for 6 wells that lie to the south of the Arkansas River valley. The wells are listed in order of increasing distance directly south of the Arkansas River. Four of the wells are used for irrigation. One of the other two wells was constructed to serve an observation well; the other is unused but serves as an observation well. The two wells closest to the Arkansas River are screened in the Quaternary alluvial aquifer and have depths of 50 and 65 ft. The other 4 wells are screened in the High Plains aquifer. The depths of these 4 wells range from 299 ft to 367 ft and increase with distance from the river. The two alluvial wells lie within the irrigation service area of the South Side ditch. The well in 24S-35W-04 is located at the edge of the alluvial aquifer just outside the boundary of the South-Side ditch service area. The other 3 wells lie at increasing distances from both the alluvial aquifer and the ditch-irrigation area and are within the band of sand dunes south of the river valley. The land-surface elevation for the well locations generally increases with distance south from the Arkansas River.

The hydrographs for the 6 wells listed in Table 2 are graphed in Figure 5. The depths to water for the two alluvial wells are the shallowest of the 6 wells. The water-level depths in the two wells were relatively similar and remained within 6 to 14 ft of the surface from the late 1950's to 1974. After 1974, the water levels declined until reaching a low around 1983. From 1984 to 1988, the water levels rose and then began a slow downward trend to 1995.

Water-level measurements were discontinued for one alluvial well after 1994. The water level for the other alluvial well fluctuated about a constant depth for 1995-2000. Although the relative magnitude of the water-level changes is smaller for the alluvial wells than for the wells in the ditch-irrigation area to the north of the river, the patterns contain some similar elements. The water levels in the alluvial aquifer are mainly controlled by the river stage but also by the amount of ground-water withdrawals and recharge from river diversions in the South Side ditch area.

The hydrographs for the 4 wells screened in the High Plains aquifer south of the Arkansas River all show substantial continuous declines in ground-water levels (Figure 5). In general, the farther the well is located south of the river, the steeper was the rate of decline. The farther the well is from the river and alluvial aquifer, the smaller is the recharge water volume that flows in the subsurface to the well. The depth to water in the most southern well (25S-35W-26) dropped from 74.3 ft below land surface in June 1975 to a depth of 190.5 ft in January 2000, a fall of 116.2 ft in 24.7 years or a rate of 4.7 ft/yr. 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 small changes that may correspond to the high river flows and diversions during the mid-1980's. The slopes of the general water-level declines in the 3 wells outside the alluvial aquifer boundary decreased somewhat starting around 1983. The well with the most pronounced relationship to the mid-1980's flow and diversion increases was that farthest to the south (25S-35W-26). In addition, the large drop in water level at this well in 1986 does not correspond to diversion and river flow patterns. This suggests that the mid-1980's variations for this well could also be related to other factors such as changes in pumping that correspond to rainfall received at the well location.

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 north of the river ranged from 13 to 36 ft above the river-water surface. At the well locations 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 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 8-10 show the hydrographs in Figures 3-5 relative to the Arkansas River level. The earliest water levels for all of the wells with records that begin before 1970 were above the river surface. The ground-water levels dropped below the river surface at all of the wells during the early 1980's. 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

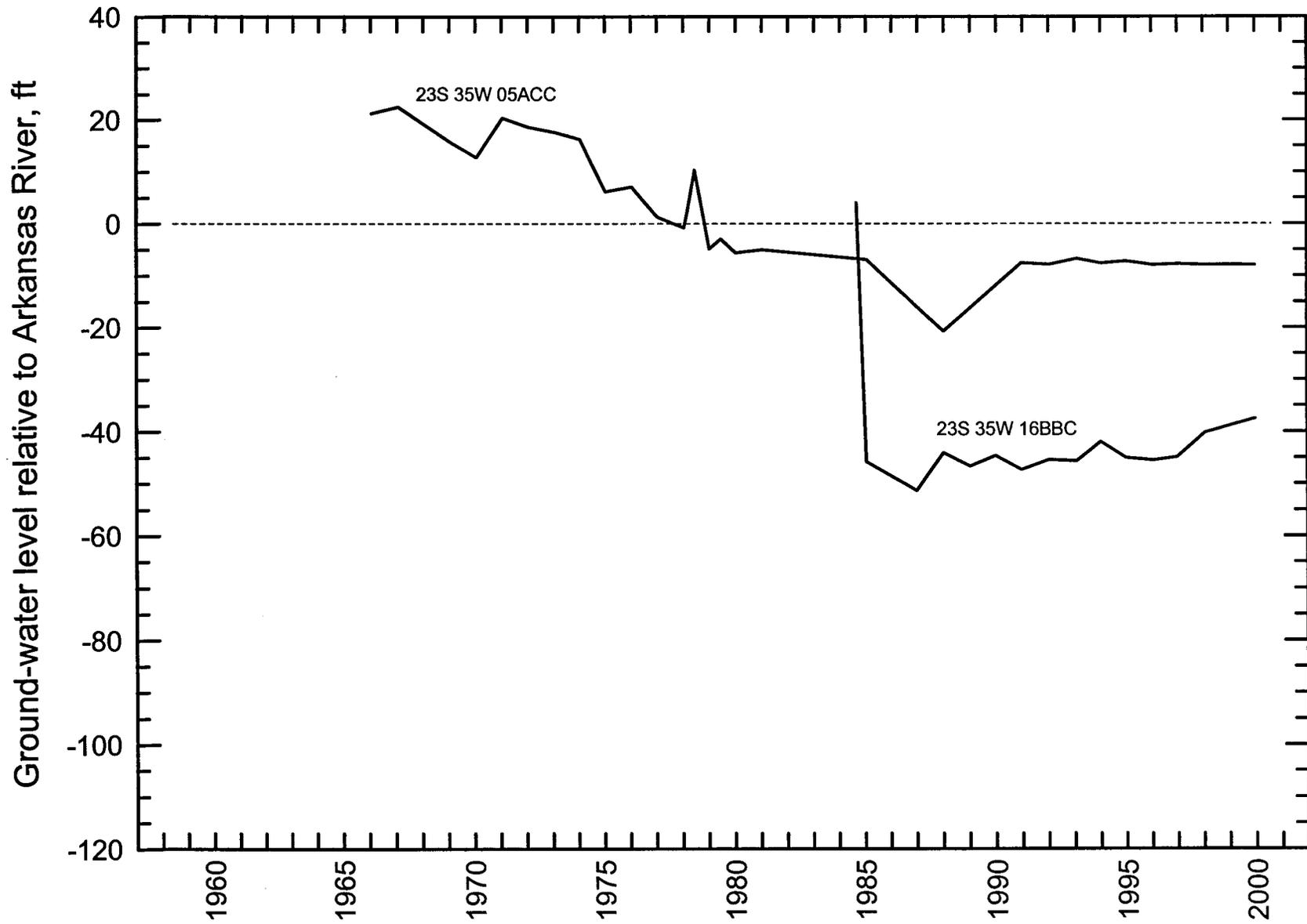


Figure 8. Hydrographs for wells in Figure 2 represented as water levels relative to Arkansas River elevation.

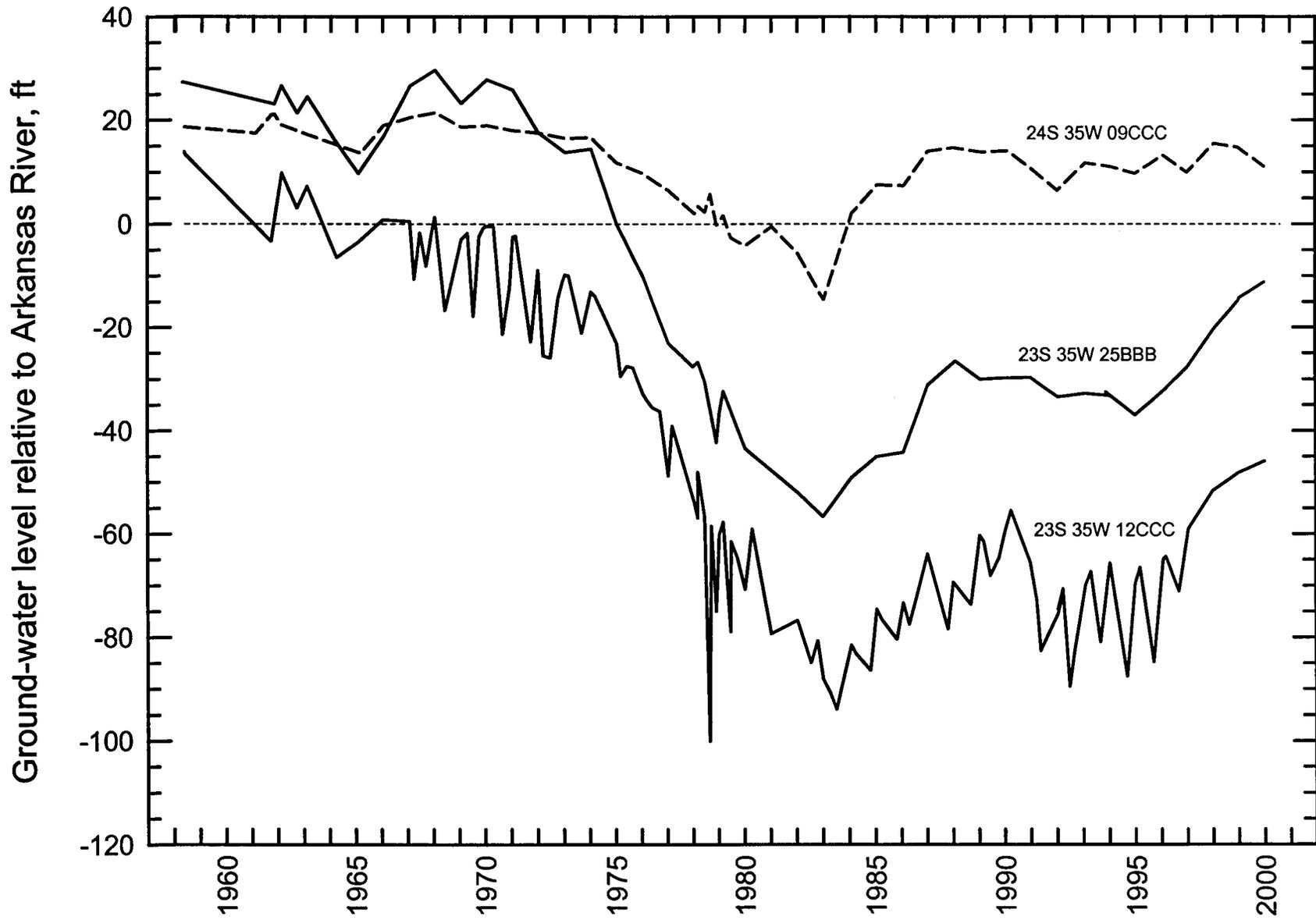


Figure 9. Hydrographs for wells in Figure 3 represented as water levels relative to Arkansas River elevation.

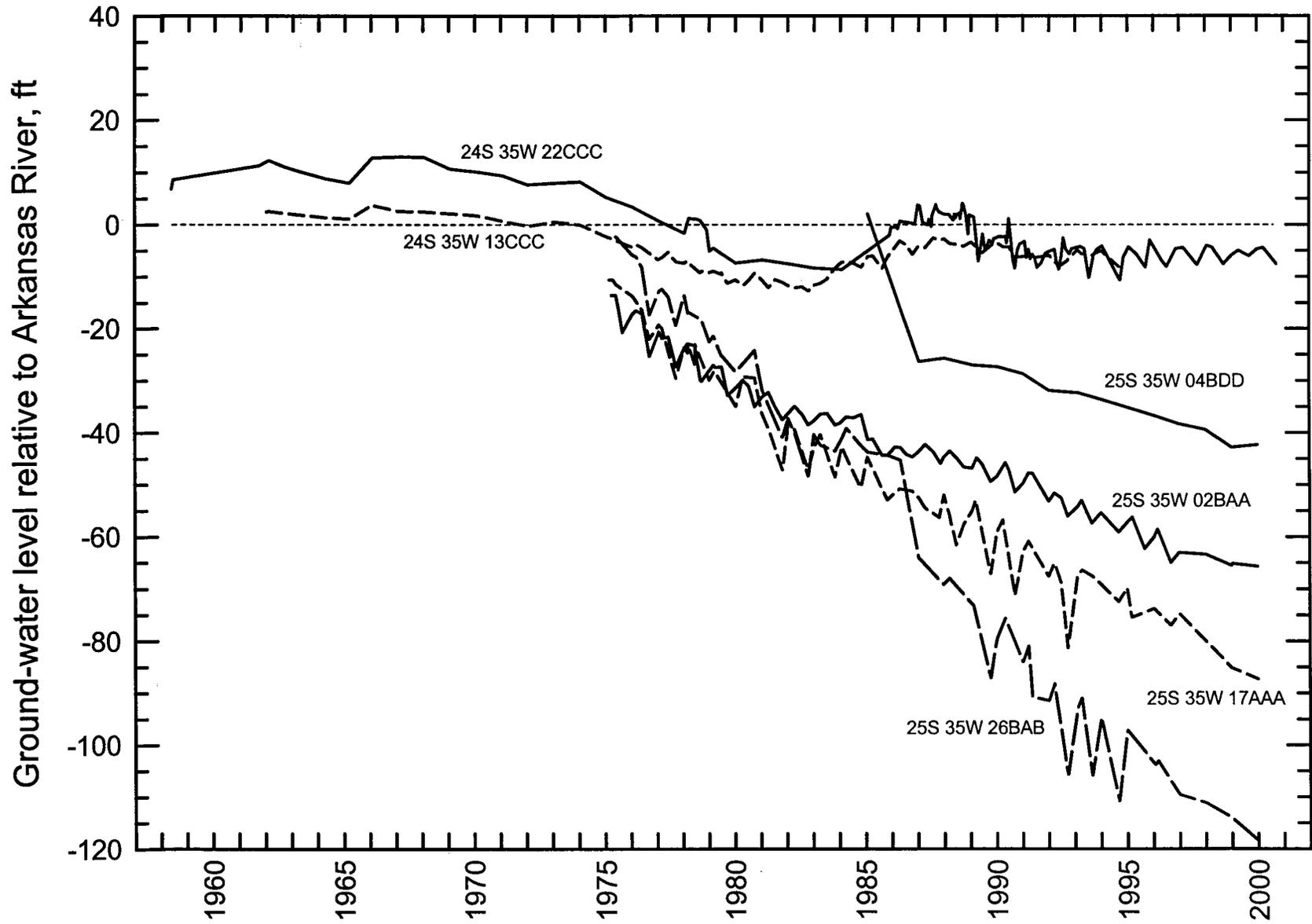


Figure 10. Hydrographs for wells in Figure 4 represented as water levels relative to Arkansas River elevation.

(24S-35W-09CCC) has remained above the river surface since 1984 (Figure 9). The well is sited close to the Great Eastern canal and near the seepage from Lake McKinney. The water-level data in this area indicate that there is some ground-water flow from the ditch service area towards the alluvial valley. Because the water levels farther to the north are substantially below the levels for this well, there must be a northerly component of flow farther to the north. The January 2000 measurement shows that the ground-water level in the next well to the north (23S-35W-25) is only 10 ft below the river surface as interpreted from the USGS topographic map.

Extrapolation of the steep rate of water-level decline for the wells in the High Plains aquifer south of the river back in time indicates that the water levels were probably somewhat above the river surface before the mid-1960's (Figure 10). This fits with the 1940 data that show water levels above the river surface at these locations. The continual decline of water levels in the High Plains aquifer south of the river has increased the hydraulic head gradient from the river valley to the wells. If the elevations for the January 2000 measurements are subtracted from the river surface elevation (with an 5 ft adjustment for channel deepening, see paragraphs below), and divided by the distance between the well and the river, the head gradients from the river to the wells range from about 11 to 17 ft/mi. The gradient for the well in the High Plains aquifer at the edge of the alluvium (25S-35W-04) is the smallest (approximately 11 ft/mi), whereas the gradient for the 3 wells to the south of the alluvial valley are all in the range 15-17 ft/mi.

The long-term trend in the hydrographs for the two alluvial wells is a declining water level (Figure 10). 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 photorevised 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 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 10). 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.

### **Ground-Water Recharge from Arkansas River Water**

Arkansas River flow decreases substantially from the Colorado-Kansas line through southwest Kansas and many years the river has been dry at Dodge City and some years at Garden City. Figure 11 shows the much smaller annual flow at Dodge City in comparison with that at Syracuse, where the gauged record is longer than that at Coolidge near the state line. The mean annual flow at Syracuse has been close to that at Coolidge for years during which the gages were both recording rivers stages. A large amount of flow is diverted for irrigation use, primarily in Kearny and Finney counties. Figure 12 shows the total ditch diversions in comparison with the flow at Syracuse. However, an even greater amount of flow infiltrates from the river channel into the alluvium. The riverbed sediments are primarily sands and gravels and the alluvium contains coarse sand and gravel, thereby allowing relatively rapid infiltration into the alluvial aquifer. The alluvium is generally underlain by lower permeability sediments than the deeper main aquifer and acts to slow infiltration. Although some of the alluvial aquifer water is consumed by phreatophytes in the river valley, most of the recharge enters the underlying High Plains aquifer in the river corridor. A small amount of river water is also lost by evaporation from the river surface.

Large flow losses from the Arkansas River between Coolidge (or Syracuse) and Dodge City started in the early 1980's (Figure 13) when river flow increased after ground-water levels had substantially declined. Figure 14 shows the amount of the total flow loss between Coolidge (or Syracuse) and Garden City. Figure 15 accounts for the irrigation diversions from the river and represents the flow losses along the river channel between Coolidge (or Syracuse) and Garden City. There has been a substantial increase in the flow loss from the 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 16). 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 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

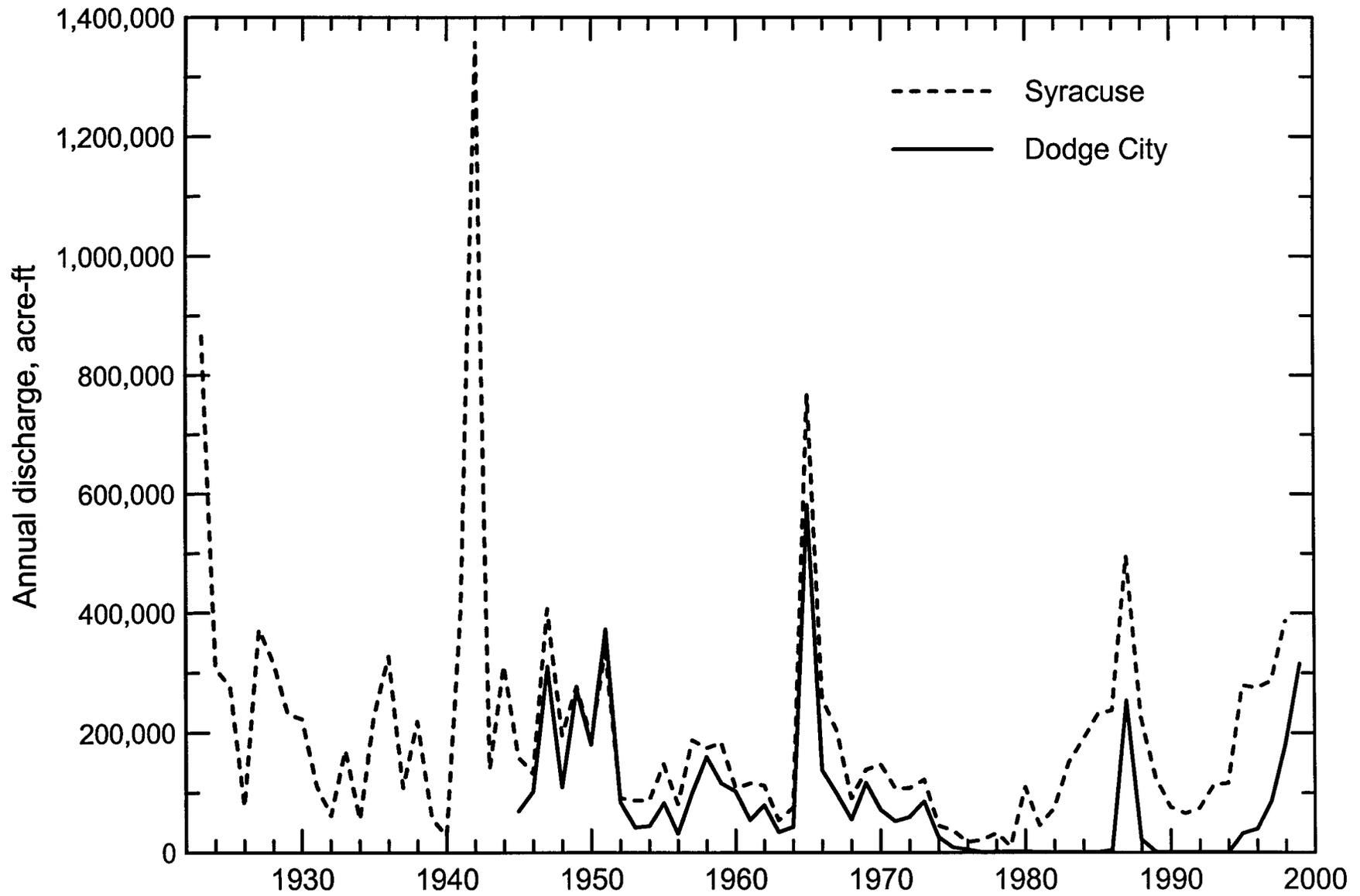


Figure 11. Annual flow of the Arkansas River at Syracuse and Dodge City.

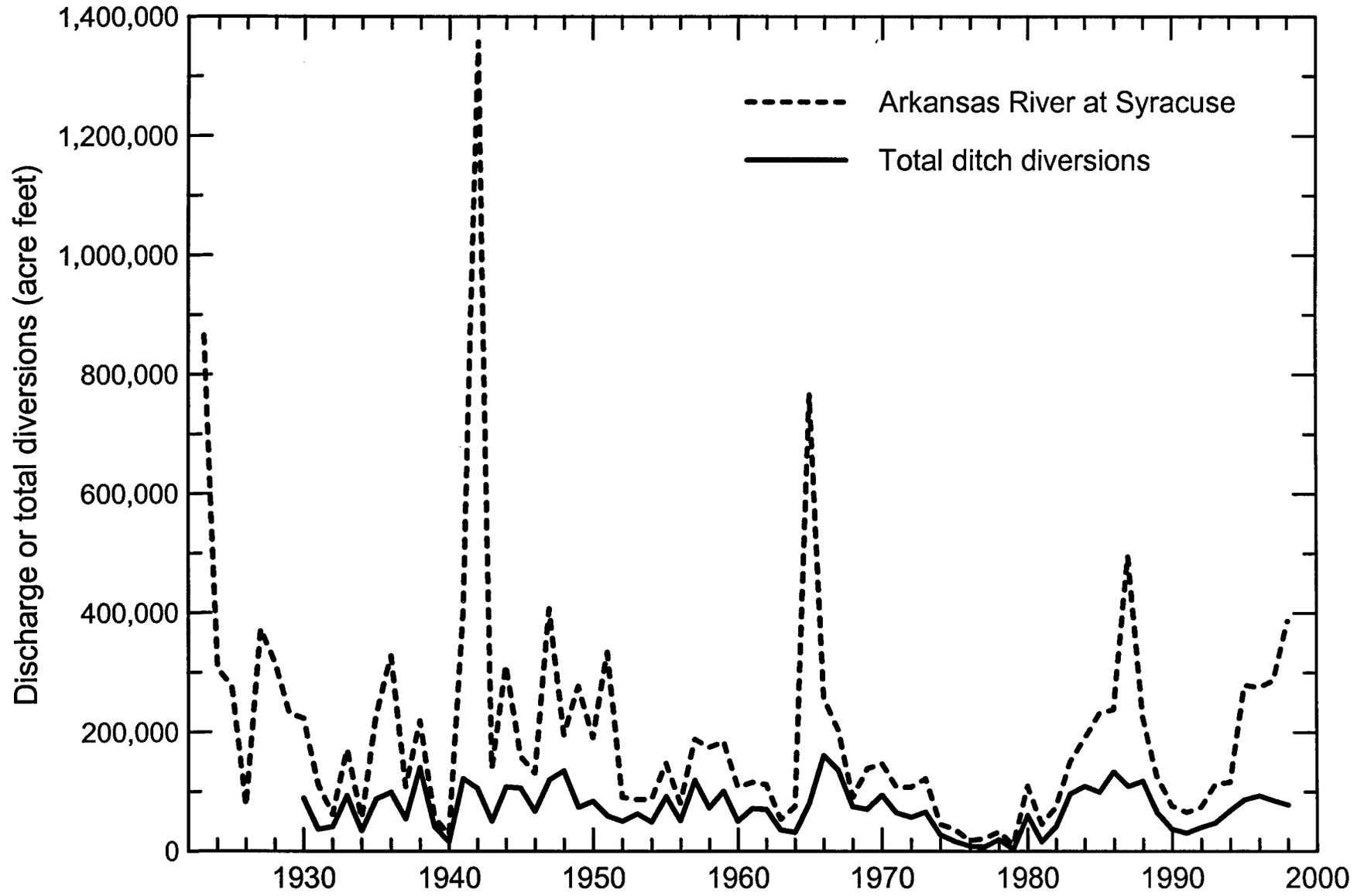


Figure 12. Annual flow of the Arkansas River at Syracuse and total irrigation diversions in Kearny and Finney counties.

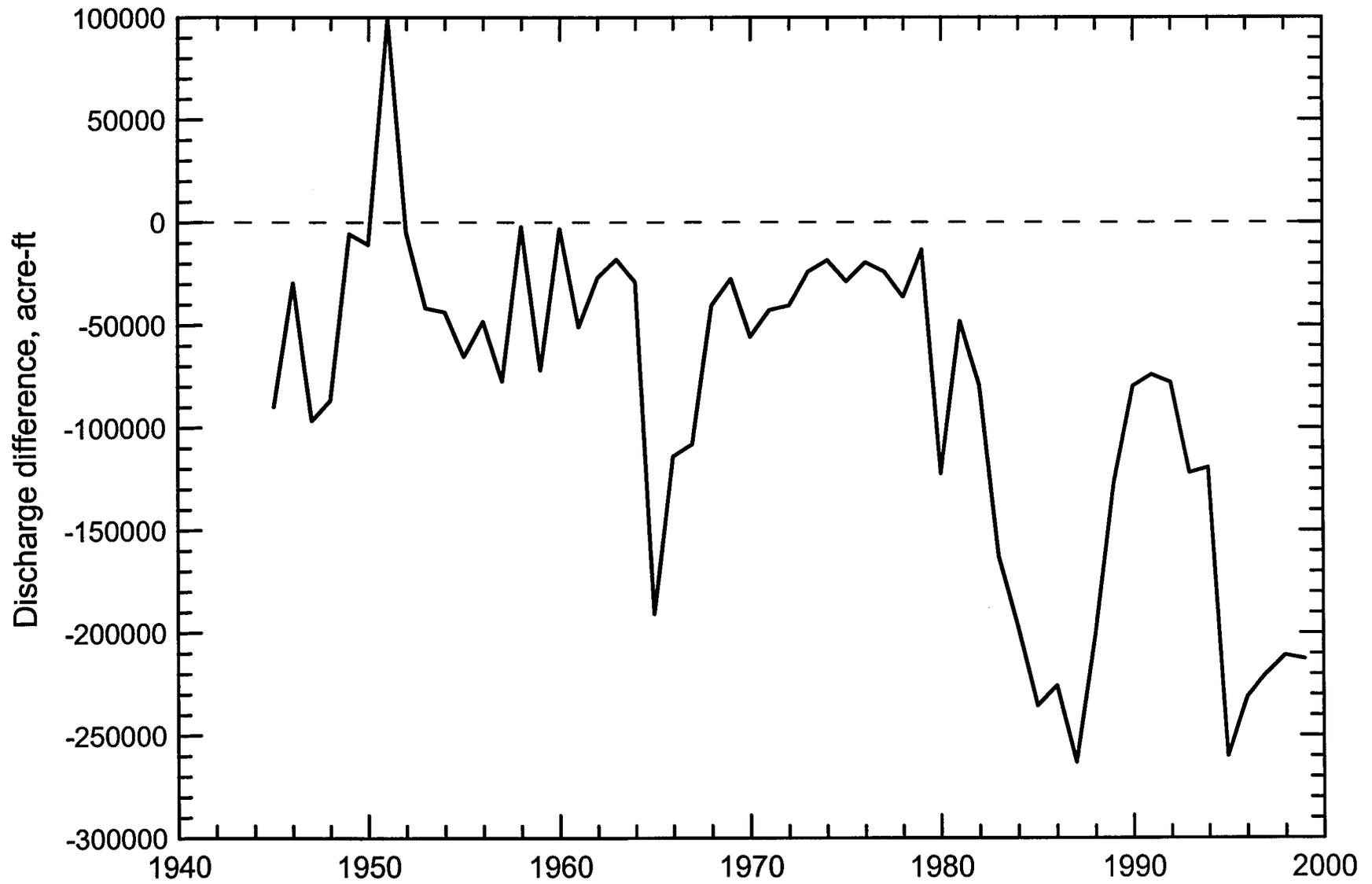


Figure 13. Annual flow of the Arkansas River at Dodge City minus the flow at Coolidge or Syracuse.

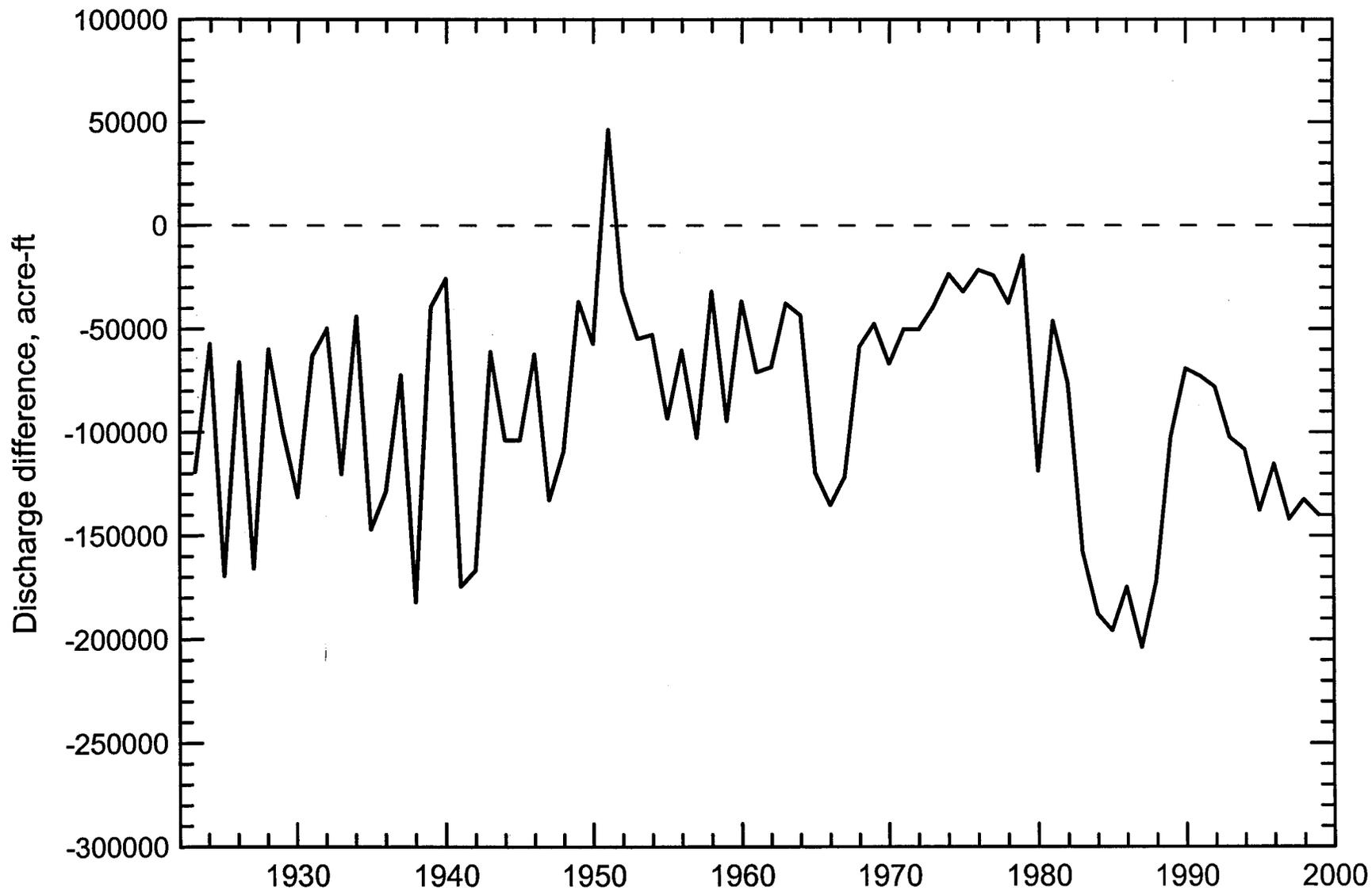


Figure 14. Difference in annual flow of the Arkansas River between the Colorado-Kansas border and Garden City.

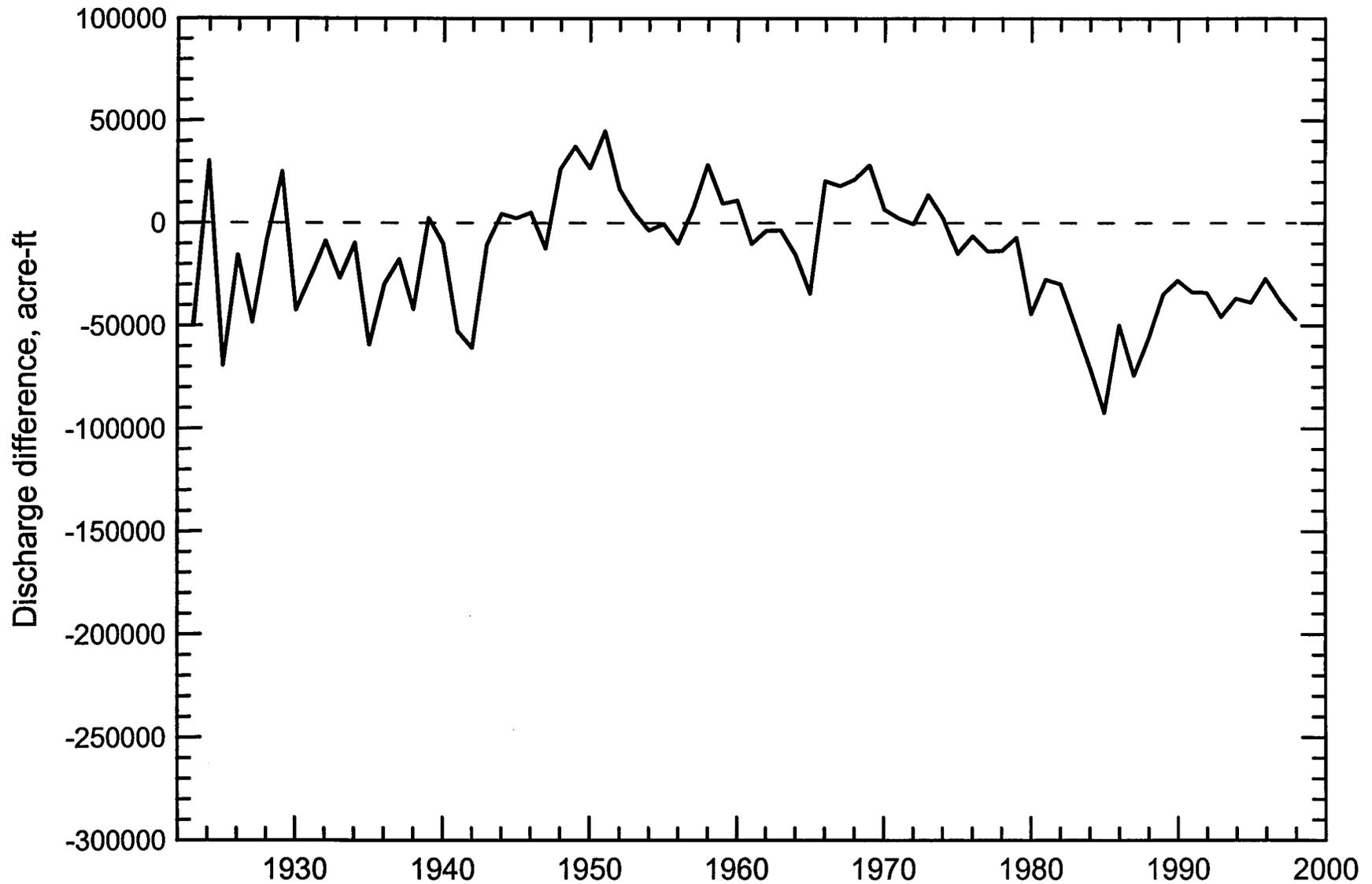


Figure 15. Net gain or loss from the Arkansas River channel computed from the annual river flow at Garden City plus total irrigation diversions in Kearny and Finney counties minus flow at Syracuse. The scale is the same as in Figure 14.

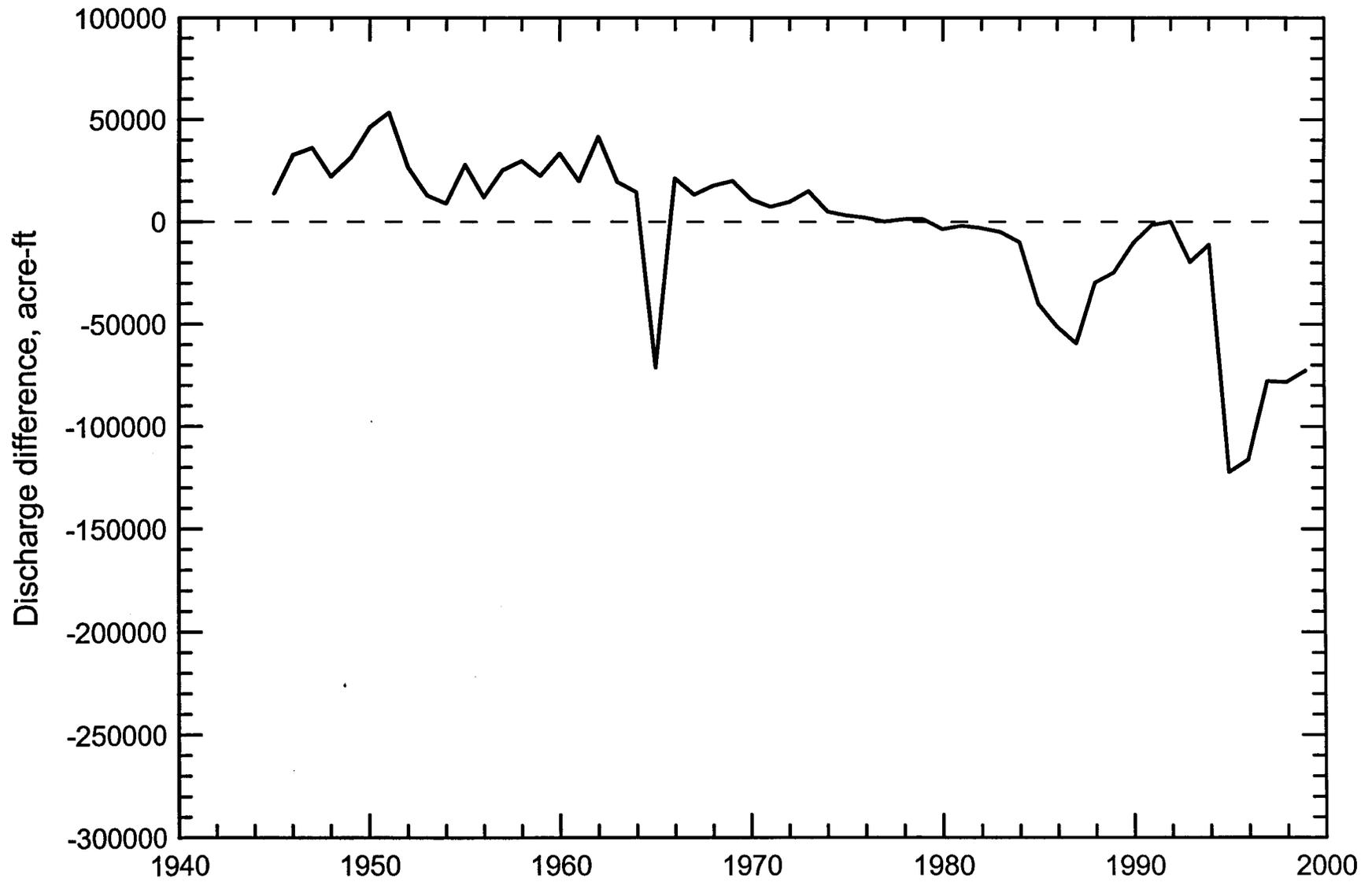


Figure 16. Difference in annual flow of the Arkansas River between Garden City and Dodge City. Negative values indicate flow loss.

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,  $1.66 \times 10^8$  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 in the 5 counties of the study area.

Most of the river water diverted for irrigation is 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 seeps from below canals, ditches, and fields irrigated with the river water and recharges the underlying aquifers (Meyer et al., 1970). A small amount of this recharge appears to discharge to the alluvial aquifer and then 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 estimated amount of water lost from the surface of the river to evaporation is 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. 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. 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 recharges ground water was about 73,000 acre-ft/yr if approximately half of the phreatophyte consumption was from river flow. Thus, the total recharge from the ditch diversion system and the river channel was nearly 90,000 acre-ft/yr during 1989-1998. If  $\frac{3}{4}$  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 and High Plains aquifers in southwest Kansas has substantially exceeded 100,000 acre ft during the last 6 years. The ground-water recharge in the river corridor is on the order of large recharge projects each costing tens of millions of dollars in the United States such as in Orange and Kern counties, California and the Central Arizona Project. However, the Arkansas River recharge is not a specifically

planned project but rather the result of water-table declines in the High Plains aquifer that cause seepage from the overlying alluvium and induce recharge from the channel, and of irrigation diversions that partially act as artificial recharge.

### **Transport of Salinity into the Alluvial and High Plains Aquifers**

Before the start of ditch irrigation and pumping of high capacity wells in Colorado and Kansas, the Arkansas River in southwest Kansas was a gaining stream during most periods through all the 5 counties of the study area. Ground water flowed from the alluvial aquifer underlying the sand dunes south of the river in Hamilton and western Kearny counties to the Quaternary alluvium and then discharged to the river. The quality of this discharge was very fresh as indicated by current fresh ground waters in most of this area. Intermittent runoff and a small amount of ground-water flow from the uplands entered the river valley along the north side of the valley in Hamilton and western Kearny counties. Overall, this water would also have been fresh, although the TDS concentrations were probably greater than the discharge from the alluvium under the sand hills because some dissolved solids could have been added from runoff and ground-water discharge from the Cretaceous bedrock that is exposed along parts of the valley wall and underlies the shallow ground-water system to the north of the river valley. In general, the mix of different discharge sources to the Quaternary alluvial aquifer in Hamilton and western Kearny counties is expected to have been fresh before anthropogenic development of surface and ground-water resources.

Before the start of development in the late 1800's, the Dakota aquifer was artesian along the Arkansas River valley from southeastern Colorado into western Hamilton County. The Dakota aquifer probably discharged a very small amount of water to the river valley in western Hamilton County. Ground water in the Dakota aquifer underlying the Arkansas River valley in eastern Colorado and southwestern Kansas is fresh but contains higher sulfate concentrations (usually 50-300 mg/L) in comparison with the water in the alluvium underlying the sand dunes (Macfarlane et al, 1994, 1998). From eastern Hamilton County to Ford County, the High Plains aquifer recharges (moves down into) the Dakota aquifer, therefore, water quality in the Dakota aquifer would not affect that in the High Plains aquifer. This also indicates that water does not come up into the High Plains aquifer from underlying bedrock along the Bear Creek fault in southern Kearny County. The quantities of water discharging from or to the Dakota aquifer are relatively small in comparison with lateral flows in the alluvial and High Plains aquifers and seepage from the river and irrigation diversions.

Ground water in the High Plains aquifer is expected to have been fresh (less than 1,000 mg/L TDS content) throughout the entire corridor of the upper Arkansas River before the late 1800's. However, the TDS concentration was generally greater north of the Arkansas River in eastern Kearny, northern Finney, and northwest Gray counties than south of the river. The Scott-Finney depression or basin extends from southern Scott County to the Arkansas River valley (Latta, 1944). The approximate location of the basin is along R. 33 W. and the western half of R. 32 W. Runoff from the sides of the basin, primarily from the west, entered the depression and resided temporarily in playas before recharging the underlying aquifer. Evapotranspiration concentrated dissolved solids in the runoff that entered the shallow playas

or soils before infiltrating to the ground water. Over thousands of years, the TDS content of the ground water in the High Plains aquifer in the center of the basin rose because of this process. The highest TDS concentrations (around 2,000 mg/L) are in ground waters in part of Scott County. In Finney County, the highest TDS (just over 1,000 mg/L) and sulfate concentrations (around 500 mg/L) attributable to natural causes are just south of the Scott County line. The ground waters of the High Plains aquifer were fresher to the west and east of the depression and became fresher from the Scott County line towards the Arkansas River. Sulfate concentrations generally ranged from less than 50 to near 100 mg/L in the High Plains aquifer underlying the northern part of the river valley. South of the Arkansas River, the sulfate concentration of water in the High Plains aquifer appears to have been less than 50 mg/L in essentially the entire river corridor (Whittemore, 2000b).

Ground-water flow from the High Plains aquifer entered the alluvial aquifer from most areas of eastern Kearny County through Ford County before and during the initial stages of ground-water development. The main exception is a part of the eastern-half of Kearny County south of the Arkansas River where the ground-water flow directions in McLaughlin (1943) suggest that water from the alluvial aquifer could have moved into the shallow part of the High Plains aquifer near the alluvium boundary. The flow from the High Plains aquifer into the alluvial aquifer along most of the river corridor would have kept much of the ground water in the alluvium fresh, especially near the margins of the alluvial valley. Before ditch irrigation systems were constructed in the 1870's in Colorado, the Arkansas River flowed enough during most periods to maintain shallow water tables in the alluvium near the river. The river channel was much broader and shallower than today; human impacts decreasing the river flow have caused deepening and narrowing of the channel. During extended dry periods the dissolved solids content of the shallow ground water in the floodplain would have increased because evaporation of moisture from the sediment could occur as capillary action pulled water up above the water table. Transpiration by plants growing in the floodplain also would have increased the TDS content of shallow ground water in the alluvium during dry periods. However, the plants would have been mainly grasses and bushes before the start of phreatophyte infestation in the early 1900's (mainly cottonwood and willows at first followed by the later dominance of salt cedar after the mid-1900's). During drought periods in the river basin in Colorado and southwest Kansas, the river stage would have fallen and some of the shallow ground water near the water table in the alluvium underlying the floodplain would have moved along curved flow lines downward and towards the river and then upwards to the river channel as discharge. This would have resulted in moving the shallow water with elevated dissolved solids deeper into the alluvium before discharging to the river.

During periods when low flow of the Arkansas River entered Kansas, the river water could have been somewhat saline. However, because the alluvial aquifer would have discharged water towards the river in the valley in southwest Kansas, the river water could not have entered most of the alluvial aquifer to increase the ground-water salinity. Water during the initial period of higher flows in the Arkansas River that resulted from rain over eastern Colorado could have been slightly saline if the high flows flushed surface salts and saline waters to Kansas. If the river stage were higher than ground-water levels, some of the river water would have infiltrated into the alluvium. High flow events with fresh river water would

have resulted in some infiltration of river water into the floodplain sediments, thereby diluting the upper part of any slightly saline water in the alluvium near the river, but also driving some of the shallow water with elevated dissolved solids deeper into the alluvium. When the high stage receded to low flows, the diluted ground water would then flow back towards the river. Heavy atmospheric precipitation also would have infiltrated to the shallow alluvial waters and caused dilution of elevated TDS concentrations in the aquifer.

Before human impacts, the combined effects of the evapotranspiration concentration of shallow ground waters during dry periods, dilution by flooding and infiltration of rainwater, and bedrock discharge would have reached a state of approximate equilibrium about which the TDS concentration in the alluvial aquifer would vary with climatic changes. Slightly saline ground waters, but with dissolved solids contents much lower than the levels observed today, could have occurred in the alluvial aquifer below the floodplain near the river. In general, the farther the distance downstream in the Arkansas River valley, the less saline the water in the alluvium would have been because the increase in mean annual rainfall would have caused increased dilution from direct infiltration and greater ground-water discharge from the High Plains aquifer to the valley.

After irrigation started in Colorado in the 1870's, the Arkansas River flow entering Kansas decreased in quantity and became more saline. After the 1880's, the Kansas diversions would have also decreased flow somewhat, although the amounts used in Kansas have always been substantially less than those used in Colorado. The more saline river waters would not have affected the alluvial ground waters much during low flow periods except in local areas of the broad river channel, because ground-water discharge to the river from alluvium underlying higher terraces in the valley and the High Plains aquifer, where present, would have prevented movement very far away from the channel zone. However, high-flow events that flushed salinity from ditch-irrigated areas in Colorado could have resulted in water infiltrating into the shallow alluvium covered by the flood waters that was slightly saline. The greatest salinity of the river water would be expected at the beginning of the high flow just after locally heavy rainfall flushed salts from irrigated fields and saline water from return-flow ditches. In addition, the front of a flood event caused by rains or snowmelt in the Rocky Mountains or locally heavy rain could have mixed with saline low-flow to produce water with elevated dissolved solids that would have been the first water to seep into the alluvium as the river stage rose.

After ground-water use in the alluvial aquifer started near 1900, the pumping wells would produce local cones of depression in the water-level surface that could cause some of the slightly saline ground water in the shallow alluvium to migrate farther from the river. In addition, pumping from the Dakota aquifer in southeastern Colorado and far southwestern Kansas began to reduce the artesian head to levels such that today they are below the river channel. Thus, discharge of freshwater from the underlying Dakota aquifer to the river valley in western Hamilton County decreased. Continued pumping of the alluvial aquifer and later development of the High Plains aquifer caused further declines in ground-water levels. Once the water levels in the alluvium away from the river declined enough that river-water seepage

became substantial, the alluvial water began to become appreciably more saline from the high TDS river water.

The saline water diverted from the Arkansas River for irrigation use in Kansas became more saline from further evapotranspiration. Some of the saline water seeped from below canals and irrigated fields to the alluvial aquifer or High Plains aquifer. The infiltrating water would have been most saline in the period before water was pumped from the alluvial or High Plains aquifer and used along with ditch water for irrigation. Some areas did not add ground water to the ditches or fields; salinity increases below these irrigated areas would be expected to be greater than where fresh ground water was used. As ground water pumped from the alluvial and High Plains aquifers became more saline from river water infiltrating from ditch irrigation and the river channel, the capacity of the ground water to dilute the saline water applied to the fields decreased. The recycling of the saline infiltration resulted in a continued increase in the salinity of the recharge below the irrigated fields. However, supplemental irrigation with ground water from the Dakota aquifer would still be able to dilute the saline river water used for irrigation.

As ground-water level declines in the High Plains aquifer became more pronounced in eastern Kearny County eastward through the study area, saline waters in the alluvial aquifer began to migrate farther from the river. Saline water infiltration from fields irrigated with river water also penetrated to greater depths into the High Plains aquifer. The migration pathway of the saline water is affected by the heterogeneity of the aquifer. Both the alluvial and High Plains aquifers contain layers and lenses of sediments of greatly differing permeability. Clay layers slow the downward movement of saline waters but allow more lateral flow within overlying permeable sands; the saline water can perch on the less permeable zones. Such a situation appears to exist in eastern Kearny and western Finney counties near and to the north of the Arkansas River. The ground-water levels present in the alluvial aquifer near the river are now substantially higher than in the High Plains aquifer along much of the river corridor. Leakage from the alluvial aquifer has produced a ridge of higher water levels below the river valley than away from the valley. Saline water from the river and alluvial aquifer is moving downward and farther away from the river in many areas.

The salinity of Arkansas River water entering Kansas has increased substantially since the start of irrigation diversions in Colorado to the present (Whittemore, 2000a). Thus, the salinity source that has elevated the TDS concentrations of ground water in the river corridor in Kansas has increased in intensity. In addition, loss of water by evapotranspiration from the heavy infestation of phreatophytes, particularly salt cedar, since the early 1900's has increased the salinity of shallow ground waters in the alluvium near the river. The average salinity of the Arkansas River in southwest Kansas prior to surface-water and ground-water development in Colorado and Kansas is expected to have decreased downstream as a result of dilution by fresh ground-water discharge. As the location in the river alluvium where substantial amounts of fresh ground-water discharge entered the valley moved farther downstream due to declining ground-water levels, the location where dilution was appreciable slowly moved farther downstream. Today, the dilution point is east of Dodge City. Thus, the river salinity at the state line now does not change significantly as the river flows through southwest Kansas. In

addition, increases in salinity in the alluvial aquifer caused by phreatophytes are no longer substantially diluted.

### **Major Components of the Conceptual Model**

The only substantial source of salinity causing increases in the dissolved solids contents of ground-waters in the river corridor in southwest Kansas is the saline water in the Arkansas River. Evapotranspiration by phreatophytes along the river and during irrigation use further increases the salinity but the location of the saline water that seeps into the alluvium and High Plains aquifers is not changed by the evapotranspiration. Discharge records for the Arkansas River in southwest Kansas indicate that the river has generally lost appreciable quantities of flow from the state line to Garden City since the beginning of continuous flow measurements in the 1920's. A large amount of this loss is water diverted for irrigation in the ditch systems, particularly in Kearny and Finney counties. In comparison, substantial flow losses from Garden City to Dodge City began in the mid-1980's. Flow losses from the state line to Dodge City for the two highest discharge years (1987 and 1998) during the last three decades have been approximately 50% of the river volume crossing the state line. The total flow loss for the years 1975-1998 is 83% of the state-line discharge.

The river water lost from the state line to Garden City leaves by a combination of evapotranspiration to the atmosphere and infiltration to the alluvial and High Plains aquifers. Most of the water diverted from the river for irrigation in southwest Kansas has been consumed by evapotranspiration. However, water-level and ground-water quality data indicate that appreciable amounts of diverted water have infiltrated to the aquifer underlying the irrigation canals and fields. Some irrigation water pumped from the aquifers also returns to the subsurface as ground-water recharge. Meyer et al. (1970) indicated that "deep-percolation losses (those penetrating more than 6 ft) in a well-drained system are frequently 20 percent or more." They stated that "Approximately 25 percent of the applied water is estimated to return to the reservoir."

Appreciable leakage from the alluvial aquifer to the underlying High Plains aquifer began when water levels in the deeper aquifer fell substantially below levels in the alluvial aquifer. The appreciable increase in ground-water withdrawals for irrigation from the High Plains aquifer during the 1970's caused water-levels to decline enough below the shallow aquifer that saline water could penetrate deeper. The leakage from the alluvial aquifer is the main cause of increased recharge from the river to the alluvial aquifer, and therefore decreased river flows.

There are no water-quality and water-level data available for a truly predevelopment period in the upper Arkansas River corridor. Such data would have had to have been collected prior to 1860. However, there is a generally good set of data for wells, including location, use, water level, pumping rate, and water use, along with some water-quality information, available for the period 1938-1942. In addition, data exist for this period for Arkansas River flow and the quantity and destination of river water diverted for irrigation along the corridor. Although the flow of the river had already been reduced substantially by

diversions and the river salinity had appreciably increased by 1940, the amount of water pumped from the alluvial and High Plains aquifers had not greatly affected regional water levels. In comparison, the large declines in water levels caused by pumping, especially after 1970, have substantially changed river- and ground-water flows and the movement of saline waters into the corridor ground waters. The following sections on numerical modeling involve both local and regional simulation of the ground-water flow and movement of salinity in the system.

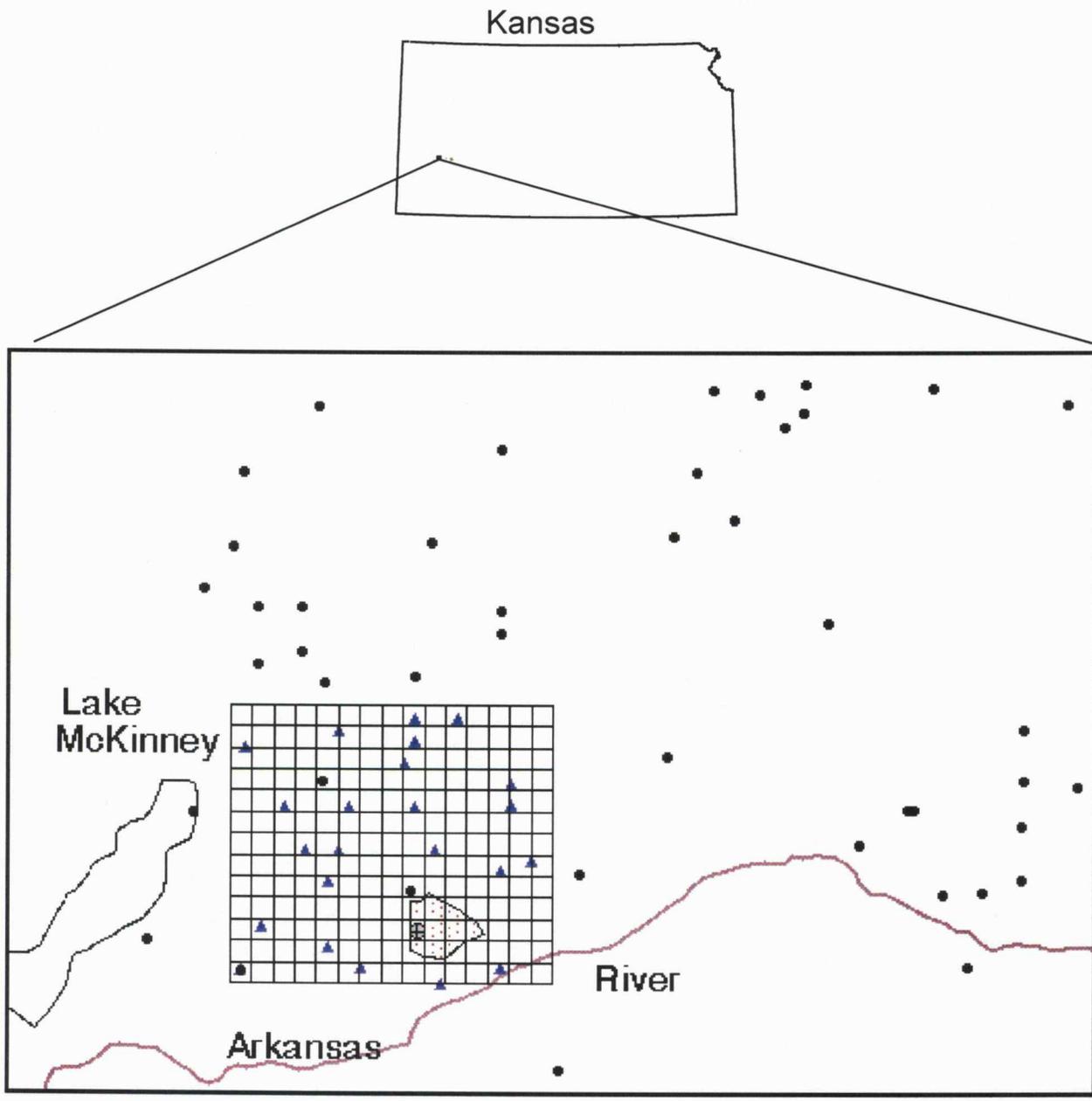
## LOCAL NUMERICAL MODELING IN EAST-CENTRAL KEARNY COUNTY

Ground-water flow and solute transport in the area around Deerfield in east-central Kearny County were modeled to evaluate factors controlling saline water migration. The area includes the City of Deerfield, nearby fields irrigated by diverted Arkansas River water and pumped ground water, and the Arkansas River (Figure 17). The public water supply for Deerfield is pumped from 3 wells in the High Plains aquifer within the city. The water pumped from the High Plains aquifer at Deerfield from 1950 to the early 1970's was very fresh and contained sulfate concentrations that were always between 100 and 150 mg/L (Figure 18). During the early 1980's, the salinity in the well water started to increase rapidly; by 1990, the average sulfate concentration in the well waters rose above 250 mg/L. The recent data in Figure 18 represent an average for the water pumped from the different wells. During the 1990's the sulfate content of the water pumped from the wells has fluctuated but has remained substantially above 250 mg/L in two of the wells all the time and in one well most of the time. The ground water in the High Plains aquifer underlying Deerfield is generally fresher than ground water in the surrounding area. This is also supported by the freshwater in the bottom of the High Plains aquifer at the multi-level observation well site installed by the KGS (Whittemore et al., 2000). Additional information on ground-water quality in the Deerfield area is in Whittemore (2000a).

Factors controlling the transport of saline water in the aquifer include the hydrogeologic characteristics of the aquifer, the hydraulic head distribution, and the location and timing of saline water movement from the surface to the subsurface. A GIS-based ground-water modeling system with automated calibration was developed and applied to evaluate saline water movement in the High Plains aquifer in the Deerfield area. The system integrates spatial databases (Arc/Info), numerical models for ground-water flow and contaminant transport, and a method for parameter identification through a graphical user interface customized within ArcView. A special feature of this parameter identification method is that the available lithologic data are directly incorporated into the inverse problem.

### Model Area

The area that includes the water-level observations and lithologic well logs used for model calibration is 13 km by 19 km as shown in the GIS overlay of Figure 17. The small irregular polygon in the southeast portion of the grid area in Figure 17 is the boundary of the City of Deerfield. The Arkansas River passes to the south of the city. Lake McKinney, a shallow reservoir for storing diverted river water for irrigation, lies to the west of the grid area. Irrigation canals direct water from the Arkansas River and Lake McKinney to area fields. The black dots represent locations of 47 wells for which water-level observations are available. The grid area encloses the locations of 24 supply wells (triangles) and a multi-level observation well site for which lithologic logs exist. The alluvial aquifer near the river consists of coarse sands and gravels generally underlain by clays. The main High Plains aquifer underlying the alluvium and the rest of the area contains interbedded clay, silt, sand, and gravel and was considered as a single unconfined system. An evaluation of the well logs



□ grid for one-layer aquifer

▨ Deerfield

• water-level wells '89

▲ 24 well logs

⊕ multi-level wells



Figure 17. The location of the Deerfield study area, water-level wells, and lithologic logs.

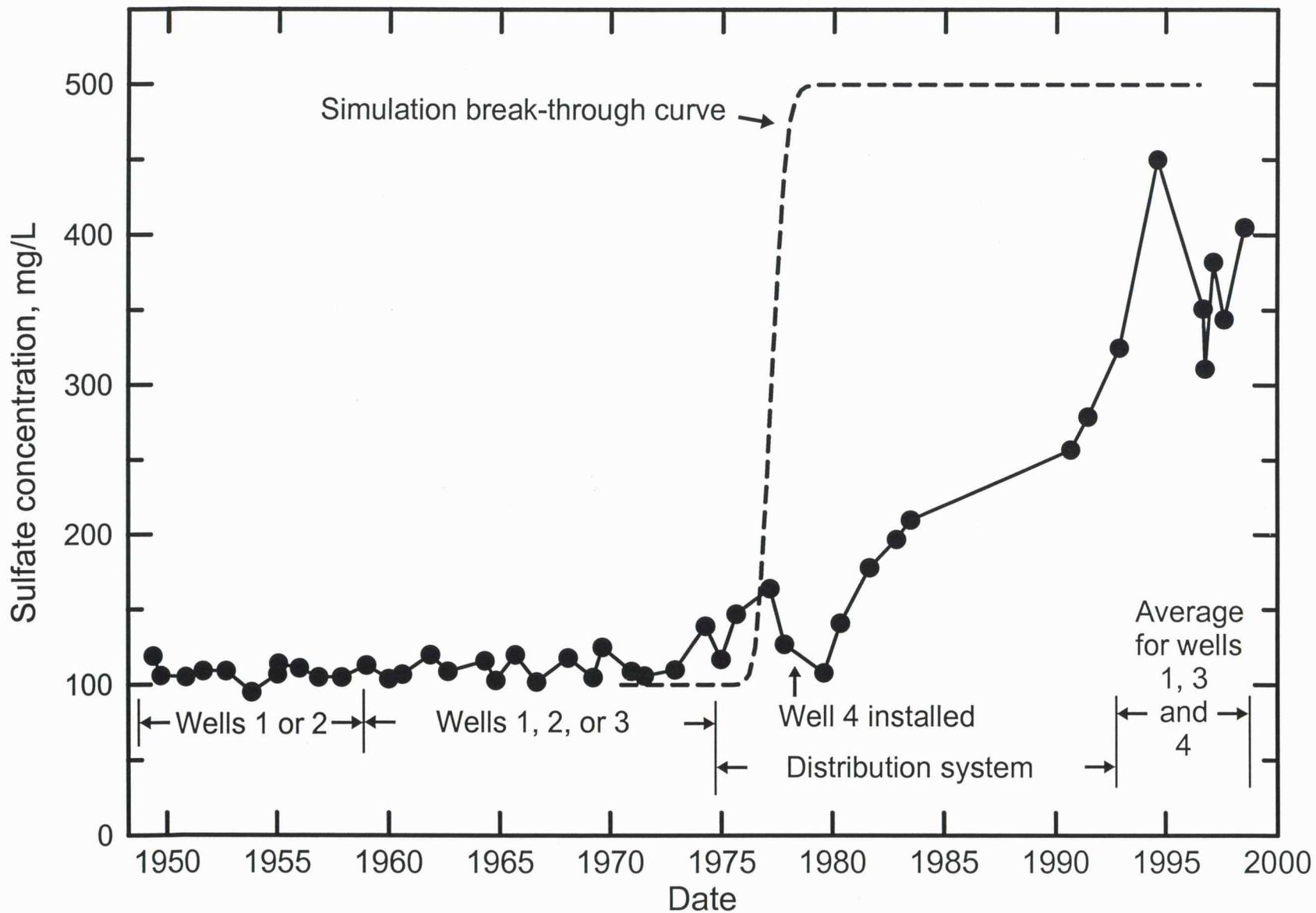


Figure 18. Temporal variation in sulfate concentration of the Deerfield public water supply and the simulation break-through curve. Filled circles represent individual or averaged analyses for the municipal wells or water distribution system.

shows that clay layers or lenses scattered in the aquifer are extensive enough to retard downward vertical movement of ground water.

### **Integrated Modeling System**

Commercially available systems for modeling that incorporate GIS are valuable for many applications and are supported by the supplying institutions. However, development of special applications with these packages may be limited because the source code is not available for change. Codes for the software MODFLOW (McDonald and Harbaugh, 1988) and MT3D (Zheng, 1992) are available and programming languages are included with Arc/Info and ArcView so that additional code can be developed for special links. An integrated modeling system was developed that includes both a graphical user interface and the power of the most widely-used, powerful GIS software, Arc/Info and ArcView. In addition to pre-processing and post-processing for modeling simulation, the modeling system included integrated automated model calibration. The modeling system integrated the spatial database and analysis functions of Arc/Info, the numerical ground-water models MODFLOW and MT3D, and a model parameter identification method into the ArcView environment, thereby permitting interactive model simulation and calibration. More detailed discussion of the integrated system is presented elsewhere (Tsou 1998).

ArcView is a windows-based GIS software that provides a user-friendly interface facilitating the organization, display, querying, analysis and publication of data. Its flexibility in linking external software makes ArcView a better platform for an integrated system than Arc/Info. ArcView does not include the advanced GIS capability of Arc/Info but mainly serves as the user interface for the integrated system, whereas Arc/Info is the GIS server in the system. The ArcView user interface was customized using AVENUE, an object-oriented script language in ArcView. Advanced spatial operations programmed using Arc Macro Language (AML), a macro language in Arc/Info, were sent to Arc/Info through inter-application communication in the software.

The disparate spatial data related to land cover, rivers, water-level wells, hydrogeological information (such as hydraulic conductivity) were stored in Arc/Info databases. These data were transferred into a master coverage through interpolation or overlay. The attributes of the master coverage were edited through the ArcView user interface. The master coverage is called the grid-point coverage in this study. The grid-point coverage is a point coverage, and the point is the center point of a grid cell. Grids in the numerical model were generated as a polygon coverage in the vector-based GIS. Model inputs and outputs were stored at each point. The advantage of a vector-based model for generating grids is that the grid cell sizes can be non-uniform by specifying variant sizes of polygons. Grids over the modeling area of interest were generated in two ways. One was to specify the coordinates of the lower left point and upper right point of a region and cell size, whereas the other was to create a rectangular region and specify column and row numbers. The grids in the modeling system could be rotated as needed.

## **MODFLOW/MT3D Programs**

MODFLOW and MT3D are two widely used ground-water flow and transport models. Both MODFLOW and MT3D have a modular structure with different model packages; each package requires a different input data file in a different format. The MODFLOW and MT3D packages in the integrated system are shown in Figure 19. Each package was accessed through the respective items listed under the menu. After setting inputs through the menu, the data in the grid-point coverage were automatically exported into ASCII files as the required input format for the ground-water model. The model simulation was started through the ArcView user interface. After the simulation, the model outputs were joined into the grid-point coverage through the 'Utilities' menu. The computed results were analyzed through display or query in the integrated system.

## **Parameter Identification**

Parameter identification in ground-water modeling mainly deals with parameterization and methods of parameter estimation. Parameterization is a procedure for reducing the parameter dimension for use in numerical schemes and has a significant effect on the "well-posedness" of the inverse problem. Parameter estimation is based on the selected model parameterization to estimate unknown parameters. In practice, the zonation method is the most widely used for estimation. The flow region is divided into a number of homogeneous and isotropic zones for model parameterization. The optimal value of the parameter(s) in each zone can be obtained through an inverse approach. However, setting up the zones optimally and effectively is a difficult problem. Sun and Yeh (1985) noted that an incorrect zonation pattern can lead to large errors in estimated parameter values. One way to improve the zonation method is to estimate the parameter structure and parameter values jointly to avoid both overparameterization and a priori zonation. Eppstein and Dougherty (1996) presented a method to simultaneously estimate transmissivities and zonation structure by combining an extended Kalman filter and an iterative partitional cluster algorithm. Even so, the weakness of the method is that the valuable geological structure information obtained from well logs is not directly included in parameter identification.

In this study, the geological structure method presented by Sun et al. (1995) was used for parameterization, and the unknown parameters were obtained by minimizing the sum of squared errors between the computed and observed water level. The parameter estimation package PEST (Doherty et al. 1994) was utilized to achieve the optimization by the Gauss-Newton-Marquardt method (Draper and Smith 1981). Sun et al. (1995) discretized the flow region of interest into a number of triangular prisms; rectangular blocks were used in the Deerfield area study. The main advantages of this method are that the lithologic well-log data can be incorporated into the inverse approach, and that the unknown model parameters, namely, hydraulic conductivity and storativity, are directly related to the different geological materials found in the aquifer. Therefore, the parameter dimension can be simplified to the number of geological materials.

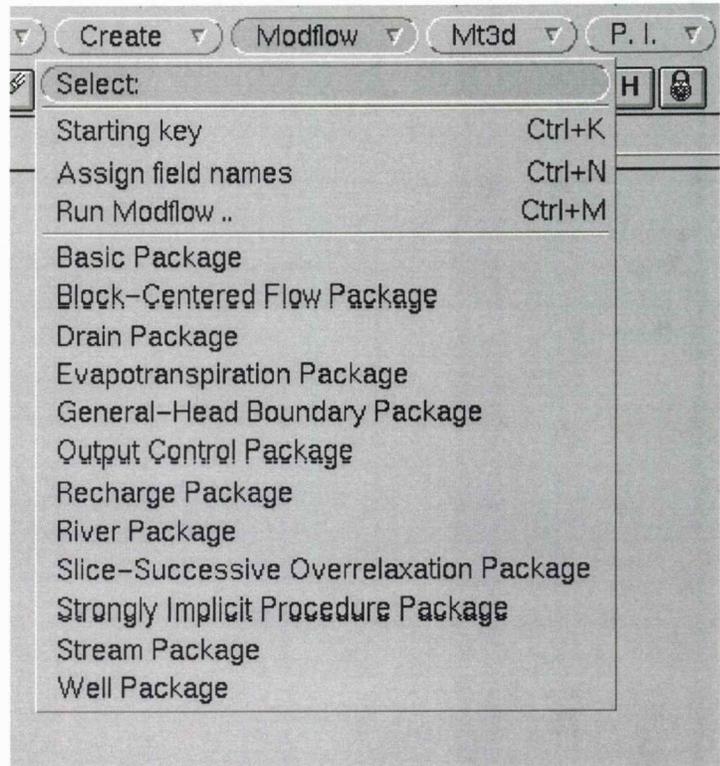
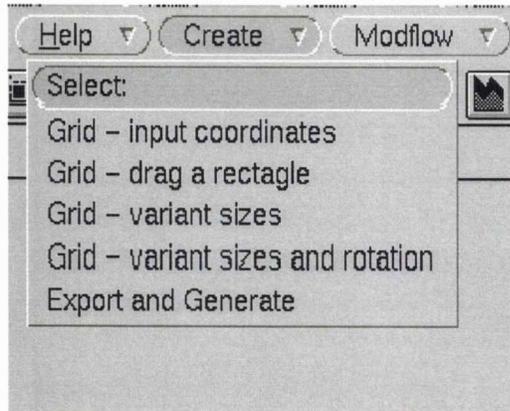


Figure 19. The MODFLOW and MT3D menus in the integrated modeling system.

The geologic information (composition of geological materials and the thickness of each material at each well location) came from an analysis of lithologic well logs. The thickness of each material at each model grid was estimated through a universal kriging method. The aquifer system was first discretized into a number of model layers; these layers were then divided into a number of rectangular blocks. Each block contained some or all of the geological materials found in the aquifer, with varying thickness generated from the spatial interpolation.

The thickness-weighted distributed parameters  $K_H$ ,  $K_V$ , and  $S$  were estimated for each block, with known  $K^n$  and  $S^n$ , by the following equations:

$$K_H(x_{ijk}) = \sum_{n=1}^{N_{ijk}} b_{ijk}^n K^n / b_{ijk} \quad (1)$$

$$K_V(x_{ijk}) = b_{ijk} / \sum_{n=1}^{N_{ijk}} (b_{ijk}^n / K^n) \quad (2)$$

$$S(x_{ijk}) = \sum_{n=1}^{N_{ijk}} b_{ijk}^n S^n / b_{ijk} \quad (3)$$

where

$K_H = K_x = K_y$ , the horizontal hydraulic conductivities in x and y directions are assumed to be equal,

$K_V = K_z$ , the vertical hydraulic conductivity,

$x_{ijk}$  = the identification of a block in which i, j, and k indicate the number of the row, the column, and the model layer, respectively,

$N_{ijk}$  = the number of geological materials in the block,

$b_{ijk}^n$  = the thickness of the nth material in the block, where  $n = 1, 2, \dots, N$ ,

$$b_{ijk} = \sum_{n=1}^{N_{ijk}} b_{ijk}^n,$$

$K^n$  = the hydraulic conductivity associated with the nth geological material,

$S^n$  = the storativity associated with the nth geological material.

The purpose of the inverse approach was to solve for the unknown parameters  $K^n$  and  $S^n$  in this study. Equations 1-3 were incorporated into a FORTRAN program MOPS (Tsou 1998), which links PEST and MODFLOW to compute the unknown parameters. After obtaining the optimal hydraulic conductivities and storativities for the geological materials, the distribution of hydraulic conductivity and storativity of the model grid for each model layer were generated using Equations 1-3. This parameter identification procedure was integrated within the user interface.

## Ground-Water Flow Model Calibration

The first modeling step involved automated calibration for determining the optimal hydraulic conductivity and storativity values (for the geologic materials) later used in the

modeling of solute transport. The area for which water-level observations were obtained (Figure 17) is larger than that for the parameter estimation that included lithologic log data (Figure 20) because there are few water-level data available in the immediate vicinity of Deerfield. The water-level data are from winter measurements so they do not reflect local conditions of summer irrigation pumping. The year (1989) has the densest set of water-level observations (47 values) and was used for the hydraulic conductivity and storativity estimation. The interpolated contours of measured piezometric head shown as solid lines in Figure 20 indicate an east to east-northeast direction of ground-water flow. The rectangular study region in Figure 20 has an area of 28.8 km<sup>2</sup> with square grid cells 400-m on a side. The interpolated piezometric heads within this area were utilized for model calibration. The model area for flow model calibration involved only one aquifer layer because insufficient multi-level observations were available for multiple layers. Constant-head boundaries were assigned to the edges of the study area. The time step for the numerical simulation was 15 days. Additional modeling details are in Tsou (1998) and Tsou et al. (1997).

The method of parameter identification described above was used to estimate the hydraulic properties of the aquifer. The basic assumption in this method is that the same geological material has the same hydraulic property throughout the study area. Five divisions of the geological materials contained in the 24 lithologic records for the wells were used (fine gravel, coarse sand, fine sand, silt, and clay) based on Young et al. (2000). The initial ranges of hydraulic conductivity and specific yield corresponding to these geological materials were selected from Freeze and Cherry (1979). Based on the well-log data, the thickness of each classified material was estimated at each cell by kriging. An example of the estimated thickness distribution for fine gravel in the study area is shown in Figure 21. The variation in the gray shades shows the nonuniform spatial variation of the estimated thickness of fine gravel. Dark shades indicate areas of greater thickness and light shades represent locations of smaller thickness. The estimated thickness distributions for the other four classifications of lithologic materials are in Tsou (1998).

The estimated thickness distributions for the five geological materials comprised the input for the program MOPS. The links of this program to MODFLOW and PEST in the integrated system automated the computation of the optimal hydraulic conductivity and specific yield for each geological material. The optimal parameter values minimized the sum of squared deviations between the computed piezometric heads shown as dashed lines and the interpolated values represented as solid lines in Figure 21. The optimal hydraulic conductivity and specific yield for the five geological materials are listed in Table 3.

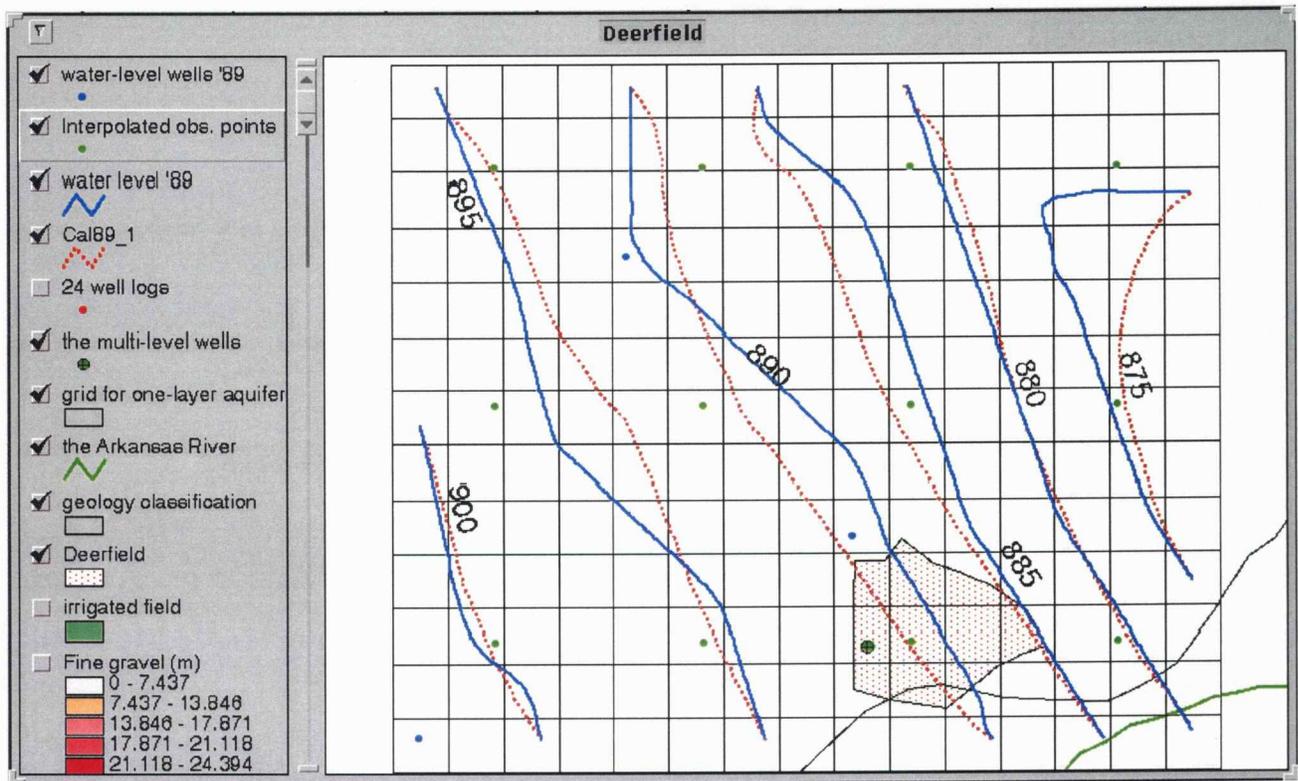


Figure 20. The water-level observation points and isolines for observed and computed water levels.

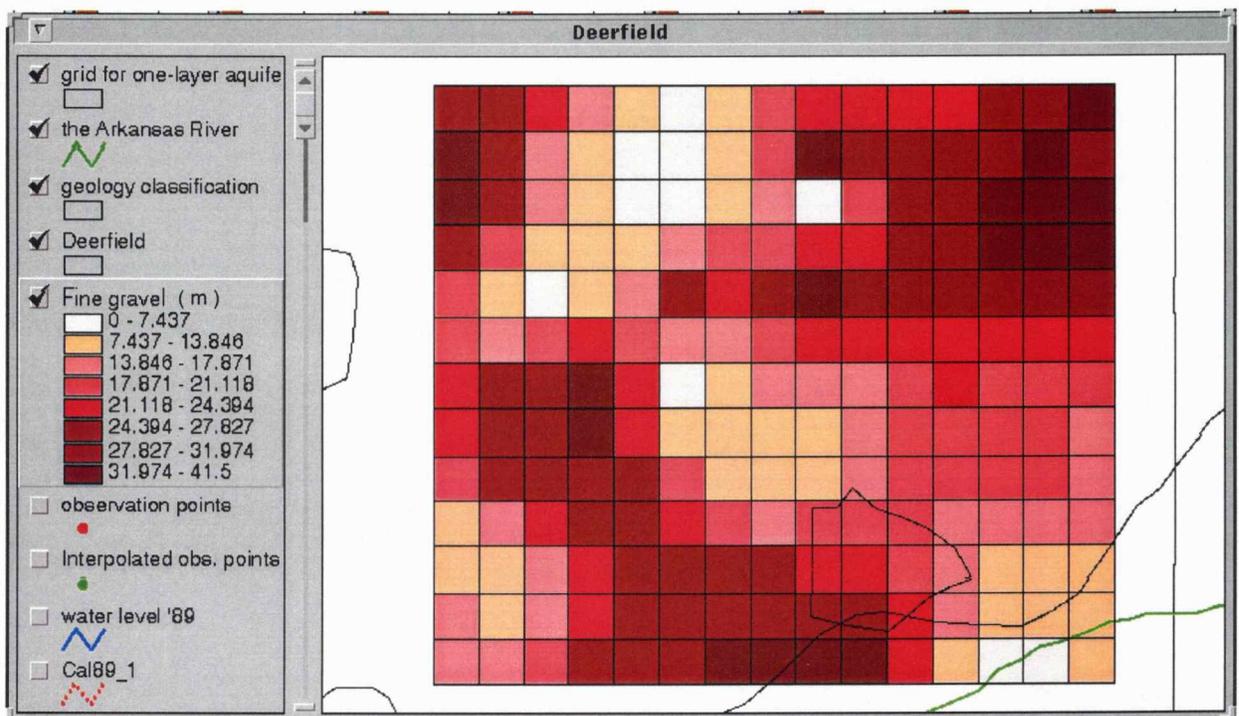


Figure 21. The estimated thickness distribution for the fine gravel classification, one of the 5 divisions of the geological materials.

Table 3. The optimal values of hydraulic conductivity and specific yield for the five classifications of geological materials in the unconfined aquifer.

Geological materials	Hydraulic conductivity (m/day)	Specific yield
Fine gravel and very coarse sand	90.0	0.30
Coarse sand and medium sand	8.64	0.30
Fine sand and silty sand	0.20	0.25
Silt and sandy clay	0.003	0.15
Silty clay and clay	5.3E-5	0.01

### Boundary Conditions and Parameters for Saline Water Modeling

The area of immediate interest for contaminant transport is bounded by the heavy black line in the center of Figure 22. Fields (shaded in Figure 22) irrigated currently or in the past with Arkansas River water, the source of the saline water, adjoin the western and northern boundaries of the area. The conceptual model involved the downward flow of saline water seepage from the diversion canals and ditch-irrigated fields into the main aquifer (Whittemore et al., 1999; Whittemore, 2000b). A portion of the downward flow could be relatively rapid because the coarse gravel packs of the irrigation wells extend to the surface or near surface (Whittemore and Butler, 1997a, 1997b; Whittemore, 2000b). The areal vertical migration depends on the thickness and continuity of clay layers in the aquifer. Once in the main aquifer, the saline water could flow laterally within the aquifer in the direction of subregional hydraulic-head gradient. Water-quality data and sulfate mass budgets indicate that the shallow ground water (such as above perching clay layers) should have high salinity. The salinity in the main aquifer can vary significantly due to retardation of downward salinity movement by clays in the heterogeneous system. An observation well site with 5 separate screened intervals was installed by the Kansas Geological Survey within Deerfield (Figure 20) for determining the salinity distribution in this area (Whittemore et al, 2000).

The aquifer was divided into two layers for the contaminant transport model based on water-quality data and lithology for the area. In addition, the two-layer division considered the depth below which the municipal wells are screened as layer 2. Sulfate concentrations of 1200 mg/L and 500 mg/L were assumed for layers 1 and 2, respectively, at the boundaries adjoining the ditch-irrigated fields based on water-quality data for the area and salinity budgets. An initial sulfate concentration of 800 mg/L was used for layer 1 as indicated by data from the multi-level observation well site at Deerfield. The initial sulfate concentration for the Deerfield area before salinity contamination was near 100 mg/L as indicated by the early part of the long-term record of water quality for the public water supply (Figure 18).

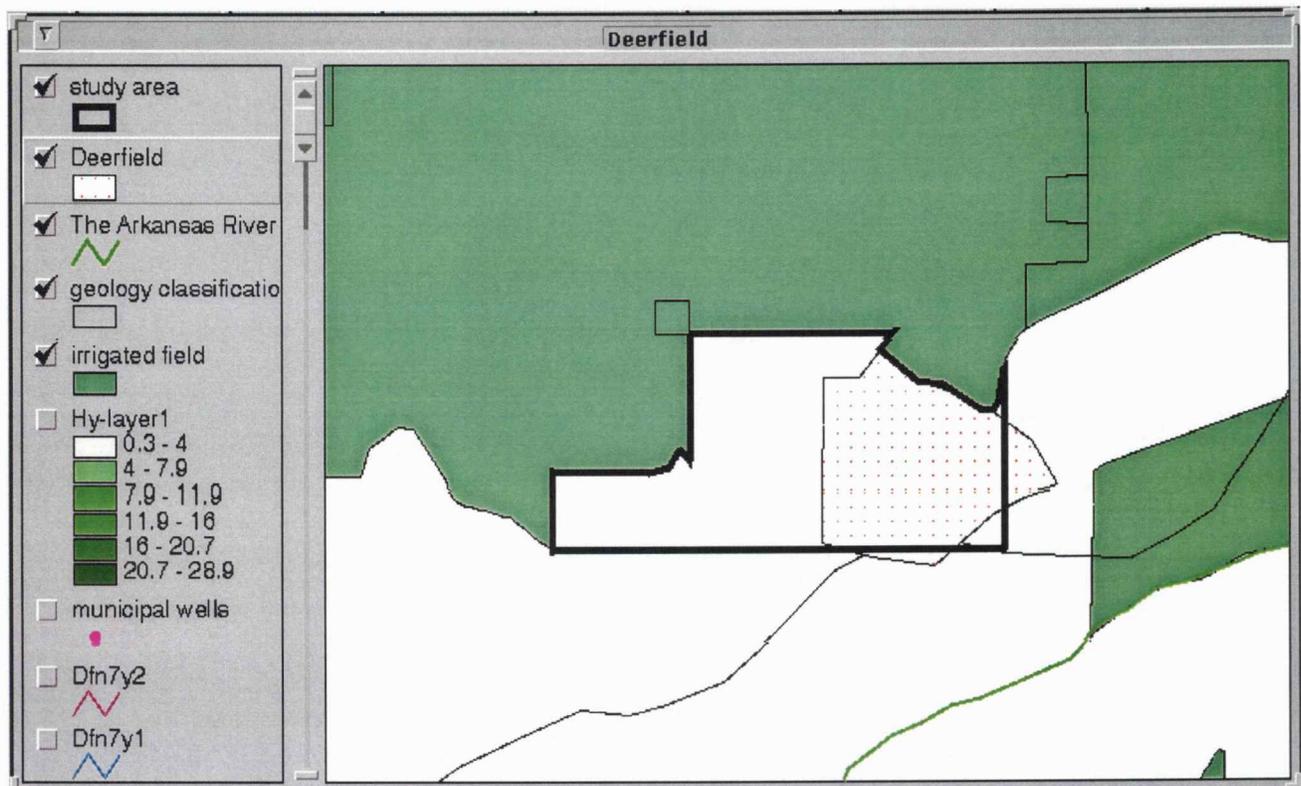


Figure 22. The study area for the simulation of saline water migration and the adjacent fields irrigated with water diverted from the Arkansas River.

The modeled area within the thick black line composing the irregular polygon in Figures 22-26 is 2.5 km<sup>2</sup>. Grid cells within the modeled area are 25-m squares, a size meeting the requirement for numerical accuracy of the solution. The simulation time was 1971-1997. The year 1971 represents the approximate beginning of substantial declines in the water level of the main part of the High Plains aquifer in the area due to increased pumping by irrigation wells (see subsection on water levels in conceptual model section above). The assumption was that the water-level decline allowed saline water to penetrate to the main aquifer. By the mid-1970's, the water levels in the main aquifer fell below the bottom of the upper aquifer and generated a substantial downward head gradient (Dunlap et al. 1985). The upper aquifer is a zone that is separated from the main aquifer by lower permeability sediments in some areas.

Annual measurements of piezometric heads at well sites within the area of Figure 17 exist for the 1971-1997 period. The piezometric heads at the boundary cells of the transport model area are values interpolated from the observed annual measurements. Because multi-level observations are not available across the model area for the two layers, the piezometric heads at the boundaries for the two layers were assumed to be the same. The assigned piezometric heads for the boundary cells were assumed to remain constant throughout a year but vary for different years in the simulation. Pumping by irrigation wells occurs in the region around Deerfield and could cause local seasonal and year-to-year variations. However, the local irrigation pumping should not significantly affect the long-term subregional migration of salinity based on the consistency in the pattern of hydraulic head contours across the region on a several-year basis.

In contrast to the seasonal operation of irrigation wells, pumping from the municipal wells of Deerfield continues throughout the year. A constant pumping rate was assumed for the three municipal wells during each particular year of the simulation period based on the total pumping of each well for each year. The pumpage records for the municipal wells are available after 1989. We assumed annual pumpages for the 1970's and 1980's that were one-third and one-half, respectively, of the total pumpage for 1996 based on the trend of generally increasing water use per person and population growth in Deerfield. The pumpages of the three municipal wells for 1996 were 51 m<sup>3</sup>/day, 213 m<sup>3</sup>/day, and 320 m<sup>3</sup>/day. The municipal wells pump from layer 2 in the model.

A TIN (Triangulated Irregular Network) interpolation of the 24 lithologic logs was used to determine the thickness distributions for the five geological materials in the two model layers. The hydraulic conductivity and specific yield distributions were obtained for the two layers by applying the optimal hydraulic conductivities and specific yields obtained previously to Equations 1 and 3, based on the assumption that the same geological material has the same hydraulic conductivity and storativity regardless of location. Figures 23 and 24 illustrate the resultant distribution of hydraulic conductivity for layers 1 and 2, respectively. The darker shades represent areas of higher hydraulic conductivity and the lighter shades areas with lower conductivity. The distribution of hydraulic conductivity for layer 1 generally has lower values across the model area except for greater conductivities in the westernmost extension and near the south-central boundary of the model polygon. The distribution of vertical hydraulic

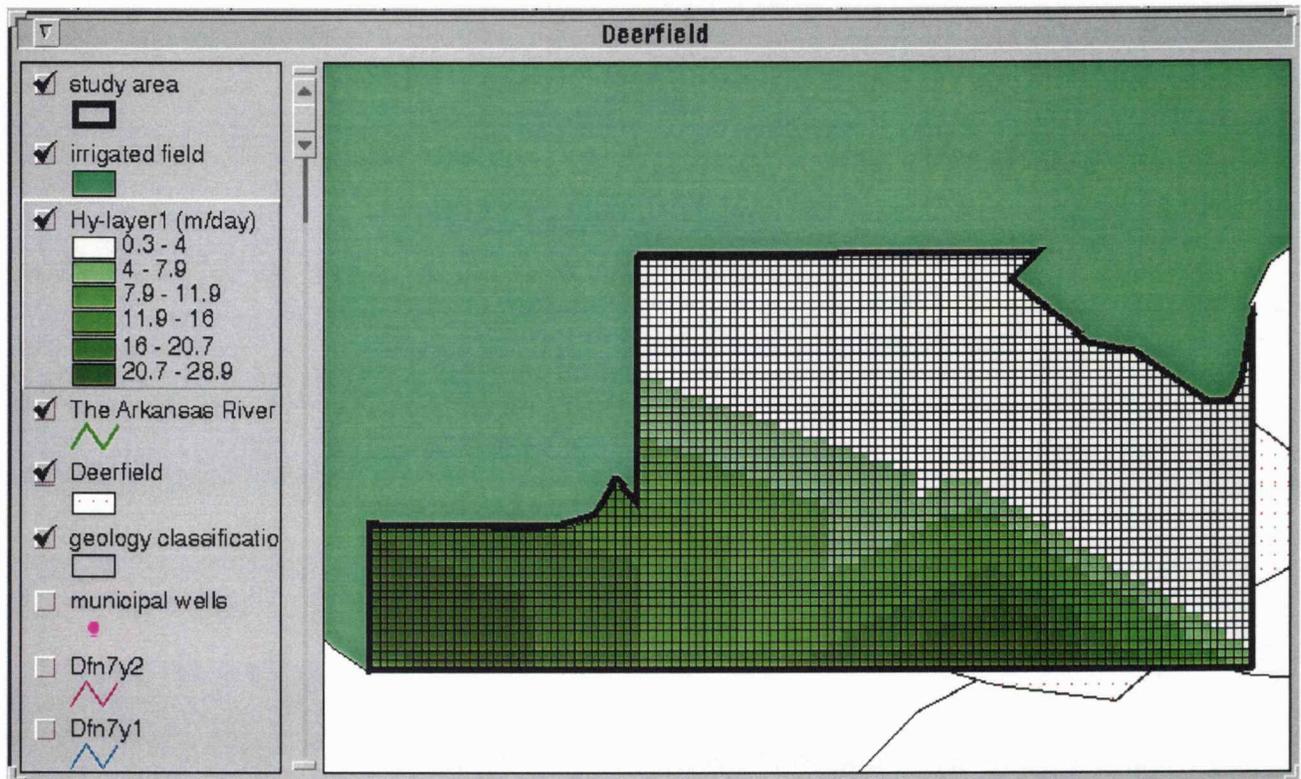


Figure 23. The estimated distribution of the horizontal hydraulic conductivity for layer 1 in the model.

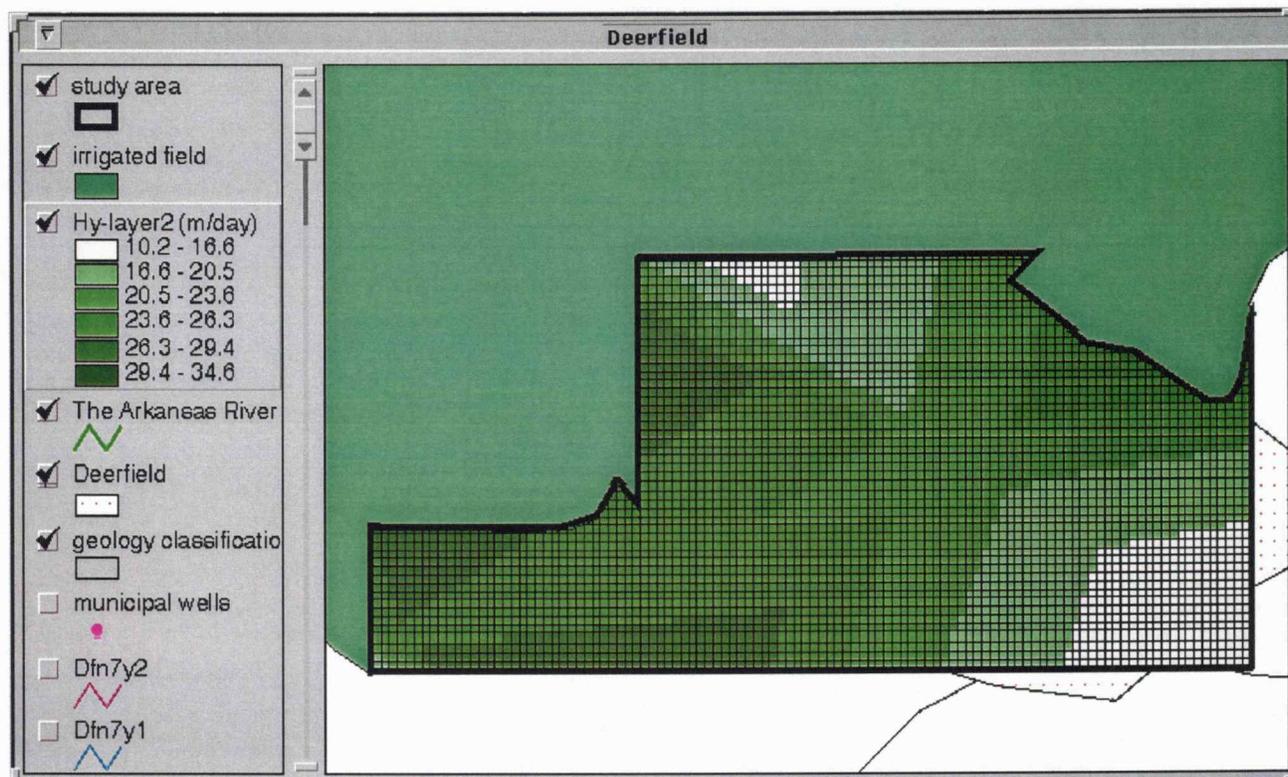


Figure 24. The estimated distribution of the horizontal hydraulic conductivity for layer 2 in the model.

conductivity was determined using Equation 2. Because the difference in the vertical values across the model area is insignificant, an average value of 0.000003 m<sup>2</sup>/day was selected for the vertical conductance.

Butler and Healey (1999) conducted slug tests for the multi-level observation wells in Deerfield (Figures 17, 25, and 26). The average hydraulic conductivities measured for observation wells screened in layers 1 and 2 were approximately 9 m/day and 5.5 m/day, respectively. The conductivities from the slug tests should be considered as low-end values due to the possibility of incomplete development inherent for wells. In comparison, the hydraulic conductivities from the computed distribution were about 16 m/day for layer 1 and 21 m/day for layer 2 (Figures 23 and 24) at the location of the observation well site. Agreement within a factor of 4 is considered good considering the uncertainty of the conductivity distribution at the scale of the available well logs.

The values of the longitudinal dispersivity and horizontal dispersivities for the model were 5 m and 0.5 m, respectively, based on the field data analyzed by Gelhar et al. (1992). The vertical transverse dispersivity is typically an order of magnitude smaller than the horizontal transverse dispersivity (Gelhar et al. 1992); therefore, the use of 0.05 m was appropriate. An effective porosity of 25% was selected based on typical values in the literature for similar aquifer systems. The values of the parameters used in the simulation are summarized in Table 4.

Table 4. Values of variables and parameters used in the numerical simulation.

Aquifer and other parameters	Source or value
horizontal hydraulic conductivity in layer 2	Figure 7
vertical conductance	0.000003 m <sup>2</sup> /day
specific yield	Figure C.1 in Tsou (1998)
storage coefficient	S <sub>c</sub> = 0.00002
porosity	θ = 0.25
longitudinal dispersivity	α <sub>x</sub> = 5 m
horizontal transverse dispersivity	α <sub>y</sub> = 0.5 m
vertical transverse dispersivity	α <sub>z</sub> = 0.05 m
initial sulfate concentration for layer 1	800 mg/L
initial sulfate concentration for layer 2	100 mg/L
time step	30 days
total simulation time	27 years (1971-1997)

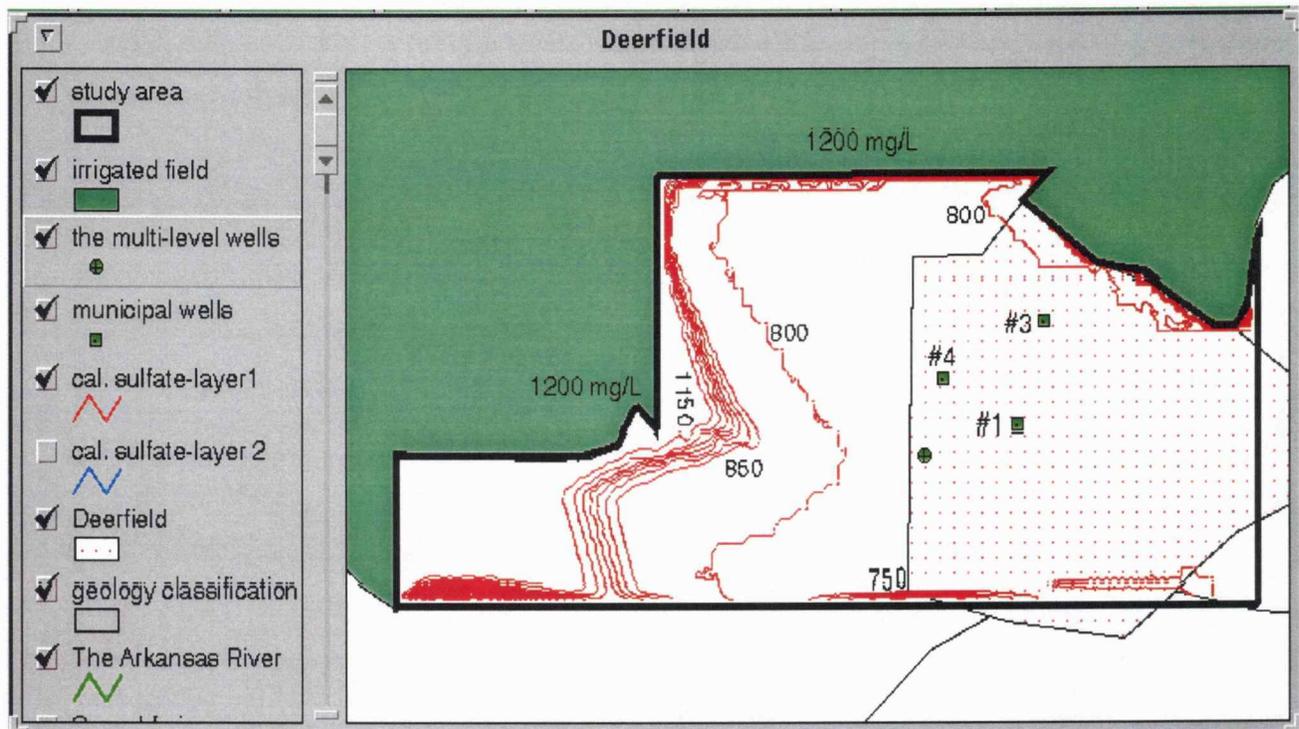


Figure 25. Isolines of the computed sulfate concentration at the end of the seventh year for layer 1 in the model.

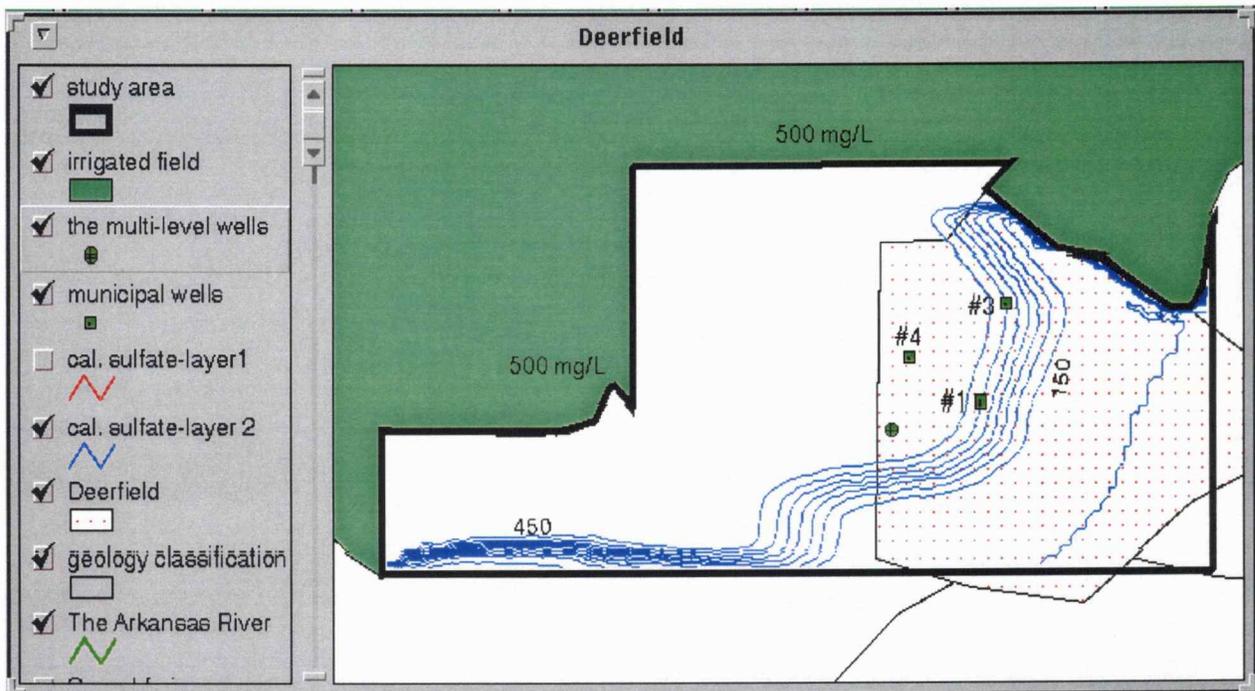


Figure 26. Isolines of the computed sulfate concentration at the end of the seventh year for layer 2 in the model.

## Results and Discussion

Figures 25 and 26 show the computed salinity distributions for layers 1 and 2, respectively, at the end of the 7th year of simulation. The municipal wells pump from layer 2. The isoline with sulfate concentrations close to the fixed boundary value of 500 mg/L in layer 2 covers over one half of the model area, has passed municipal well 4, and has nearly reached municipal wells 1 and 3 at the end of the 7 years. The large area of low hydraulic conductivity in layer 1 causes relatively slower spreading of the saline water than that in layer 2. Only about the western one-fourth of the model area contains sulfate concentrations greater than 850 mg/L at the end of 7 years in the simulation.

Figure 18 illustrates the break-through curve for sulfate concentration in layer 2 from the contaminant transport simulation at the location of municipal well 3 (Figure 26) in comparison with the observed water quality for the public water supply of Deerfield. The simulated curve shows a steep rise in the sulfate content from the beginning of 1977 through 1978. As shown in this curve and Figure 26, the simulation indicates that it takes about 7 years for the salinity front initiated within the lower aquifer at the model boundary to reach the municipal well location. The observed sulfate concentrations for the public water supply during 1949-1974 in Figure 18 are based on samples collected by the city from various of the 3 wells each year and sent to the Kansas Department of Health and Environment. State regulations changed as to what water to submit, thus, water samples during 1975-1992 were from the distribution system and could represent primarily one well or a mixture or more than one well. More recently, the KGS has sampled and analyzed the well waters. The sulfate data represent the salinity of the water samples just as for the salinity of the river water (and irrigation diversions) because the chemistry is similar.

The small variation in measured sulfate content up to the mid-1970's in Figure 18 indicates little effect of diverted saline river water on the ground water in the lower part of the aquifer where the municipal wells are screened. The first start of salinity increase in the municipal supply during the mid-1970's generally fits the timing of the simulated break-through curve. However, the time for the substantial increase to a new, much higher sulfate content took longer than illustrated by the simulated break-through curve. Comparison of the simulated and actual salinity change indicates that the main downward influx of saline water into the aquifer probably did not start until the mid-1970's when the water level dropped below the bottom of the upper aquifer zone, rather than at the beginning of the substantial water-level decline. The slower rate of increase relative to the break-through curve may also be related to differences between the model and actual hydraulic conductivity distributions. In addition, the particular mixture of well waters pumped during the period of distribution system sampling could affect the apparent changes. The more heavily pumped wells 3 and 4 currently yield water with sulfate concentrations from over 400 to over 500 mg/L. Finally, irrigation pumping and the effect of high stage in the Arkansas River to the south of Deerfield might affect the short-term rate of ground-water flow and salinity transport.

The simultaneous consideration of data from water-level measurements, well logs, hydraulic tests, and geophysical tomography was important to the numerical modeling efforts

because it allowed better approximation of actual conditions. The integrated GIS-simulation system with automated model calibration proved to be a good approach for the study. The incorporation of parameter identification and automated calibration in the integrated GIS and modeling system improved the capability and efficiency of the ground-water flow modeling. The usual parameterization approach, the zonation method, used in models is mainly for two-dimensional simulations because it lumps the vertical variation into the averaged property zones. This approach makes it difficult to handle a layered model with numerical modeling and to directly include the lithologic information from well logs. The geological structure method presented by Sun et al. (1995) is a better approach for including lithologic log data and displaying the parameter distribution without incurring the ill-posedness of the inverse problem. However, an optimal classification for geological materials is important. The optimum number of classifications can be determined through sensitivity analysis and must be based on the number of water-level observations because too many unknown parameters would make the inverse problem highly nonunique. The five geologic classifications in the modeling in this paper appeared to work well in the practical application.

The application of the integrated system to simulation of salinity transport helped improve and provide a more quantitative basis for the conceptual model of contamination of the public water supply in the High Plains aquifer at Deerfield. The time for the breakthrough curve of sulfate transport since the start of modeling generally matches the initial increase in sulfate concentration in waters from the municipal supply. However, the slower rate of observed sulfate increase, and the later time of the greatest observed rate of increase, suggest a later start of substantial downward movement of shallow saline water into the main part of the aquifer in the study area than was assumed in the initial conceptual model. This is probably related to the abundance of clays in the aquifer in the area.

# REGIONAL MODELING OF THE UPPER ARKANSAS RIVER CORRIDOR

## Overview of Model Components

The following sections describe the numerical simulation of regional ground-water flow in the upper Arkansas River corridor. The direction and rate of movement of particles following the ground-water flow paths simulates where saline water from the river and in the alluvial and High Plains aquifers will move in the future. Two periods were simulated to illustrate the contrast in the system caused by the substantial water-level decline in the High Plains aquifer. The first simulation is for 1940 and represents a low-level of ground-water development in the corridor. The second simulation is for the period of the 1990's that represents the current conditions in the river corridor.

Inflows to the modeled ground-water system consisted of areal recharge from precipitation, recharge from irrigation canals and below irrigated fields (for both surface- and ground-water irrigation), ground-water flow into the area simulated with active grid cells, recharge from the Arkansas River to the alluvium, and leakage from the alluvial aquifer to the underlying High Plains aquifer. Outflows from the ground-water system included water pumped from the aquifers, discharge from the alluvial aquifer to the river, and ground-water flow across model boundaries. Evapotranspiration losses from irrigation were accounted for in the difference between river diversions and ground-water recharge from the canals and ditch irrigation, and between water pumped for irrigation and the recharge of some of the water applied to fields. Evapotranspiration losses from the river valley were not specifically incorporated into the model but are indirectly included in the decreases in river flow that result primarily from seepage into the alluvial aquifer.

## Numerical Modeling Methods

### Interactive ArcView and MODFLOW Interface for Ground-Water Flow Simulation

Numerical simulation for ground-water modeling usually involves handling large input and output data sets. A geographic information system (GIS) provides an integrated platform to manage, analyze, and display disparate data and can greatly facilitate modeling efforts in data compilation, model calibration, and display of model parameters and results. Furthermore, GIS can be used to generate information for decision-making through spatial overlay and processing of model results.

Various commercial and public-domain systems involving the integration of GIS and ground-water models were examined for use in simulating ground-water flow and salinity transport in the upper Arkansas River corridor. These included the Groundwater Modeling System (GMS) developed at Brigham Young University. At the start of this examination, the commercial systems could not nor did not incorporate powerful GIS software. Although much additional GIS capability has been subsequently built into these systems, the GIS capabilities within the systems are not mature enough to provide the manipulation sometimes needed for complex spatial data. In addition, because publicly shared GIS data are usually in

the format of some specific GIS software such as ArcView, it would be easier to edit these data within the GIS environment. Those modeling interface systems that allow users to create custom-built interfaces distributed as add-ons, such as Argus (Argus Interware, Inc.), do not have as powerful GIS capabilities as the windows-based GIS (ArcView).

A decision was made to integrate a widely-used GIS software (ArcView) with a commonly applied ground-water flow model. ArcView is the most widely-used, windows-based GIS software that provides a robust user-friendly interface to facilitate data handling and display. An ArcView interface for the ground-water flow model MODFLOW was constructed as an extension that allows use of the windows environment. An extension is an add-on program to ArcView that provides additional specialized functions. MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) is a computer code developed by the U.S. Geological Survey (USGS) that is probably the most widely-used program for ground-water flow simulation. The MODFLOW-ArcView integration includes a user-friendly interface to allow easier use by water management scientists. The extension provides for pre-processing of spatially distributed (point, line, and polygon) data for model input and post-processing of model output. An Object Data Base is used for linking user dialogs and model input files. The ArcView interface utilizes the capabilities of the 3D Analyst extension. The advantages of this development are that the open source code will allow further development for special applications by modelers, and the integration with ArcView can serve modelers, who are also ArcView users, as a useful tool in ground-water modeling.

A description of the interactive interface is included in a paper published in the Journal of Hydrologic Engineering (Tsou and Whittemore, 2001). A copy of the manuscript is included as Appendix A.

### **Particle Tracking by MODPATH**

Computed ground-water movement path and source areas were calculated with the USGS computer code MODPATH (Pollock, 1994). MODPATH can be used in conjunction with MODFLOW to create maps of travel paths and source areas of ground water in an area modeled by MODFLOW. MODPATH is a particle-tracking postprocessing package that was developed to compute three-dimensional flow paths using output from steady-state or transient ground-water flow simulations by MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model. The particle tracking package consists of two Fortran computer codes: (1) MODPATH, which calculates particle paths, and (2) MODPATH-PLOT, which displays results graphically.

MODPATH uses a semi-analytical particle tracking scheme that allows an analytical expression of the particle's flow path to be obtained within each finite-difference grid cell. Particle paths are computed by tracking particles from one cell to the next until the particle reaches a boundary, an internal sink/source, or satisfies some other termination criterion. Both steady-state and transient ground-water flow systems can be analyzed with MODPATH. MODPATH is designed to work with MODFLOW. The number of new data files required by

MODPATH is minimized by making use of MODFLOW data files whenever possible. Output from MODPATH is in the form of a variety of numerical data files containing spatial coordinates of particles and travel time.

The MODPATH package has been widely applied to MODFLOW-based ground-water flow simulation studies. It is useful as a visualization tool to help understand flow patterns in simulated ground-water flow systems. It also has been widely used to delineate sources of water to discharge sites and aquifers in systems simulated with MODFLOW.

The particles tracked by MODPATH “are stopped whenever they reach points of termination or whenever the cumulative tracking time equals a maximum value specified by the user (Pollock, 1994, pp. 3-18). A particle can terminate when it:

1. reaches an external boundary or internal sink/source cell that captures the particle,
2. enters a cell with a special zone code that is designated as a stopping point,
3. is stranded in a dry cell, or
4. is still active at a user-specified stopping time.

“Particle pathlines are always terminated when (1) they reach a cell face that is a boundary of the active grid, or (2) they enter a cell with a strong sink from which there is no outflow to other cells... For cells with weak sinks, an arbitrary decision must be made by the user about whether to stop particles. MODPATH provides three options:

1. particles pass through cells with weak sinks.
2. particles are stopped when they enter cells with weak sinks.
3. particles are stopped when they enter cells where discharge to sinks is larger than a specified fraction of the total inflow to the cell.”

Pollock (1994) also states that “in transient simulations, particles also can be stranded in cells that go dry. Stranded particles are considered to be terminated and are labeled as "stranded" in the endpoint file.”

MODPATH prompts the user to select one of the three options for particle pathlines. The first option was used for the regional modeling of the Arkansas River corridor. The grid cell size (square with 0.5 mi sides) is relatively big due to the large size of the regional model. Thus, because most wells do not pump constantly throughout the year, the average annual areas of influence of the wells are probably not large enough to intercept all of the regional flow entering the cells.

Another option provided in MODPATH for both steady-state and transient systems allows the user to specify a maximum value of tracking time at which all particle tracking computations will be stopped. Particles that are still in the flow system when the maximum tracking time is attained are flagged as "active" particles in the endpoint file (Pollock, 1994). The option for specifying the maximum value of tracking time was used to limit the paths to 40 years in the regional modeling for the 1990's in the Arkansas River corridor.

The following paragraphs quoted or slightly modified from pages 2-17 and 2-18 of the MODPATH manual (Pollock, 1994) describe limitations of the program that must be understood if it is to be used effectively. They also explain well limitations of modeling in general as related to flow paths. "These limitations are related to (1) underlying assumptions in the particle tracking scheme, (2) discretization effects, and (3) uncertainty in parameters and boundary conditions. The semi-analytical particle tracking method used in MODPATH is valid only for the simple linear velocity interpolation scheme... The method is a consistent approach for computing and interpolating velocities from intercell flow rates for the standard 7-point, three-dimensional block-centered finite difference approximation of the ground-water flow equation (such as MODFLOW with the standard "block-centered flow" package). The method cannot be used to compute pathlines for other types of numerical approximations of the flow equation, such as finite element models. The accuracy of numerically-generated pathlines, and a proper interpretation of what they represent, depends on the extent to which the ground-water system can be realistically represented by a discrete network of finite-difference cells. The degree of spatial discretization in a finite-difference model influences (1) the level of detail at which hydrogeologic and system boundaries can be represented, (2) the accuracy of velocity calculations, and (3) the ability to accurately and unambiguously represent internal sinks. Often, a level of spatial discretization that is adequate for a flow simulation analysis oriented toward water supply may not be adequate for a pathline analysis. Time discretization also can be a significant source of error in transient flow simulations."

"The effect of spatial discretization on the representation of internal sinks is especially important for particle tracking analyses because of the ambiguity associated with the movement of particles through weak sink cells. These cells contain sinks that do not discharge at a large enough rate to consume all of the water entering the cell. The net result is a flow-through cell in which some fraction of the total inflow to the cell eventually flows out of the cell across one or more of the cell's faces. Pathlines computed for these cells are consistent with the assumption of a uniformly distributed sink within the cell; however, it is difficult to interpret the results of particle tracking analyses in systems with weak sink cells because:

1. There is no way to know whether a specific particle should discharge to the sink or pass through the cell. This means that individual particles will not correspond to a fixed volume of water, nor will flow tubes defined by adjacent pathlines represent a fixed quantity of flow.
2. Pathlines through weak sink cells may not accurately represent the path of any water in the system if they contain point sinks that cannot be represented accurately as being uniformly distributed throughout the cells" (Pollock, 1994).

"These problems are a direct result of spatial discretization that is too coarse. Using a finer grid may eliminate the problem by turning weak sink cells into strong sink cells that clearly correspond to discharge points for all particles entering those cells. From a practical point of view, however, it usually is impossible to entirely avoid weak sinks when simulating real systems" (Pollock, 1994).

“A common example of the weak sink dilemma occurs in two-dimensional areal simulations that account for the effect of rivers. In areal simulations, rivers often are represented as distributed sinks or sources of water within cells. In many systems, shallow ground water discharges to the river while deeper ground water flows underneath the river and discharges elsewhere. The shallow and deep flow systems cannot be distinguished from one another because of the averaging effect of the areal model; the averaging results in a flow through cell in which the river acts as a weak sink. This type of model cannot be used to quantitatively delineate the zone of contribution for recharge water to a well near a river with an underflow component because it is impossible to determine which particles discharge to the river and which pass under the river and enter the well. In spite of that important limitation, particle tracking still may be able to provide useful, but more qualitative, information about the zone of contribution to the well” (Pollock, 1994).

“Although this example illustrates the problem posed by rivers in areal models, it is only one example of how discretization can affect pathline computations. The important point is that discretization characteristics of the flow model place constraints on particle tracking analyses and the conclusions that can be drawn from them. Even when a cell contains a strong sink, the finite difference discretization in the immediate vicinity of the sink will not be adequate to accurately describe the pattern of flow near the sink. The only way to improve the accuracy of pathline computations near internal sources and sinks is to refine the grid of the finite-difference flow model” (Pollock, 1994).

The above limitations “relate to discretization effects and to underlying assumptions of the methodology. In fact, the most important limitation in any ground water analysis is the uncertainty in boundary conditions and hydrogeologic parameters used to define the system, and the same is true for particle tracking. Models are always idealized approximations of reality. At best, a particle tracking analysis only provides information about how water moves in the idealized system described by the model. The degree to which the model accurately represents the real system places additional constraints on interpreting the results of a particle tracking analysis beyond those relating to discretization effects and limitations of the method” (Pollock, 1994).

### **Model Area, Grid, and Layers**

The area selected for modeling includes the entire corridor of the Upper Arkansas River from the Colorado-Kansas state line to the Crooked Creek-Fowler Fault zone in eastern Ford County (Figure 27). The rectangular area was selected to incorporate the extent of the alluvial trough in Hamilton and western Kearny counties, all of the ditch irrigation service areas, and the High Plains aquifer to the north and south of the river valley. The rectangle was rotated to include all these features in a minimized area to keep the number of model cells manageable, and to orient the model rows approximately along the principal axis of the ground-water flow system. Due to the rotation, small portions of the rectangle extend outside the 5 counties that the Arkansas River crosses. The most significant of the additional county areas in terms of active cells in the model is a slice of northeast Haskell County.

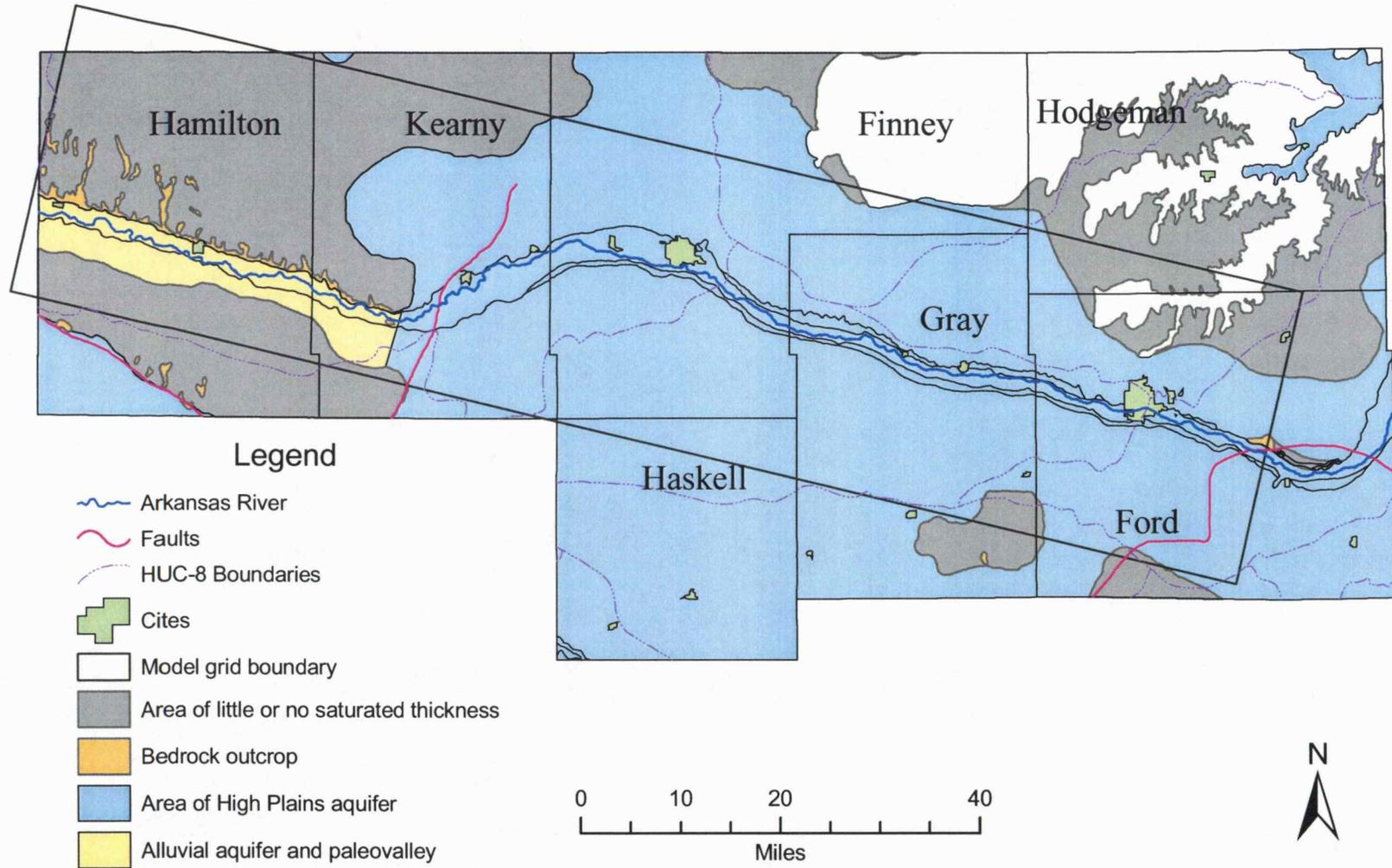


Figure 27. The location of the regional model of the upper Arkansas River corridor in southwest Kansas. The boundary of the model grid extends from the Colorado-Kansas border through Hamilton, Kearny, Finney, Gray, and Ford counties to where the Crooked Creek-Fowler Fault zone crosses under the Arkansas River. The model area also includes part of northern Haskell County and the southwest corner of Hodgeman County.

The model grid is a regular mesh of square cells that are 804.6 m (0.5 mi) on a side, giving an area of ¼ square mile or a quarter section for each cell. The base index of the grid cells is in the northwest corner 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; the base index corresponds to the top layer. Both grid and projected coordinates are in meters; the grid origin is at the southwest corner of the model area. The angle of grid rotation relative to a parallel of latitude is 12.96 deg in a clockwise direction.

The active cells in the top layer are located only within the area of the Quaternary alluvial aquifer that is present at the land surface. There are 1,421 active cells in layer one. The active cells in the second layer represent the High Plains aquifer underlying and outside the boundaries of the Quaternary alluvial aquifer. However, layer two also includes the older alluvial aquifer underlying the sand dunes south of the Quaternary alluvium boundary in Hamilton and western Kearny counties. Thus, the bedrock trough containing alluvium in Hamilton and western Kearny counties is divided into two layers of active cells as well as the area to the east of the Bear Creek Fault zone where both the alluvial and High Plains aquifers exist. The boundaries of the active cells for layer two outside the bedrock trough are the extent of the High Plains aquifer and the division between the areas of some saturated thickness and little or no saturated thickness. There are 9,313 active cells in layer two. The boundaries for the alluvial and High Plains aquifers are coverages in the aquifer database for Kansas. They are available through DASC (Data Access and Support Center) at the KGS.

### **Model Boundary Conditions and Conceptual Zones**

The ground-water simulation is applied to grid cells that are identified as active by the Ibound array in MODFLOW, subject to boundary conditions, which are given as specified heads (Dirichlet conditions) or specified flux (Neumann conditions). The Ibound array is used by MODFLOW to specify the solution domain as shown in the following table.

Cell type	Ibound	Number of grid cells, alluvium (layer 1)	Number of grid cells, High Plains (layer 2)
Active	1	1,421	9,313
Specified heads	-1	9	329
Specified no-flow (outside solution domain)	0	13,186	4,974

Grid cells specified as no-flow (Ibound = 0) represent the model area outside the solution domain, but they also represent a special case of prescribed flux (Neumann) conditions. For the Arkansas River model, the case of non-zero specified-flux is represented along certain boundaries by a component of recharge that is applied to active grid cells.

Due to its complexity, the Upper Arkansas River basin model was divided conceptually into four geographical zones that are defined in terms of the geohydrologic conditions that characterize them. The four zones, shown in Figure 28, are defined as follows:

***Zone 1 (301 active grid cells)***

The first zone comprises the Arkansas River valley from the Colorado border to the Bear Creek Fault zone, which corresponds approximately to the western boundary of the High Plains aquifer (Figure 28). Along this narrow valley, the alluvial aquifer is underlain by bedrock. This zone is represented by active nodes in both layers 1 and 2. Layer 1 represents most of the saturated thickness, while layer 2 represents a thin, bottom slice of the saturated thickness. The boundary conditions are specified by constant heads along the western boundary of the alluvial valley, and no-flow conditions on the north side of the valley (Figure 29). Active grid cells in layer 2 provide a lateral connection to the south in zone 2. Similarly, active grid cells in layer 1 are contiguous with grid cells in zone 3 to the east.

***Zone 2 (351 active grid cells)***

Zone 2 is the paleovalley with deep alluvial fill that lies directly south of zone 1 from the Colorado border to the Bear Creek Fault zone (Figure 28). This unit is not recognized as part of the High Plains aquifer, but the two units are hydraulically connected across the Bear Creek Fault. Zone 2 is represented by active model grid cells in layer 2; the grid cells in layer 1 are inactive (Figure 30). The boundary conditions include constant heads specified along the western boundary of the paleovalley. Inflows along the southern edge of the paleochannel are represented by a component of specified recharge for some of the southernmost active grid cells. The specified recharge is given by Darcy's law for approximate values of hydraulic gradient, hydraulic conductivity, and saturated thickness.

***Zone 3 (1,217 active grid cells)***

Zone 3 encompasses the Arkansas River valley from the Bear Creek Fault zone to the eastern model boundary (Figure 28). Layers 1 and 2 represent the alluvial aquifer and the underlying High Plains aquifer, respectively (Figures 29 and 30). The two units are separated by a confining layer over part of the extent of this zone. The confining layer is represented with MODFLOW by a vertical conductance that is based on the confining layer's thickness and hydraulic conductivity. Boundary conditions for Zone 3 are specified by constant heads along the eastern edge of the Arkansas River valley for both the alluvial and High Plains aquifer units. Along the northern and southern boundaries of the Arkansas River valley, no-flow conditions are specified for model layer 1, whereas layer 1 grid cells are hydraulically connected to layer 2 grid cells in zone 4.

***Zone 4 (7,841 active grid cells)***

Zone 4 includes the High Plains aquifer from its western boundary to the north, south, and east boundaries of the model area (Figure 28), and excludes the Arkansas River valley in

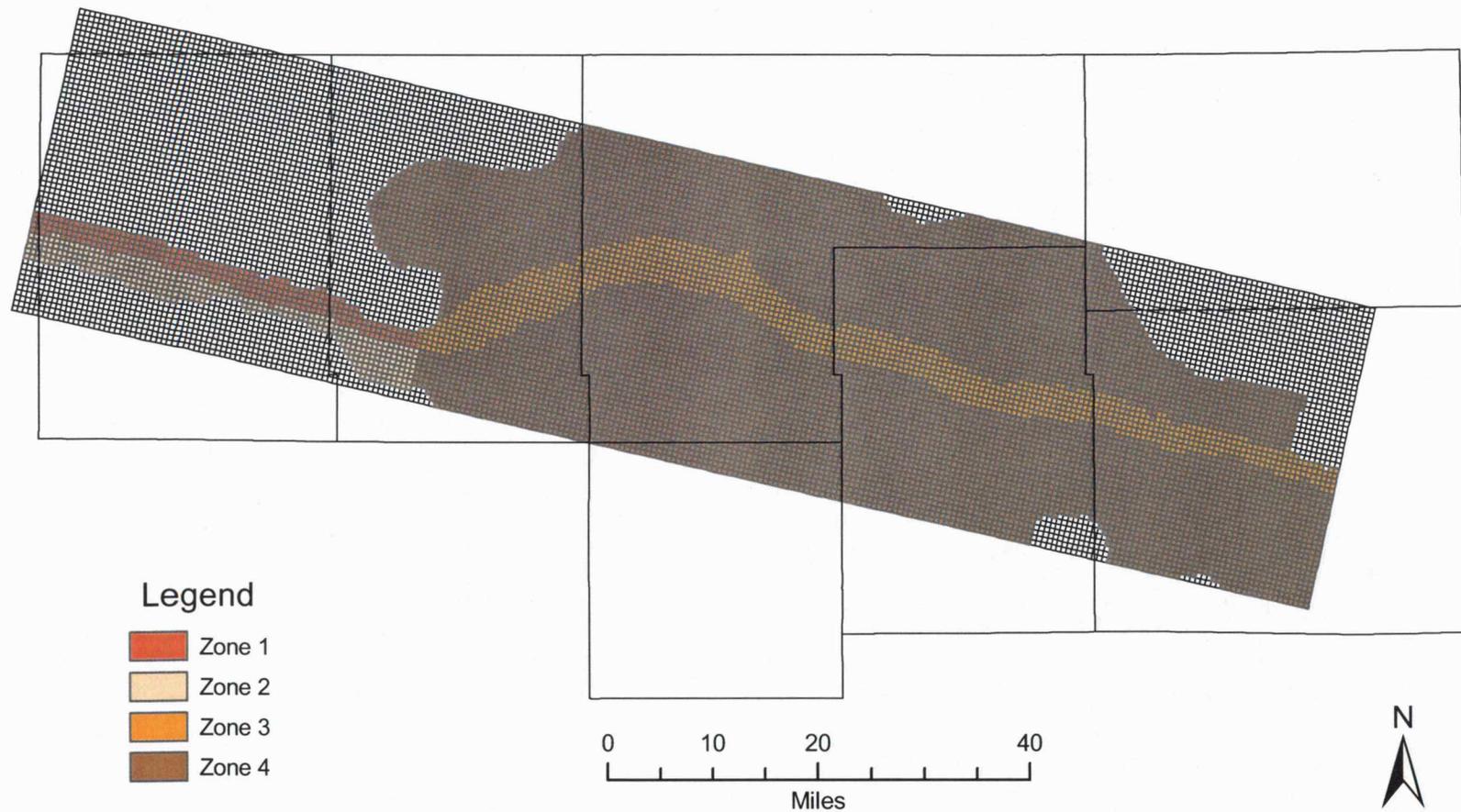


Figure 28. The four geographical zones defined according to geohydrologic conditions for the regional model. Zone 1 comprises the Quaternary alluvial aquifer of the Arkansas River valley from the Colorado-Kansas border to the Bear Creek Fault zone. Zone 2 is the paleovalley with deep alluvial fill that lies directly south of zone 1 from the state line to the Bear Creek Fault zone. Zone 3 encompasses the Arkansas River valley from the Bear Creek Fault zone to the eastern model boundary. Zone 4 is the High Plains aquifer from its western boundary to the north, south, and east boundaries of the model area.

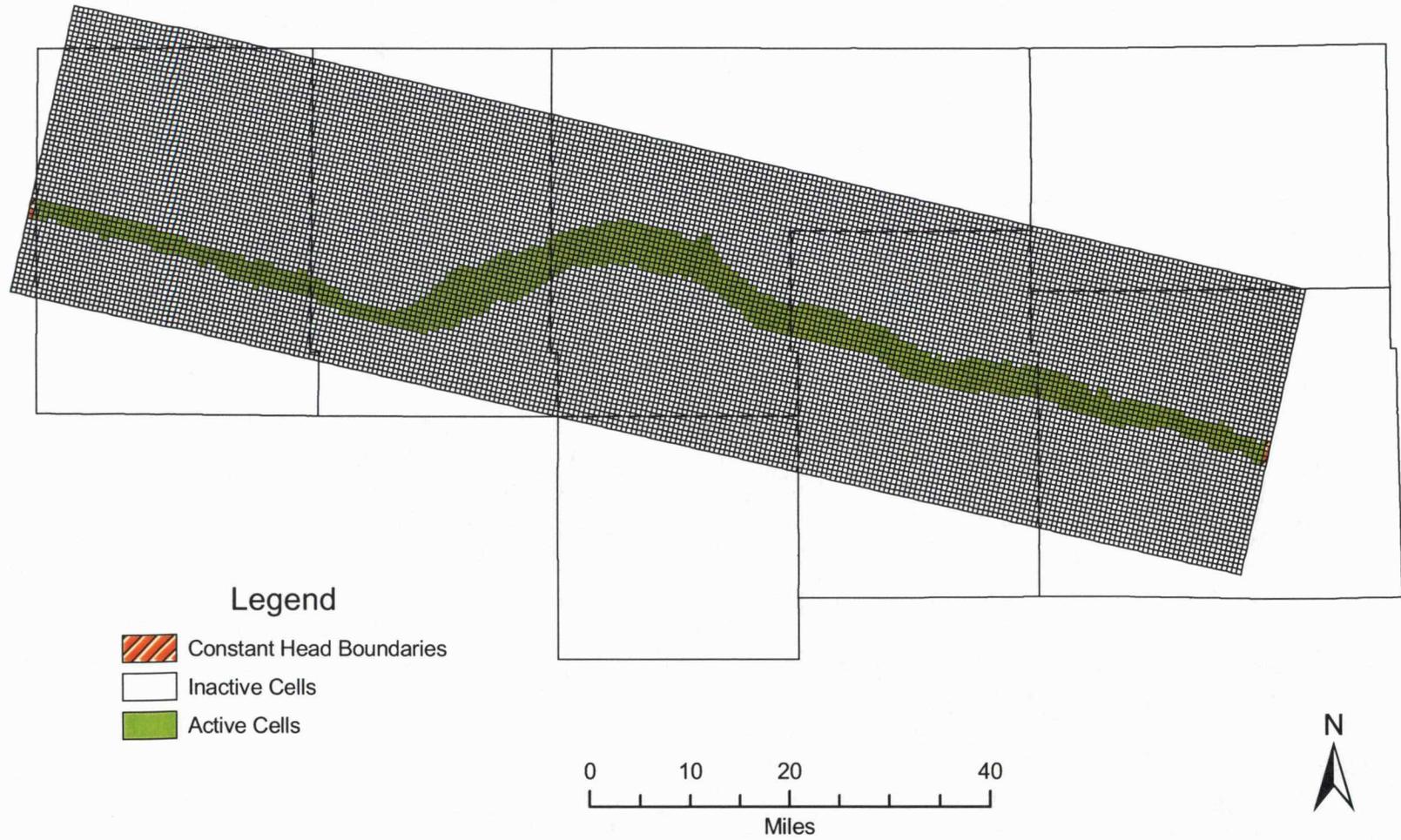


Figure 29. The location of the active and inactive cells and the constant-head boundaries in layer 1 of the regional model.

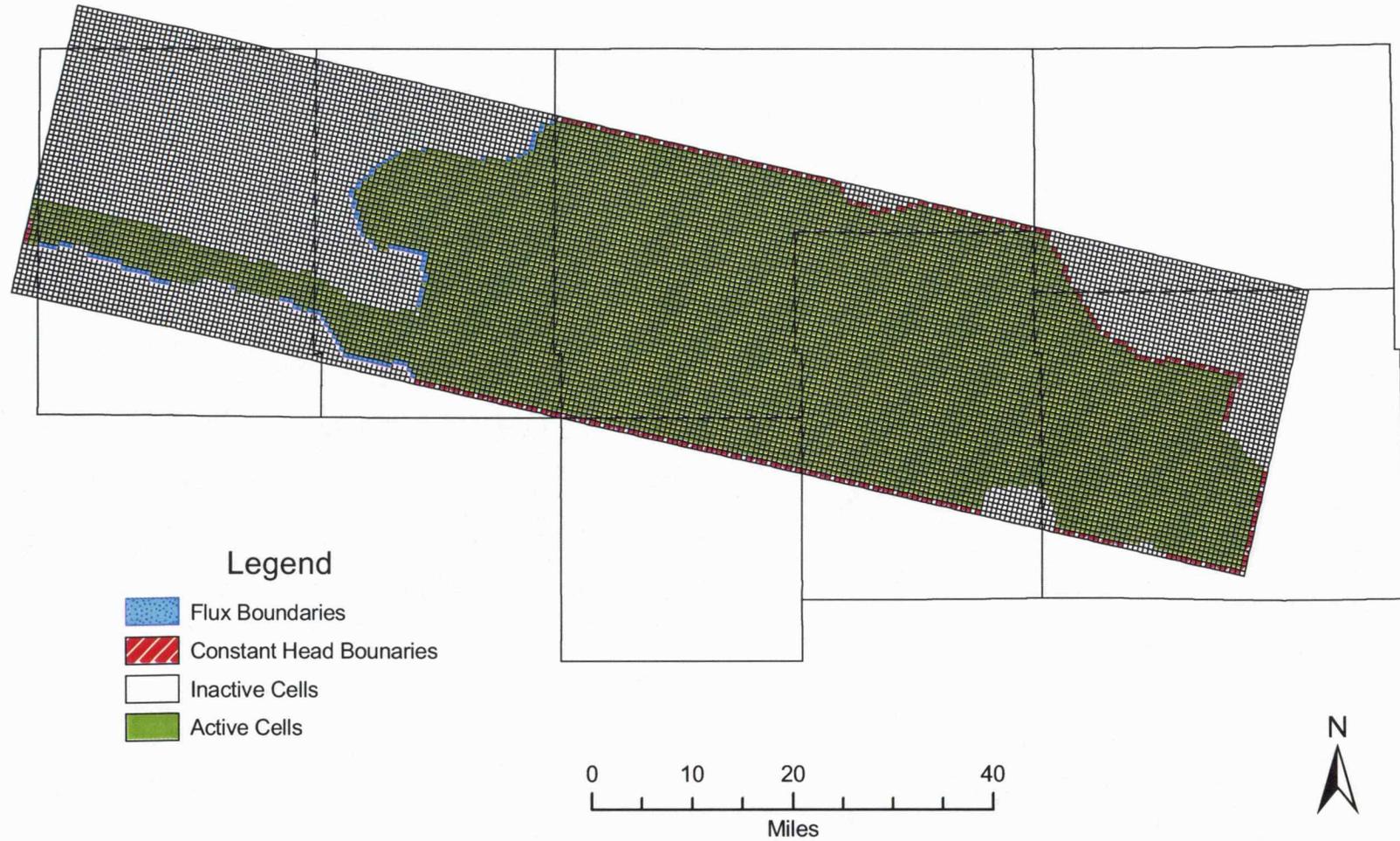


Figure 30. The location of the active and inactive cells and the constant-head and flux boundaries in layer 2 of the regional model. The southern grid boundary was changed from specified heads to specified fluxes for the 1990's transient and steady-state simulations.

zone 3. Layer 1 in zone 4 is inactive; active cells in layer 2 represent the High Plains aquifer (Figure 30). Conditions along model boundaries in zone 4 are represented either by specified-heads or specified-flows as described in the following paragraphs.

In the eastern part of Zone 4 in the model area north of the Arkansas River valley, a relatively thin zone of the High Plains aquifer, including a shallow paleochannel, provides an apparent connection between the High Plains aquifer and the Pawnee River watershed. This thin aquifer is not represented as part of the solution domain, but the boundary of specified heads in this area represents flow out of the model area. This boundary condition was incorporated to replace no-flow conditions used for calibration of the 1940 steady-state case to eliminate mounding of ground water in the area for the 1990's simulation.

Recharge was specified for layer 2 in the vicinity of the Bear Creek fault, into which occasional runoff from the Bear Creek watershed drains just south of the Arkansas River valley in south-central Kearny County. Along the southern boundary of the model area east of the Bear Creek fault, conditions were specified-heads for the 1940 steady-state model. However, this condition was problematic for a ten-year transient simulation that was run for comparison with observed changes in water levels from 1990 to 2000. For this simulation, flow rate was specified along the southern grid boundary within the extent of the High Plains aquifer. Flow rate was similarly specified along the western boundary of the High Plains aquifer in Kearny County to the north of the Arkansas River valley. Flow rates were first estimated according to Darcy's law in the form  $Q = Kwb dh/dl$  based on spatially distributed values for hydraulic conductivity,  $K$ , grid cell width  $w$ , saturated thickness,  $b$ , and hydraulic gradient,  $dh/dl$  along these boundaries. The values of these specified-flows were subsequently calibrated so that the simulated change in heads for a ten-year simulation would approximately match the interpolated, observed change in heads over the 1990's.

### **Data Sources and Input Parameters**

The key data for the model grid include elevations of the layers, hydraulic conductivity, water-level observations, water use, recharge, and characteristics of the Arkansas River related to its interaction with ground water. Representation of each of these is summarized below; further details are provided in Appendix B. Comparisons between observed and computed water levels indicate that the parameters in the model are a reasonable representation of the system.

#### ***Well lithology, aquifer geometry, and hydraulic conductivity***

The geographic extent, thickness, and hydraulic conductivity of the alluvial and High Plains aquifers within the model area have been characterized previously (Barker et al., 1983; Dunlap et al., 1985). GIS coverages of the geographic extent of the aquifers within the area of interest are available on DASC. For the purposes of the groundwater model, however, it was desirable that the aquifers be characterized with better resolution.

Elevations and hydraulic conductivity for alluvial and High Plains layers of the model grid were based in large part on approximately 460 lithologic data profiles that were interpreted and compiled in a parallel study (Young et al., 2000). The information for the lithologic profiles were obtained from drillers' well logs (WWC-5 forms), published USGS and KGS lithologic logs of wells and test holes, and logs of wells drilled for this study, and were selected along transects crossing the Upper Arkansas River valley (Appendix B, Figure B1). The profiles were used to develop spatial distributions of the top and bottom elevations and hydraulic conductivity for the alluvial and High Plains aquifers in the model area (Appendix B, Figure B2). These spatial distributions were interpolated to specify values for the model grid, and were converted from a shapefile attribute format to input files for MODFLOW using the ArcView Groundwater Modeling Extension (GME, Tsou and Whittemore, 2001). The methods for the conversion are presented in Appendix B.

### *Water-level measurements and water use*

Water-level measurements from the period near 1940 and the 1990's were used as calibration targets for the simulation model. Sources for water-level measurements and related data along the Arkansas River are presented below.

#### 1940 water levels

The water-level data for the 1940 conditions were measurements during 1939-1940 in Hamilton and Kearny counties (McLaughlin, 1943; includes a few values for 1941 and 1942), 1940 in Finney and Gray counties (Latta, 1944; includes a few values for 1939), and 1938-1939 in Ford County (Waite, 1942). The alluvial ground-water levels along the Arkansas River were assumed to coincide with the riverbed elevation for the 1940 water-level conditions. Under this assumption, an additional set of ground-water levels along the river was provided by USGS 1:24000 topographic maps as follows. Riverbed elevations were selected at each location where the river was crossed by a 5-ft or 10-ft contour. A map scale was used to determine Public Land Survey System (PLSS) locations as township, range, section, and coordinates within the section with respect to a specified section corner. These locations were converted to geographical coordinates using the KGS Leo program, and then to the Lambert projection used for the model area within ArcView.

#### 1990's water levels

Water levels for the period 1991-2000 were based on measurements made primarily by the Kansas Division of Water Resources (DWR) and the KGS. Unlike the 1940 model (described above), alluvial ground-water levels along the river were not assumed to coincide with the riverbed elevation. Further, measurements were distinguished by which aquifer in which they are screened; wells screened in the Dakota aquifer were excluded. Ten-year averages of winter water-level measurements were taken over the period 1991-2000 for data from DWR and KGS as follows:

Source	No. observ. locations	Layer 2 10-yr averages	Shapefile name on ghpc18, in d:\uarc\sp\ua90s\
DWR	41	130	WL_DWR90pj.shp
KGS	159	234	WL_KGSpj.shp
KGS (Haskell Co.)	75	36	WL_Haskell.shp

For each layer, available data points from these three shapefiles were included in the generation of TINS, which were then interpolated to obtain water elevations as discrete values for each grid cell in layers 1 and 2. Some minor adjustments were then made to the interpolated values. In a few areas where the alluvial aquifer is shallow, the interpolated water levels for layer 1 lay slightly below the interpolated elevations of the bottom of the alluvial aquifer, on the order of 2 m. The interpolated water levels were taken as evidence that the bottom of the alluvial aquifer was deeper than the values given for the layer 1 in the model. In these areas, the bottom of layer 1 was lowered by 5 m. Corresponding adjustments were made so that the top and bottom elevations of layer 2 lay at or below the bottom of layer 1.

For the 1990's river model, channel elevations were given by the values used for the 1940 model minus an estimated value for channel entrenchment, which was based on changes at the USGS gaging stations and long-term water-level changes in the alluvial aquifer near the river. From the 1940's to the 1990's, the river channel entrenchment was estimated to be 1 m for the river valley through Hamilton and western Kearny counties, and 2 m for the valley overlying the High Plains aquifer east of the Bear Creek Fault zone. The section on changes in ground-water-levels earlier in this report explains the channel deepening in more detail.

#### 1940 water use

The data for the water quantity pumped from wells in 1940 were generated from information in the KGS bulletins by McLaughlin, (1943), Latta, (1944), and Waite, (1942). These publications list a variety of information, including location, principal aquifer unit, water use, and pumping rate, for the water wells in the 5 counties of the study area. Although the pumping rate is listed for the individual wells, the annual water-use is not reported for most wells. The publications give an estimate of the total amount of water pumped per year in each county, including a separation into pumping in the river valley and on the uplands. The ratios of the pumping rate and the total pumping were determined for each area by summing the pumping rates and comparing to the total quantity of water pumped. The factors were used to convert the pumping rate for each well into an annual quantity pumped. For selected wells, such as municipal supply and industrial wells, the annual amount of water pumped and the pumping rates were reported. These data were also used to help estimate the factors for converting pumping rate to annual water use for municipal and industrial wells. The DWR also provided data for selected wells within the study area that were compared to the estimates generated from the KGS bulletins. The final set of water-use data was selected on the basis of all the information available. The water use was assigned to the wells as either irrigation wells or non-irrigation wells because recharge from irrigation seepage was computed in the simulations.

### 1990's water use

The data for well water use in the 1990's were obtained from WIMAS, the database management system of the DWR for permitted wells. To avoid duplicating water use reports, a unique identifier was defined as a composite of record identifiers; details are given in Appendix B. Water use within the model area is summarized in the following table.

Classification	Geologic unit code	GW Model Layer	Number of water rights	Water use 1990s (acre-ft/yr)
Alluvial wells	QA	1	131	12,162
High Plains wells	HP	2	8,136	1,069,239
Dakota wells	KD	--	27	4,186
Surface water use	--	--	36	37,181

### Ditch irrigation

Ditch irrigation water use was obtained from the reports of the Arkansas River Compact Administration and the DWR. The average water use for the period 1991-1998 was computed for each of the ditch systems. The values used, in acre-ft/yr, are the following:

Ditch System	1940 use (acre-ft)	avg 1991-1998 use (acre-ft/yr)
Amazon	20,518	20,000
Farmers	12,877	15,361
Frontier		*6,055
Garden City	2,678	2,013
Great Eastern	24,776	17,971
South Side	10,885	10,514

\* Estimate based on a 10-year average, 1979-1988.

The location of the irrigation diversion canals is from a coverage available from the DWR. The area irrigated by ditch diversions that was used for the 1940 simulation is based on data collected by Colorado for the 1942 ditch-water system. These data were obtained as photocopied tables from the DWR. The area irrigated by ditch diversions in the 1990's simulations was based on a map coverage prepared by the DWR for the system in 1988. There are no other readily available data or maps for location of fields irrigated by river diversions.

### ***Ground-water recharge***

The initial value of areal precipitation recharge of ground water used in the model was 1.5 cm (0.6 in). The initial value of water seeping underneath the main canals was estimated as 1% per mile of the diversion for each ditch service area. The main canals were selected

from the GIS coverage of the ditch irrigation system. The total amount of water diverted in the Amazon and Great Eastern system was summed for use in the seepage of the main canal to Lake McKinney. A similar approach was used to sum the Farmers and Garden City diversions where the main canal served both systems before splitting to the individual ditch systems. The initial values of recharge for the water applied to fields for irrigation were calculated as 25% of the ground water pumped from irrigation wells and the surface water spread by ditches. 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 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. The spatially distributed recharge calculated by this procedure was used for input to MODFLOW. Recharge and hydraulic conductivity were subsequently adjusted to calibrate the simulation of the 1940 ground-water conditions.

### ***River–Ground-Water Interactions***

The river-aquifer interaction was computed using the River package of MODFLOW. The River package calculates the flow rate across the streambed for each active grid cell through which the river passes according to Darcy's law in the form

$$Q_s = C(h_s - h),$$

where  $C$  = conductance,  $h_s$  = stream surface elevation, and  $h$  = hydraulic head in the aquifer. The conductance can be represented by

$$C = K_s Lb/T,$$

where  $K_s$  = streambed hydraulic conductivity,  $L$  = stream reach length within the grid cell,  $b$  = stream width, and  $T$  = nominal streambed thickness, the path length over which the hydraulic difference,  $h_s - h$ , is taken. This flow rate,  $Q_s$ , represents either stream gain (baseflow) or loss (seepage), depending on the sign of the hydraulic gradient across the streambed. Manning's equation (see Appendix B2) was used to calculate stream depth based on average streamflow conditions in the Arkansas River channel. The initial geometry of the Arkansas River used was based on first selecting an average flow of about 200 cfs that is close to the long-term mean flow. This flow was selected to be less than the average 310 cfs for 1990-1999 at the Colorado-Kansas state line to indirectly account for decreases in flow from free surface evaporation and phreatophyte evapotranspiration that are not included in the model.

The streambed leakage and channel geometry were factors considered in the computations by Manning's equation. A hydraulic conductivity of 5 m/day was used for the sediment layer underlying the river across which seepage flowed between the alluvial aquifer and the river. For the 1990's model, the streambed parameters were adjusted to take into account an estimate of streambed degradation, resulting in a decline of streambed elevation on the order of 1-2 m, and to make an improved estimate of stream-stage elevation, using Manning's equation to calculate depth based on an estimated streamflow, width, bed slope, and Manning  $n$ . The adjustments were made using ground-water elevations as targets, not streambed leakage. The resulting adjusted data were used as input to the MODFLOW River

package. Appendix B2 presents more details of the methods and assumptions used to represent the river-aquifer interaction.

### **Calibration of Model Parameters**

Ground-water and river channel parameters were adjusted to meet model calibration targets, which consisted of ground-water level elevations under three sets of conditions: 1940 steady state, 1990's transient, and 1990's steady state. For the steady-state cases, simulation model parameters were adjusted to reduce solution error with respect to ground-water elevations (the calibration target). On the other hand, calibration for the 1990's transient case was based on comparison of the change in heads for a ten-year simulation with the change in measured ground-water elevations for the period 1990-2000.

Model parameters were calibrated primarily using a GIS-assisted approach in which the parameter values for each grid cell were adjusted independently. This approach was applied to distributed model parameters, including hydraulic conductivity and recharge for the 1940 case, recharge boundary conditions for the 1990's transient case, and irrigation water use for the 1990s steady-state case. These parameters were represented by attribute fields in a polygon shapefile associated with model grid cells. Vector operations were applied to shapefile attribute fields in ArcView that allowed treating grid cells for a given parameter as independent variables, allowing for spatial variation in parameter sensitivity to model error on a cell-by-cell basis.

For steady-state cases, the GIS-assisted approach was followed by application of an automated procedure using PEST (Doherty, 1994). Automated calibration requires appropriate definition of parameter zones, which are treated as independent variables. This approach cannot practicably extend zonation to the scale of grid cells as in the GIS-assisted method. Although automated calibration can more rapidly optimize parameters than manual calibration, the results for automated calibration may not necessarily be better than for the manual calibration of the model for the upper Arkansas River corridor due to the model complexity. Using PEST, model error showed little sensitivity to calibration parameters, including zoned values of hydraulic conductivity and ground-water recharge for the steady-state 1940 simulation.

Model verification consists of showing satisfactory agreement between simulated and measured values that have not been used for model calibration. For this purpose, streambed leakage computed by the River package of MODFLOW was compared to streamflow differences between gaging stations across the model area for steady-state cases of both 1940 and the 1990's. These comparisons account for diversions to irrigation ditches, and are presented in this report.

#### ***Calibration of 1940 steady-state simulation***

The calibration step involved estimating hydraulic conductivity and recharge values based on data and then adjusting these parameters to reduce the computed head error. The

approach to estimating hydraulic conductivity and recharge as spatially distributed properties for the ground-water model were reviewed above. Spatially distributed adjustments were made to both  $K$  and  $R$  to minimize the error between computed and observed, interpolated heads. Methods for doing this are based on calculations that were performed in the ArcView environment, and are summarized in Appendix B3. For 1940, streambed leakage approximated the gain between gaging stations without adjusting streambed hydraulic conductivity.

### *Calibration of 1990's simulations*

A different approach was taken for the 1990's, since the approach used for 1940 was not effective for the 1990's. The approach for a transient simulation involved approximately matching the temporal changes in ground-water heads over a ten-year period during the 1990's. As part of this approach, the southern grid boundary condition was changed from specified heads to specified recharge. A spatially variable adjustment was applied to specified recharge in order to approximately match the change in heads along this boundary. The result from this calibration was used for generating the 40-year transient simulation for which particle paths were calculated.

The conditions used for the 40-year transient case, including estimated water use, were also applied to a solution allowed to run to steady-state equilibrium in MODFLOW with a small adjustment to the recharge boundary condition to improve the match in heads along the southern grid boundary; The flow-field results from this solution were imported into MODPATH and used to project the 40-year particle paths based on assuming a steady-state condition. A second steady-state case was run in which irrigation water use was adjusted in order to approximately maintain ground-water heads at the 1990's levels, which was then used to compute particle paths. For this case, irrigation water use by wells was reduced to about 16 percent without return flow. There were minor spatial variations in the reduction that were selected to fit the head distribution. Additional information on the calibration is presented in Appendix B3.

### *Automated calibration of recharge*

The inverse modeling program PEST (Doherty, 1994) was applied to the ground-water model for 1990's conditions. Since the distribution of hydraulic conductivity was well calibrated for the predevelopment period and was assumed to be appropriate for the 1990's, the recharge pattern in model layer 2 was the parameter to be estimated in the automatic calibration. The initial recharge distribution was generated from the field data. Based on the distribution, eight classifications were selected and identified as eight zones over the modeling area. The mean values for the zones were used as the initial values for the recharge parameters. The steady-state case with pumpage from original data was run. The computed water levels were generally insensitive to the recharge parameters, which means the optimal values for the recharge parameter cannot be obtained through this calibration. One of the reasons for this was that the pumpage from the original data was too great for the quasi-

steady-state case for the 1990's. Additional information on the calibration is presented in Appendix B4.

### Grid and Data Conversions

The Lambert conformal conic projection of geographic coordinates was chosen for specific application to the model area. The geographic coordinates are based on the North American Datum of 1927 (NAD27) and the Clarke 1866 geoid. The Lambert projection parameters for the GIS-based model are listed in the following table. Locations of all data used for the model were transformed to this datum and projection from geographical coordinates (longitude, latitude) and from other projections and their associated datum references. These transformations were made using either ArcInfo or the Projection Utility in ArcView 3.2a.

Parameter	Units (dd: dec. deg.)	Units (DMS: deg min sec)
Central meridian	-101.0 DD	-101 00 00
Reference latitude	37.5 DD	37 30 00
Standard parallel 1	37.9 DD	37 54 00
Standard parallel 2	38.2 DD	38 12 00
False easting	0 m	0 m
False northing	0 m	0 m

Locations of some features were available in terms of the PLSS, given by township, range, section, and subsections. Transformations from PLSS-coded locations were applied in two steps. The KGS program Leo was first applied to convert PLSS to geographical coordinates, which were then projected using the ArcView Projection Utility.

MODPATH results are given in terms of grid coordinates, which were transformed to projected coordinates (Lambert projection) by applying a translation, a rotation, and a scaling as follows:

Translate from grid coordinates origin  $(x_{g0}, y_{g0}) = (0,0)$  to projected coordinates  $(x_0, y_0) = (-95872, 46488)$ .

Rotate grid coordinates clockwise about the grid origin  $(0,0)$ .

Scale: grid and projection coordinates are both in meters, so apply a scaling factor of 1.

The angle of rotation,  $\theta$ , was given by the normalized dot product

$$\cos(\theta) = \frac{a \cdot b}{|a||b|} \quad (1)$$

where  $a$  is a vector extending from the origin of the grid coordinates to a point  $P_g = (x_g, y_g)$ , and  $b$  is the corresponding vector in the translated projection extending to  $P' = (x-x_0, y-y_0)$ . For  $P_g = (252.804.6, 0)$ , that is, 252 columns to the right of the origin, the corresponding

projected and translated point  $P' = (197607, -45475.5)$ . Using (1), we obtain  $\theta = 12.96$  deg (0.2262 radians;  $\cos \theta = 0.97453$ ,  $\sin \theta = 0.22427$ ).

Grid coordinate pairs  $(x_g, y_g)$  were transformed to projected coordinates  $(x, y)$  by applying

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} + \begin{pmatrix} c\theta & s\theta \\ -s\theta & c\theta \end{pmatrix} \begin{pmatrix} x_g \\ y_g \end{pmatrix}, \quad (2)$$

which combines translation, rotation, and scaling operations. This transformation was applied within Microsoft Excel 97 as a postprocessing operation to MODPATH results for particle paths. The transformed coordinates for particle paths were exported from Excel as a comma-delimited file (with extension \*.csv). This file was imported into ArcView (after renaming the filename extension to \*.txt) through its "Add Table" operation. The table was then added to a view using "Add Event Table" and then converted to a point shapefile. Figure 31 shows a set of paths in both grid and projected coordinates. Viewing of the graph after each transformation operation helped verify that the transformation results were correct.

(Note: If one preferred to reproject the GIS-based model from the Lambert projection described above to the one used as a standard in Kansas (central meridian = -98.25 deg, reference latitude = 36 deg, standard parallels = 33 deg and 45 deg, NAD27/Clarke 1866), the corresponding transformation from grid coordinates to this projection given in equation (2) would be based on the origin (-336047, 218861) and angle 15.1705 deg.)

Grid cell indexing included a global node number in terms of (layer, row, column). For  $nrow$  rows and  $ncol$  columns, a global node number,  $n$ , is given in terms of layer, row, and column indices  $(k, i, j)$  by

$$n = ncol[nrow(k-1) + (i-1)] + j \quad (3)$$

Depending on the user's option, MODPATH references cells either in terms of layer, row, and column indices  $(k, i, j)$  or in compact form by the global node number.

The ArcView-based model has a unique grid cell identifier named `uagrid_id` that is related to the global node number defined for MODPATH as follows:

$$uagrid\_id = 1 + \text{mod}(n-1, nrow \cdot ncol) \quad (4)$$

If `uagrid_id` =  $n$ , then layer  $k = 1$ ; else layer  $k = 2$ . More generally, the difference between global node number,  $n$ , and the identifier `uagrid_id` is a multiple of  $nrow \cdot ncol$ , so the layer index,  $k$ , is given by

$$k = 1 + (n - uagrid\_id) / (nrow \cdot ncol) \quad (5)$$

## Simulation Procedure

MODFLOW and MODPATH were used in conjunction with ArcView according to the following procedure to simulate the cases of interest (see Appendix B5 for details).

- 1a. Set up input files for MODFLOW using the interface provided by the Groundwater Modeling Extension (GME; Tsou and Whittemore, 2001).
- 1b. Run MODFLOW to obtain a solution for heads in layers 1 (alluvial) and 2 (High Plains) as a sequential text file. 1c. Import the text file into ArcView through the "Import a File" function on the Utilities menu of the Groundwater Modeling Extension (GME).
- 2a. Run MODFLOW again to write heads and flow rates to binary files. This is not done as part of step 1 because the Output Control package of MODFLOW allows heads to be written only one way, either as a sequential, text file or as a direct, binary file.
- 2b. Run MODPATH, and read the binary files from step 2a. This should produce a text file of final particle locations or particle paths, depending on the options chosen. The locations are given in grid coordinates.
- 2c. Postprocess MODPATH simulation results as follows:  
Import the particle path results file into Excel.  
Transform the particle paths from grid to projected coordinates (see "Grid and Data Conversions", below).  
Write the results out to a comma-delimited file (\*.csv) and change the extension to "txt".  
Import the renamed comma-delimited file into ArcView ("Add table"), convert to a shapefile, and convert the point shapefile to a line shapefile.

## Summary of Simulation Cases

The ground-water simulations were run for two general sets of conditions corresponding to circa 1940 and the 1990's. The ground-water model cases that were developed in the ArcView environment and simulated using MODFLOW are summarized below (simulation case names are shown in parentheses).

### *Predevelopment (circa 1940)*

(K2opt2) Steady-state case with calibrated recharge and hydraulic conductivity.

### *Postdevelopment (1990's)*

#### Transient cases: 40-year simulations

(R3trn50) Base case: Average 1990's reported water use

(R3tm50) Irrigation water use halted within a moratorium area south of Garden City.

#### Steady-state cases

(R3s) Base case: Average 1990's water use run to a steady state solution in MODFLOW that was then imported into MODPATH to calculate 40-year particle paths under a steady-state condition.

(R3s\_mor) Variation on R3s, with the “moratorium area” for irrigation imposed.

(Wc16n) Ground-water use curtailed sufficiently to maintain 1990’s ground-water levels.

(Wc16nmor) Variation on Wc16n with the “moratorium area” for irrigation imposed.

For each of the above cases, MODPATH was run twice to track particle paths starting first in the alluvium along the Arkansas River, and then in the High Plains aquifer along the 500-mg/L sulfate contours for the 1990’s. In addition, MODPATH was run for the steady-state case under the 1940 conditions with particles starting in the High Plains aquifer along the ditch irrigation system. Further details regarding simulation of these cases are provided in Appendix B5. Results for all of these cases are presented in the following section.

## **Numerical Modeling Results**

### **Early Development Period (Circa 1940)**

The simulation for 1940 represents the early development period during which the ground-water pumping had not yet caused substantial declines in the ground-water levels of the High Plains aquifer. This period is often referred to as the predevelopment period in Kansas because the amounts of ground-water use were much less than from the 1950’s up to the present. Although some local water levels had been affected by pumping by 1940, data in McLaughlin (1943), Latta (1944), and Waite (1942) indicate that the water levels in the alluvial and underlying High Plains aquifer were generally the same within the boundaries of the alluvium in the late 1930’s and early 1940’s. Thus, the ground-water levels were assumed to be the same in layers 1 and 2 of the 1940 model within the alluvial valley. The simulation was run as a steady-state solution and was calibrated.

The distribution of measured water levels in 1940 for the Arkansas River corridor is shown in Figure 32. The simulated distribution of ground-water levels is in Figure 33. The isolines for the measured and computed water levels are similar (Figure 34) and indicate how closely the simulation for the 1940 condition fits the observed data. In general, the water-level isolines are oriented in a south-southwest to north-northeast direction approximately parallel to the columns of the model grid. There is a broad “V” shaped bow pointing upstream where the isolines cross the Arkansas River. The bow in the water-level isolines indicates that there is a component of ground-water flow towards the river. The bow is slight near the western end of the High Plains aquifer close to the Bear Creek Fault zone and becomes more pronounced in an eastward direction. This change fits with the increased ground-water discharge to the river in an eastward direction across the area of the High Plains aquifer. In Kearny County east of the Bear Creek Fault zone, the water-level isolines in Figure 34 and in Plate 1 of McLaughlin (1943) indicate that ground-flow directions (perpendicular to the isolines) in the area near and within the Arkansas River valley were towards the river on the north side of the river and slightly away from or parallel to the river to the south of the river.

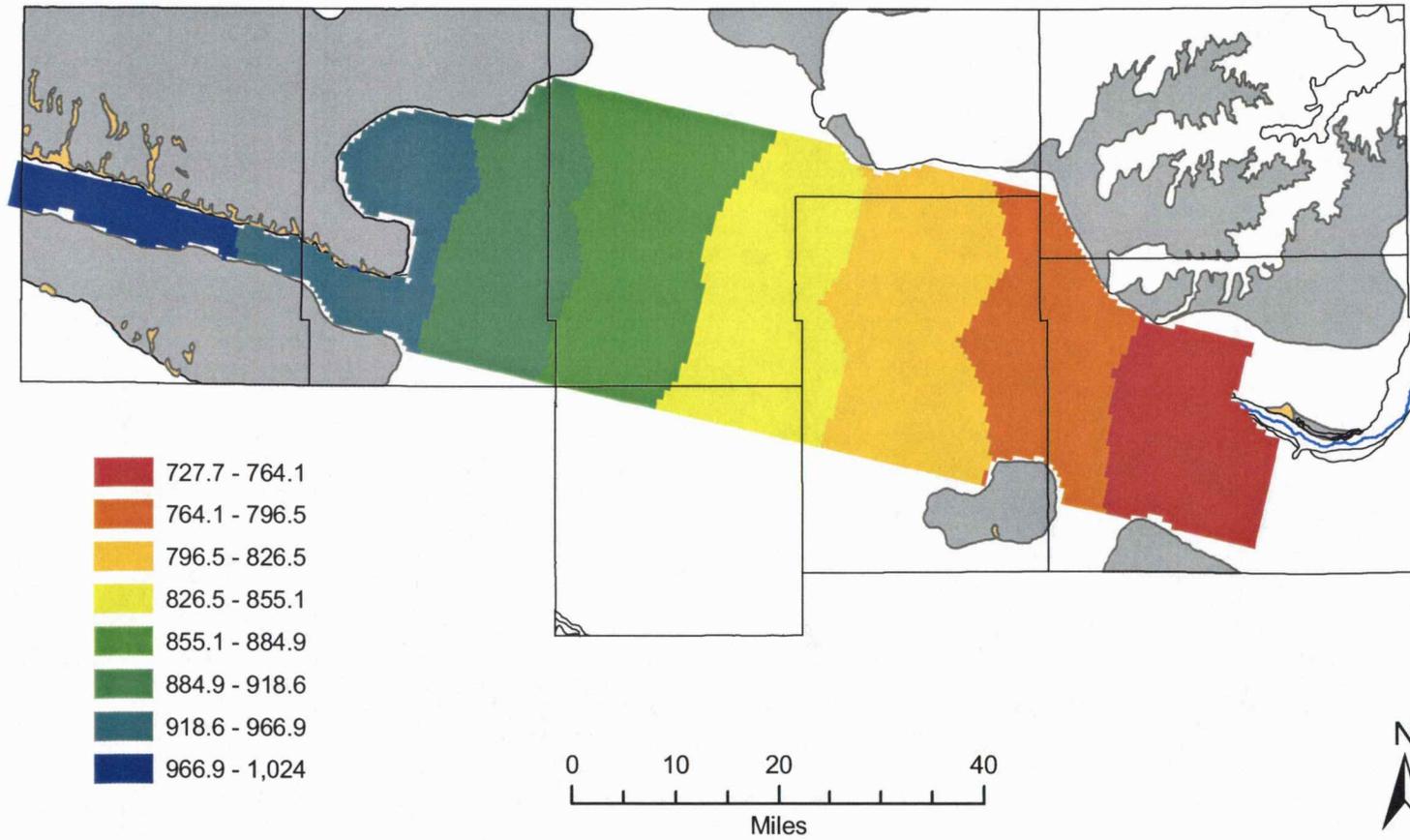


Figure 32. The observed water-level surface for 1940 represented as color-shaded intervals. The elevations range from a maximum of 1024 m (3360 ft) in the west to a minimum of 727.7 m (2387 ft) in the east part of the regional model.

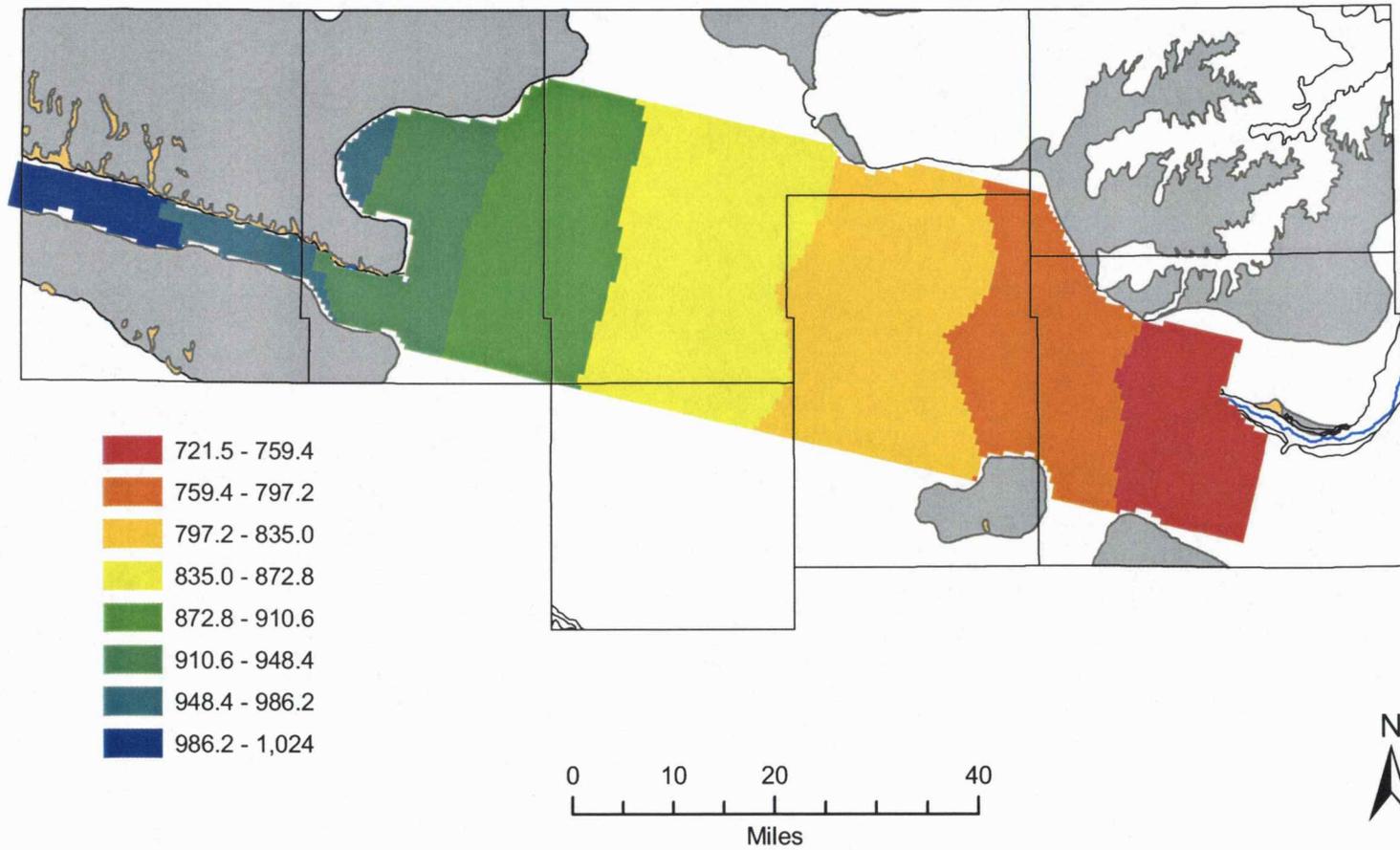


Figure 33. The water-level surface from the steady-state simulation for 1940 represented as color-shaded intervals. The elevations range from a maximum of 1024 m (3360 ft) in the west to a minimum of 721.5 m (2367 ft) in the east part of the regional model.

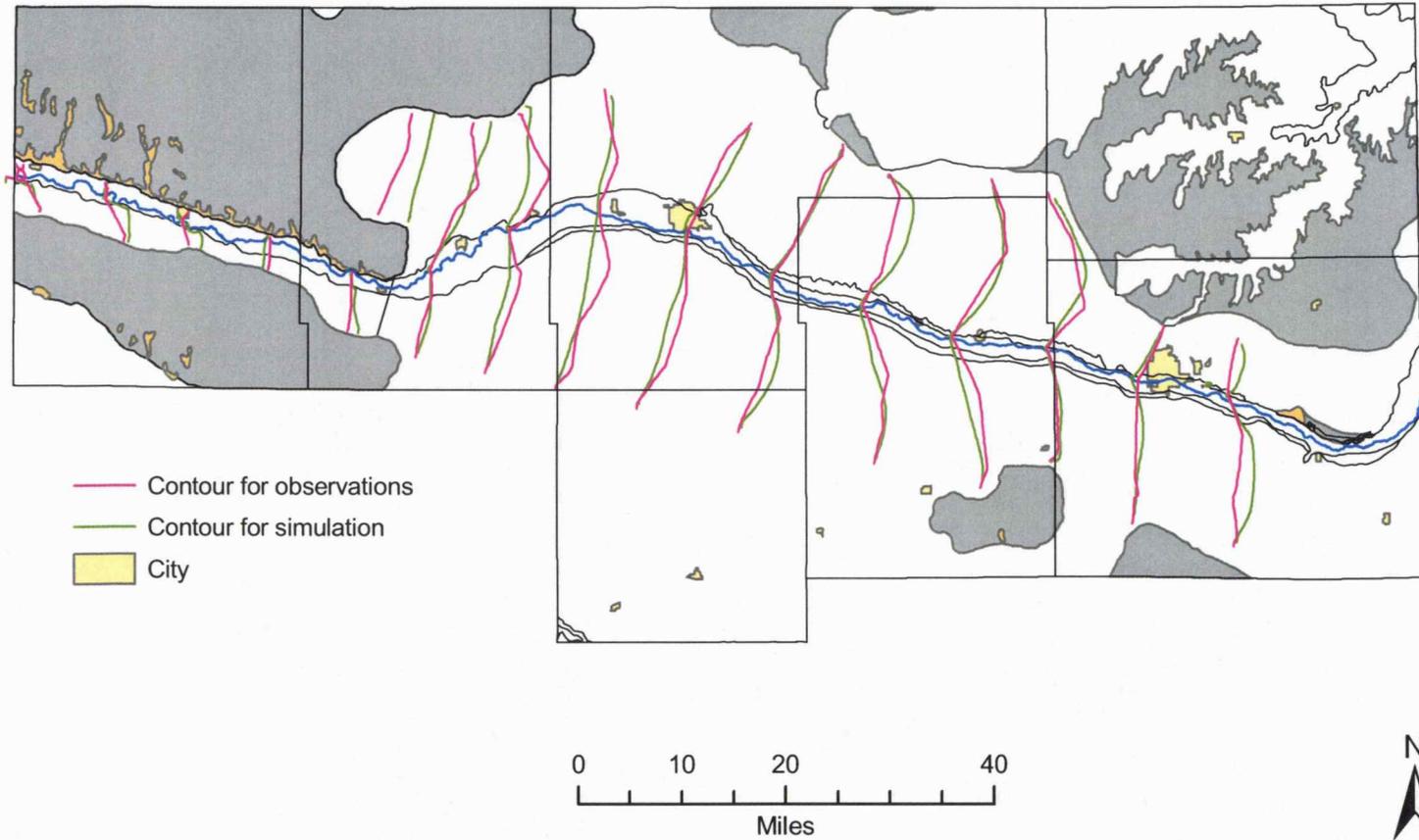


Figure 34. Comparison of the water-level contours for the observed data and the steady-state simulation for 1940 in the regional model. The two contours near the Colorado border are for 1020 m and the two at the east side of the model are for 740 m.

Figure 35 shows the simulated gains or losses of the flow of the Arkansas River resulting from river-aquifer interactions. Adjustments in the ground-water model based on average river flows at gaging stations were made to match simulated with observed ground-water levels and not river flows in the river-ground-water simulation. The modeled river flows indicate how well the calibrated ground-water system simulates the streamflow without modifying parameters to force the streamflow to fit observed data. The results generally fit the observed data, indicating that the ground-water flow simulation is a good representation of the actual conditions. The metric results generated by the simulation were converted to cfs for easy comparison to river flows as recorded by the USGS. The top line in Figure 35 (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 all less than  $\pm 2$  cfs along the entire length of the river in the corridor model. The lower line in Figure 35 represents the cumulative baseflow gains from ground-water discharge 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. The results from the stream and river packages of MODFLOW were essentially the same; the lines for the two simulations are superimposed upon one another. The vertical lines next to the city names indicate the stream reach in which a USGS gaging station is located.

Figure 35 indicates that a small amount of flow (about 10 cfs) was gained from the state line to Garden City based on the simulation. Most of the gain was between Coolidge and Syracuse. The simulated gain between Syracuse and Garden City was only a couple cfs. The USGS gaging stations at Syracuse and Garden City operated through the 1930's and 1940's. Flow was not recorded at Coolidge and Dodge City continuously throughout a calendar year until 1951 and 1945, respectively. The net gains or losses of channel flow due to river-aquifer interactions between Syracuse and Garden City can be computed by subtracting the flow at Syracuse from the sum of the irrigation diversions and the flow at Garden City. During the 1930's and 1940's, most of the computed values indicated net losses of flow from the river between Syracuse and Garden City. However, during some of the years the river gained flow between the stations. Most of the data for ground-water levels for the 1940 model were collected in 1939 and 1940. In 1939 the river gained an average equivalent of 3.3 cfs and in 1940 lost an average of 17 cfs. Because the simulated model does not directly include evapotranspiration, the net actual gain in flow could be expected to have been smaller than simulated (or a small actual loss rather than a gain). Thus, the simulated baseflow for the western half of the model area is actually a good representation of the actual conditions. Evapotranspiration could be expected to consume as much as 10-15 cfs along the river, placing the net result between the two values observed for 1939 and 1940. The ground-water flow directions implied by the water-level isolines in Figure 34 and in Plate 1 of McLaughlin (1943) indicate that flow additions to the river in the eastern half of Kearny County would have been primarily from the north side of the river.

The net gain in Arkansas River flow as simulated by the model for 1940 between Garden City and Dodge City is approximately 50 cfs (Figure 35). As stated above, a stream gage did not operate for a full year until 1945 at Dodge City. The net flow difference between Syracuse and Garden City (considering the diversion loss as above) for 1939-1940 was similar

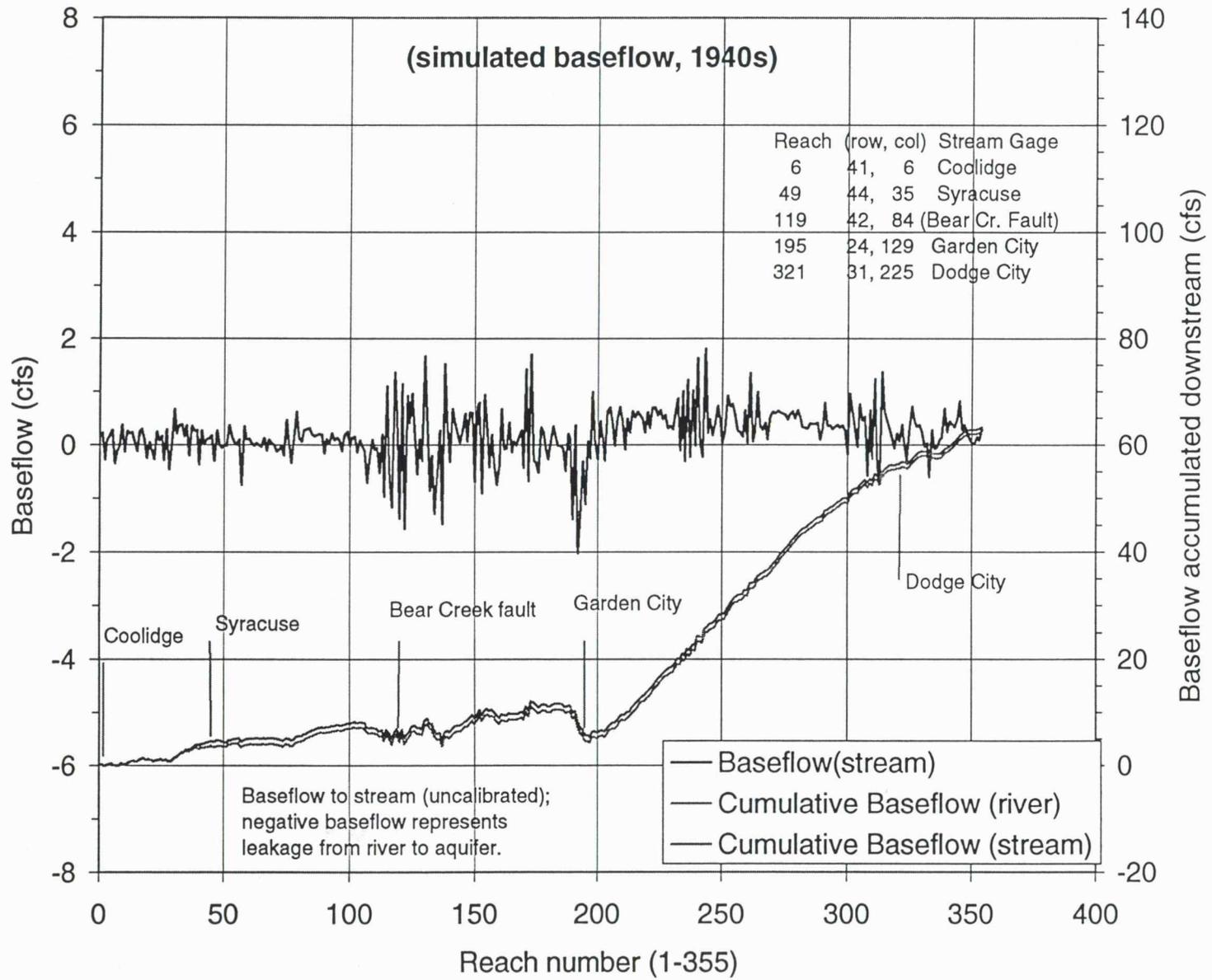


Figure 35. Baseflow of the Arkansas River computed from the steady-state simulation for 1940s conditions.

to that for 1945-1947. The river gained an average of 38 cfs between Garden City and Dodge City during 1945-1948; the range in the gain was 29-50 cfs. As indicated above, the observed flow difference would be expected to be somewhat less than that simulated due to the evapotranspiration losses from the river. Thus, just as for the Syracuse to Garden City stretch of the river, the computer model simulated the flow gain well for this river stretch.

### **Present Conditions (1990's) and Projections (MODFLOW)**

MODFLOW simulations were run for both the 40-year transient case and a steady-state solution starting with the average conditions of the 1990's, and also a steady-state case in which the 1990's ground-water levels were maintained as constant. The average ground-water levels for the High Plains aquifer in the 1990's show the same general pattern of regional flow towards the east-southeast (Figure 36) as for 1940 (Figures 32-34). However, there are important differences as indicated by the steeper gradient in the water-level surface from eastern Kearny County to western Finney County and the eastward pointing rather than westward pointing V's along the Arkansas River.

The ground-water system in the 1990's was dynamic because there were substantial water-level changes in large areas of the upper Arkansas River corridor. The most pronounced declines were in the High Plains aquifer south of the Arkansas River from southeast Kearny County through west-central Gray County (Figure 37). From 1991 to 2000, water levels dropped over 17 ft (5.3 m) within most, over 26 ft (8 m) in a large part, and over 33 ft (10.2 m) in some portions of this region. Conditions to the north of the river are substantially different from those to the south. Water levels in the High Plains aquifer rose from 1991 to 2000 in the ditch service area north of the river in part of east-central Kearny and west-central Finney counties. The rises were greater than 10 ft (3 m) in a substantial portion of this area. The water-level rises and large declines are also illustrated by the hydrographs (Figures 3-5) described in the section on water-level changes earlier in this report. Ground-water levels in the alluvial aquifer along the river valley from the Colorado-Kansas border through eastern Kearny County remained nearly constant. Water-level changes in the High Plains aquifer underlying the alluvial aquifer from eastern Kearny County to central Ford County ranged from nearly constant to both substantial rises and declines. The main rises were in part of the ditch service area north of the river in west-central Finney County. The largest declines under the river valley were in the central part of Gray County.

The 40-year transient simulation used for particle tracking represents the conditions that would be expected to occur starting from the 1990's. The simulation run to a steady-state equilibrium starting with the 1990's ground-water pumping represents the result that could occur if the present trends in water-level changes and ground-water flow were allowed to proceed. The steady-state simulation based on maintaining the average 1990's ground-water levels required substantial reductions in the current ground-water pumping. The estimated water use was reduced sufficiently to obtain an approximate match between computed and observed heads for the 1990's. The reduction made in the average irrigation pumping for the 1990's was approximately 84 percent. Thus, 16 percent of the 1990's average pumping was

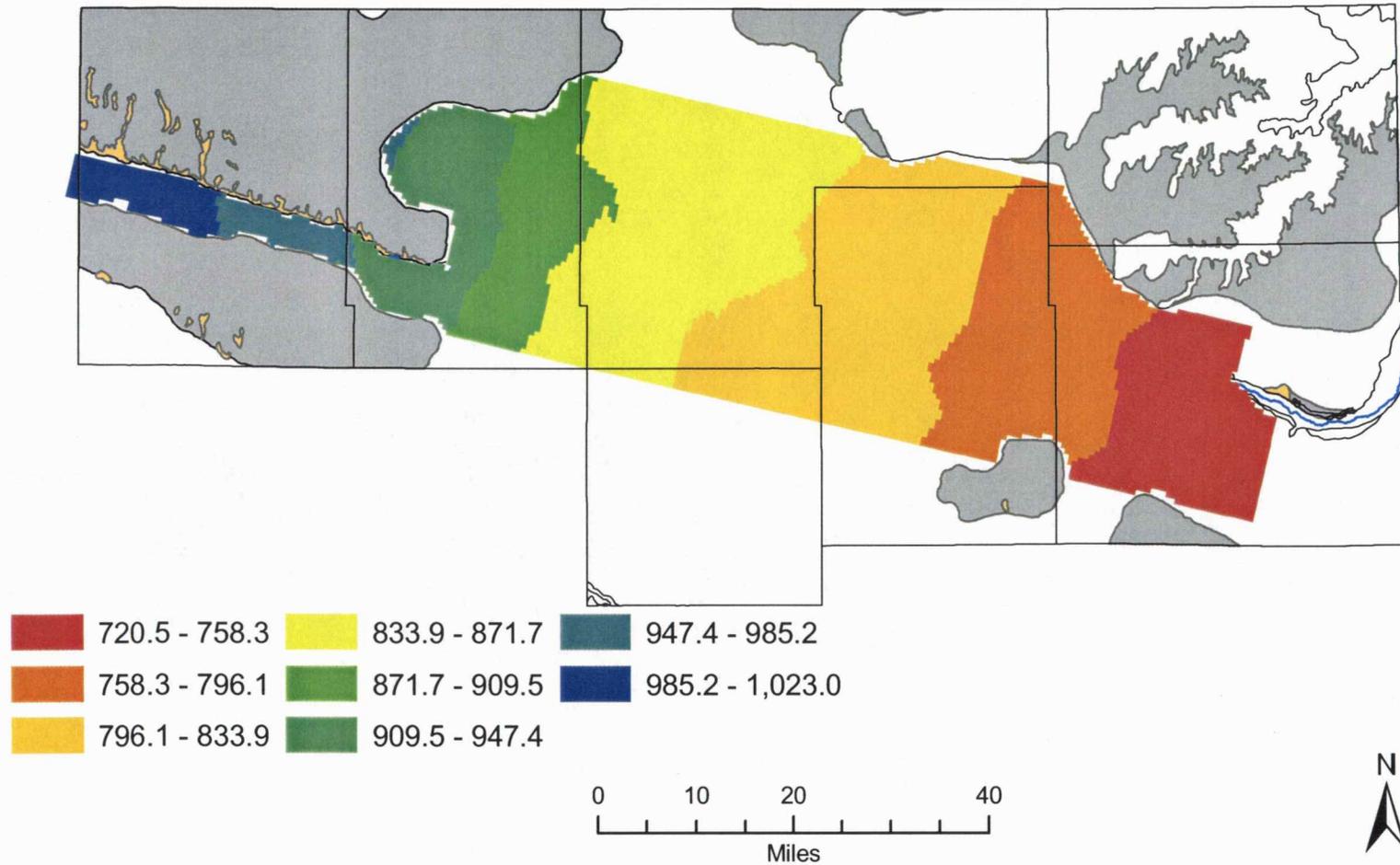


Figure 36. The observed water-level surface for average values during 1991-2000 represented as color-shaded intervals. The elevations range from a maximum of 1023 m (3356 ft) in the west to a minimum of 720.5 m (2364 ft) in the east part of the regional model.

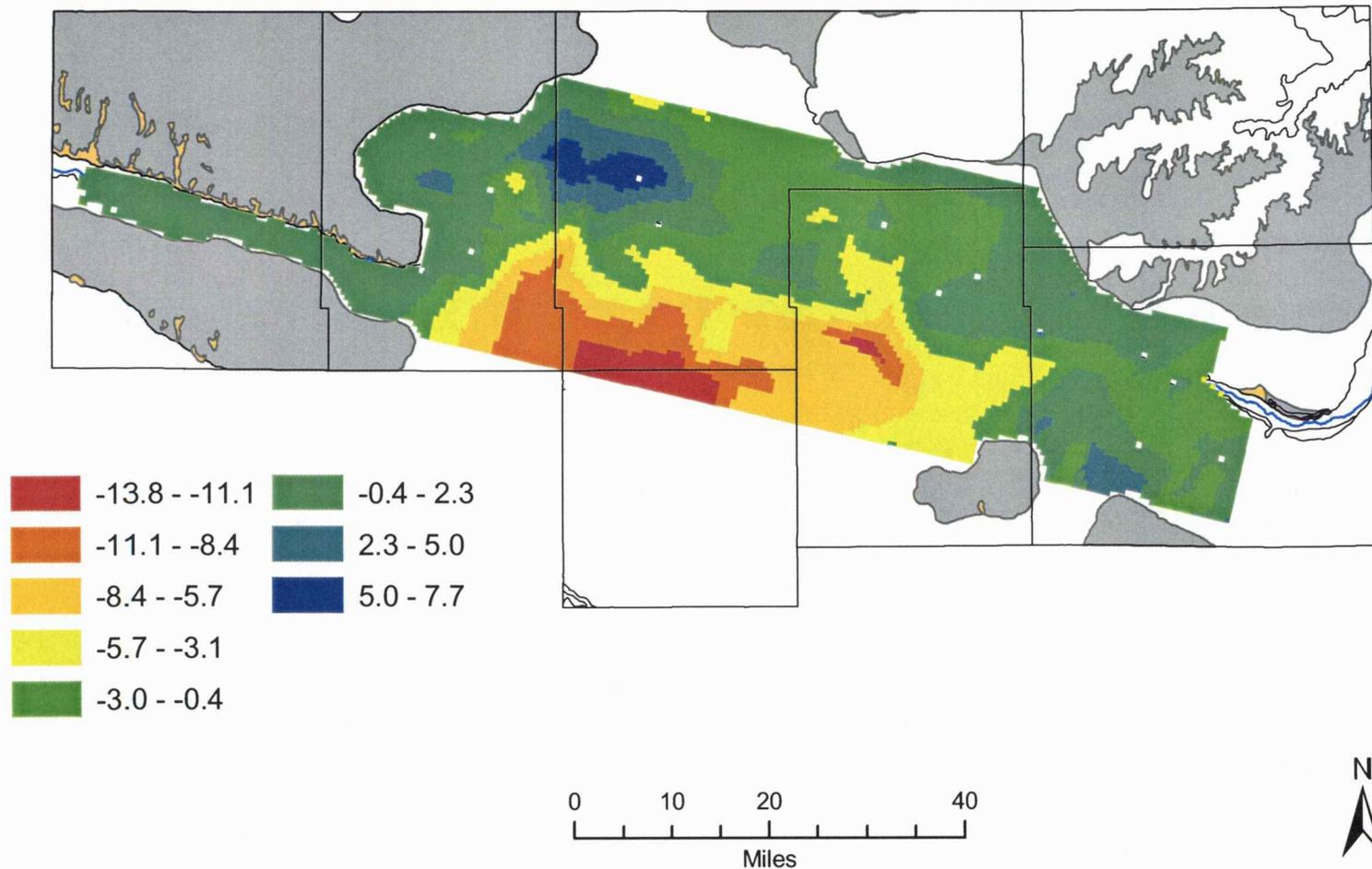


Figure 37. Change in the water-level surface between 1991 and 2000 represented as color-shaded intervals. The intervals range from a maximum water-level decline of 13.8 m (45 ft) to a maximum water-level rise of 7.7 m (25 ft).

used in the model but with zero return flow. These conditions correspond roughly to reducing irrigation pumping to 21 percent of estimated use with a 25 percent return flow.

The solution run to a steady-state equilibrium for 1990's water use and the steady-state simulation in which 1990's water levels were maintained represent extremes in the hydraulic head distributions for the future. The run for a steady-state solution based on average 1990's water use gives the steepest gradients in heads probable in the future in the High Plains aquifer from the river valley to the south. The steady-state case based on maintaining the average 1990's water levels represents an extreme situation in which current ground-water levels become fixed. The particle tracks calculated for the first one or two decades of the 40-year transient simulation are expected to be relatively close to future observations. After one or two decades, the actual tracks could start to shift in the direction of the results of the steady-state simulation in which 1990's water levels are maintained, assuming that substantial decreases in the rate of pumping from the High Plains aquifer actually occur in the future.

#### *Forty-year transient simulation*

Water level changes for the 1991-2000 period were estimated from water-level measurements for the 1990's. Initially, transient simulations were run for a ten-year stress period to allow comparison of the computed change in water levels with observations. This comparison provided a basis for calibrating flux rates to obtain a rough match to observed water-level changes for this period. Over this decade, water-rights appropriations for irrigation did not change significantly. Since the rate of ground-water pumping was much greater than the rate of recharge, adjustment of the recharge by return flow was used to attempt an approximate match of computed and observed ground-water level changes. In addition, specified-flux conditions along the southern boundary were adjusted to approximately match water-level changes along this boundary over the ten-year period. The specified flows out of the model area along this boundary increased from zero at the Bear Creek Fault zone in south-central Kearny County to maximum values in northern Haskell County, and then gradually back to zero in southeastern Gray County. This boundary condition should better fit the hydraulic head gradient from the river corridor to the south than constant heads along the southern boundary, a condition that was adequate for the 1940 simulation but which is unrealistic over a simulation time period in which large decreases in water levels have been observed.

A limit of 40 years was placed on the transient simulations because longer times would produce results that could have too large an uncertainty to be valid. The longer was the time within the 40-yr period, the greater was the uncertainty in the results. Three time steps per year over the simulation time period were found to be sufficient to obtain a converging solution. A specific yield of 0.18 was assumed for unconfined conditions in layers 1 and 2, and a storage coefficient of 0.0018 was assumed for confined conditions in layer 2.

The resultant water-level surface in the High Plains aquifer for the 40-year simulation shows a relatively steep gradient in an east-southeast direction from south-central to southeast Kearny County (Figure 38). In Finney County, the water-level surface shows that the

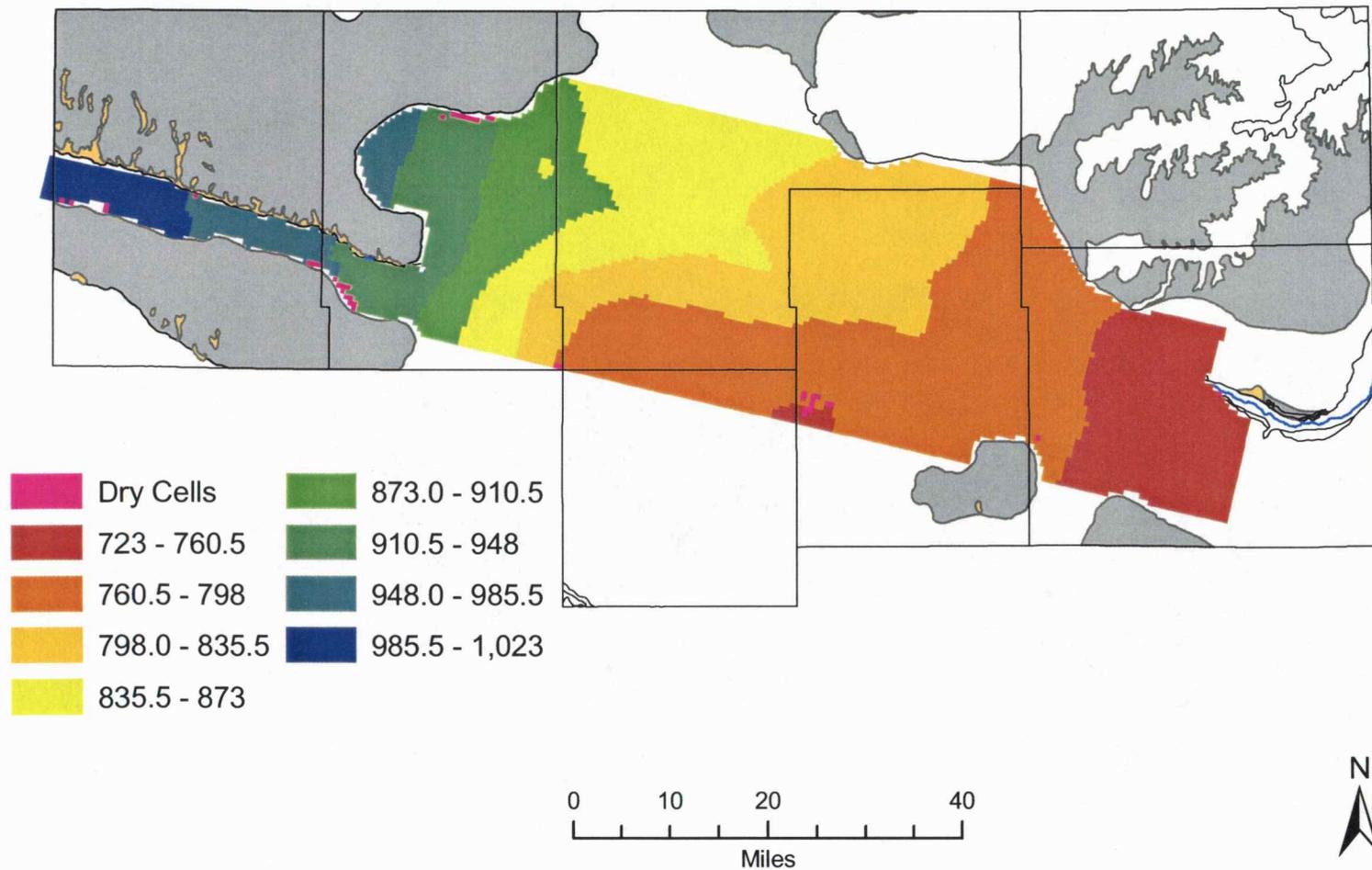


Figure 38. The water-level surface from the 40-year transient simulation based on average 1990's conditions. The elevations range from a maximum of 1023 m (3356 ft) in the west to a minimum of 723 m (2372 ft) in the east part of the regional model.

hydraulic head gradient is to the south. The pronounced downstream V's in the water-level contours indicate that there is substantial flow from the river valley outwards in the High Plains aquifer.

Comparison of the water-level isolines for the 40-year transient simulation with those observed during the 1990's shows that the water levels are similar in the alluvial valley in Hamilton County and western Kearny counties west of the Bear Creek Fault zone (Figure 39). The isolines are also relatively similar to the north of the Arkansas River in Gray and Ford counties and somewhat similar south of the river in eastern Gray County and southwest Ford County. The greatest differences in the isolines are in the region south of the river in southeast Kearny County and southern Finney County. These differences reflect the substantial water-level declines in the High Plains aquifer south of the river.

#### *Simulation run to steady-state equilibrium starting with 1990's water use*

This steady-state solution was based on initial conditions of the transient simulation, including the specified-flow conditions along the southern boundary of the model from the Bear Creek Fault zone to southeastern Gray County. The amount of recharge along this boundary that was required for the model to converge was equivalent to approximately 1 inch of water over the area of each grid cell along the boundary. Figure 40 displays the water-level surface for the simulation run to a steady-state. The results show that a large area of grid cells went dry from southeast Kearny County through southern Finney County and northern Haskell County to west-central Gray County. This is an expected result based on extrapolation through time of actual estimated recharge, ground-water pumping, and streambed leakage, or if at least the relative contributions of each are reasonably accurate.

The 40-year transient case and the steady-state solution for 1990's water use compare well in that the spatial distribution of computed head errors after ten years in the transient simulation (beginning with the "average 1990's" groundwater surface) appeared to be growing towards the error distribution obtained for the steady-state case. In addition, the general patterns that developed in the water-level surface for the transient simulation were similar to those for the steady-state simulation (Figure 40). This steady-state solution indicates that continued consumptive pumping of ground water from the High Plains aquifer in the area south of the river corridor would completely exhaust the aquifer based on the 1990's conditions.

#### *Steady-state simulation for constant 1990's water-level conditions*

The steady state simulation in which the average 1990's water levels were maintained as constant required a reduction of about 84 percent in the 1990's water use with no return infiltration. As indicated above, this is approximately equivalent to reducing irrigation pumping to 21 percent of estimated use with 25 percent return flow (aquifer recharge). The pattern in the water-level surface for this simulation (Figure 41) is generally similar to that for the observed data (Figure 36), although the simulated surface is generally smoother in some areas than the detailed differences of the observed surface. A comparison of the isolines for

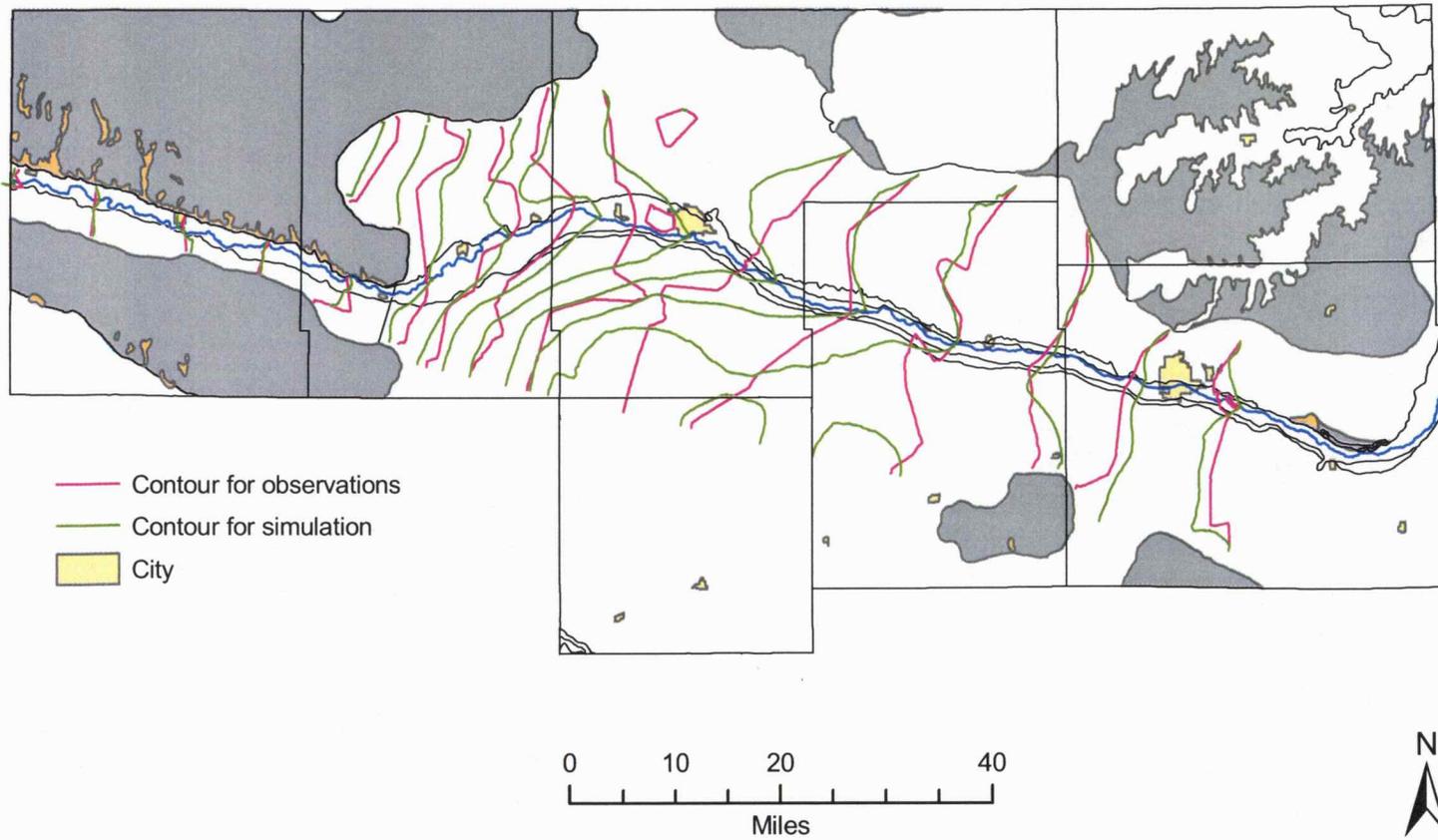


Figure 39. Comparison of the water-level surface contours in model layer 2 for the average 1990's observations and the 40-year transient simulation based on the 1990's conditions. The two contours near the Colorado border are for 1020 m and the two at the east side of the model are for 740 m.

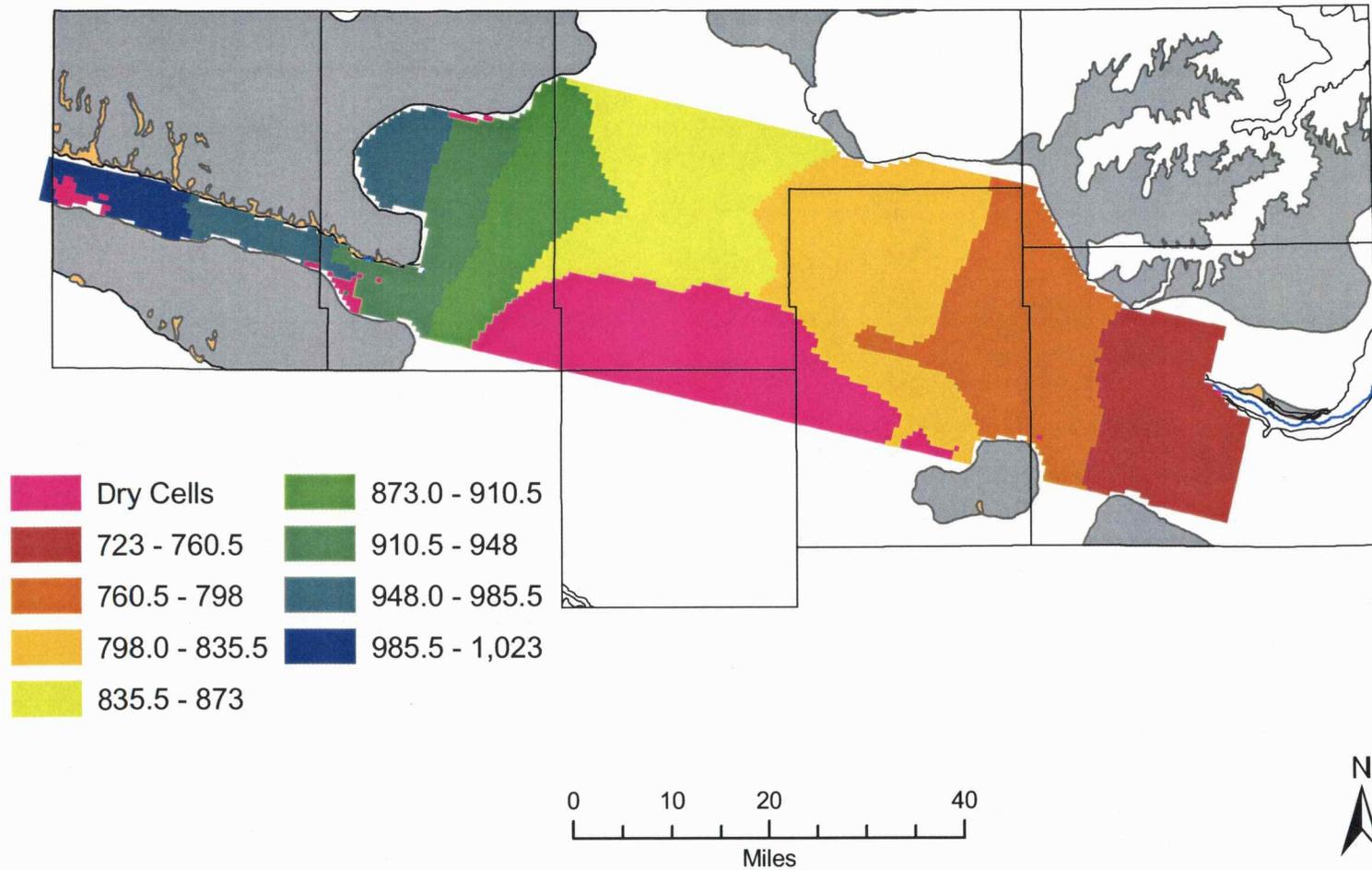


Figure 40. The water-level surface from the steady-state simulation based on average 1990's water use and specified fluxes along the southern boundary of the model from southeastern Kearny County to southeast Gray County. The elevations range from a maximum of 1023 m (3356 ft) in the west to a minimum of 723 m (2372 ft) in the east part of the regional model.

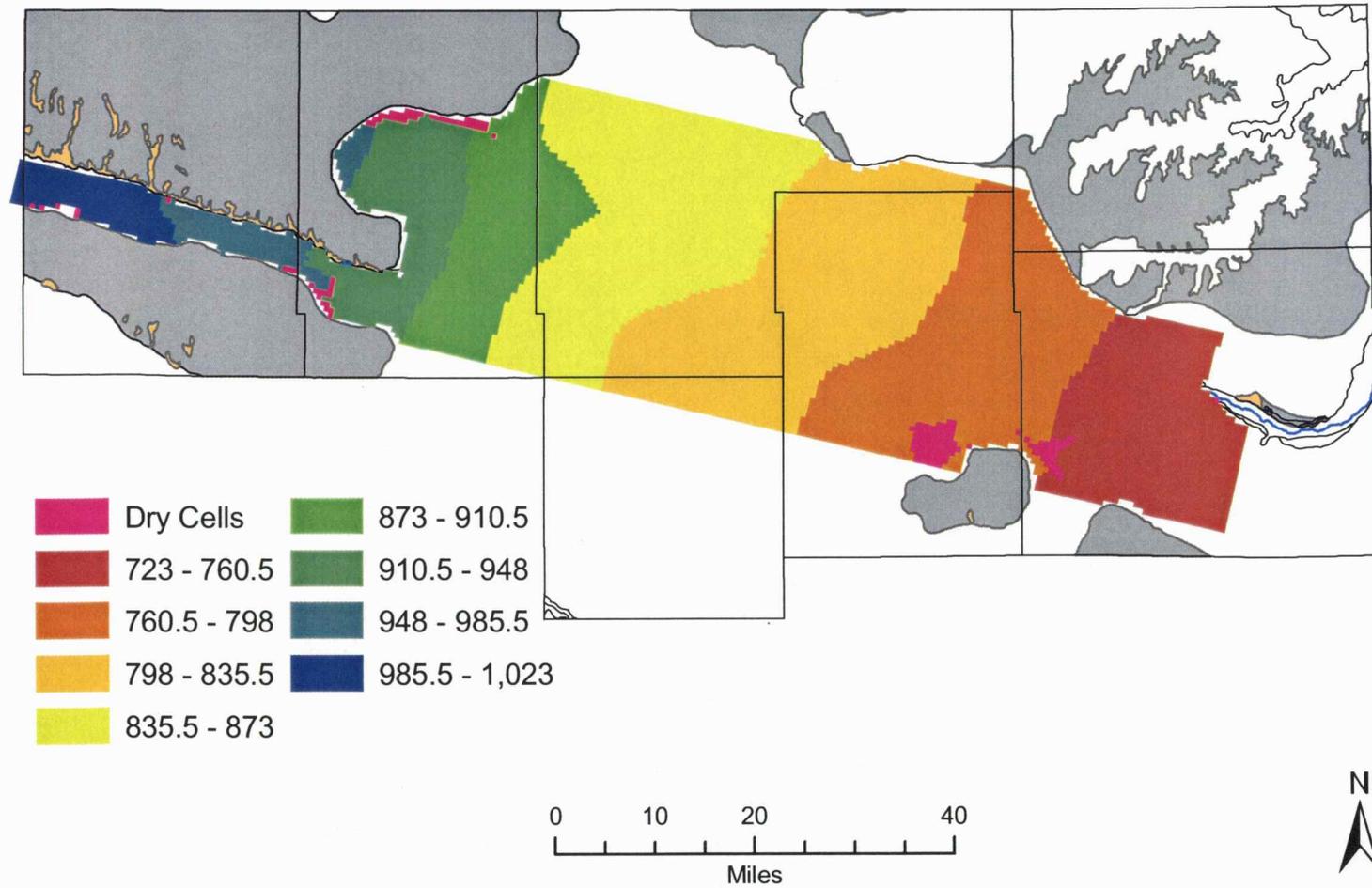


Figure 41. The water-level surface in model layer 2 for the steady-state simulation with water use reduced sufficiently to maintain average ground-water levels of the 1990's.

both the simulated and observed water-level surfaces indicates that the steady-state simulation maintains the 1990's water levels relatively well across the model area (Figure 42). The location with the greatest difference is in central Gray County where the simulated water levels are somewhat lower than the observed. This suggests that pumping would have to be reduced even more than 84 percent in central Gray County to maintain average 1990's water levels.

Figure 43 shows the simulated baseflow or seepage of the Arkansas River for the steady-state case with water use reduced sufficiently to maintain 1990's ground-water levels. As for the 1940 steady-state case, the river-flow simulation was not forced by recalibration of the model to be similar to the observed flow. Thus, the results reflect what the ground-water flow simulation produced in terms of river-aquifer interactions. The line in Figure 43 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  $\pm 3$  cfs of a running average along the river in the corridor model. The smooth line in Figure 43 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.

In contrast with the 1940 observed and simulated baseflows that indicated cumulative gains in flow along the Arkansas River from the state line to Dodge City (Figure 35), the simulated 1990's streamflow indicates substantial losses (Figure 43). The pattern in the flow losses is similar to the observed flow changes along the corridor 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 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 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 negligible between Coolidge and Syracuse (Figure 43). As indicated in the discussion of Figure 35, 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 insignificant change that was simulated. The actual average change in flow from Coolidge to Syracuse during 1991-1999 was a loss of 10.3 cfs.

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 43). 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 43). Considering that evapotranspiration consumption of water would make the

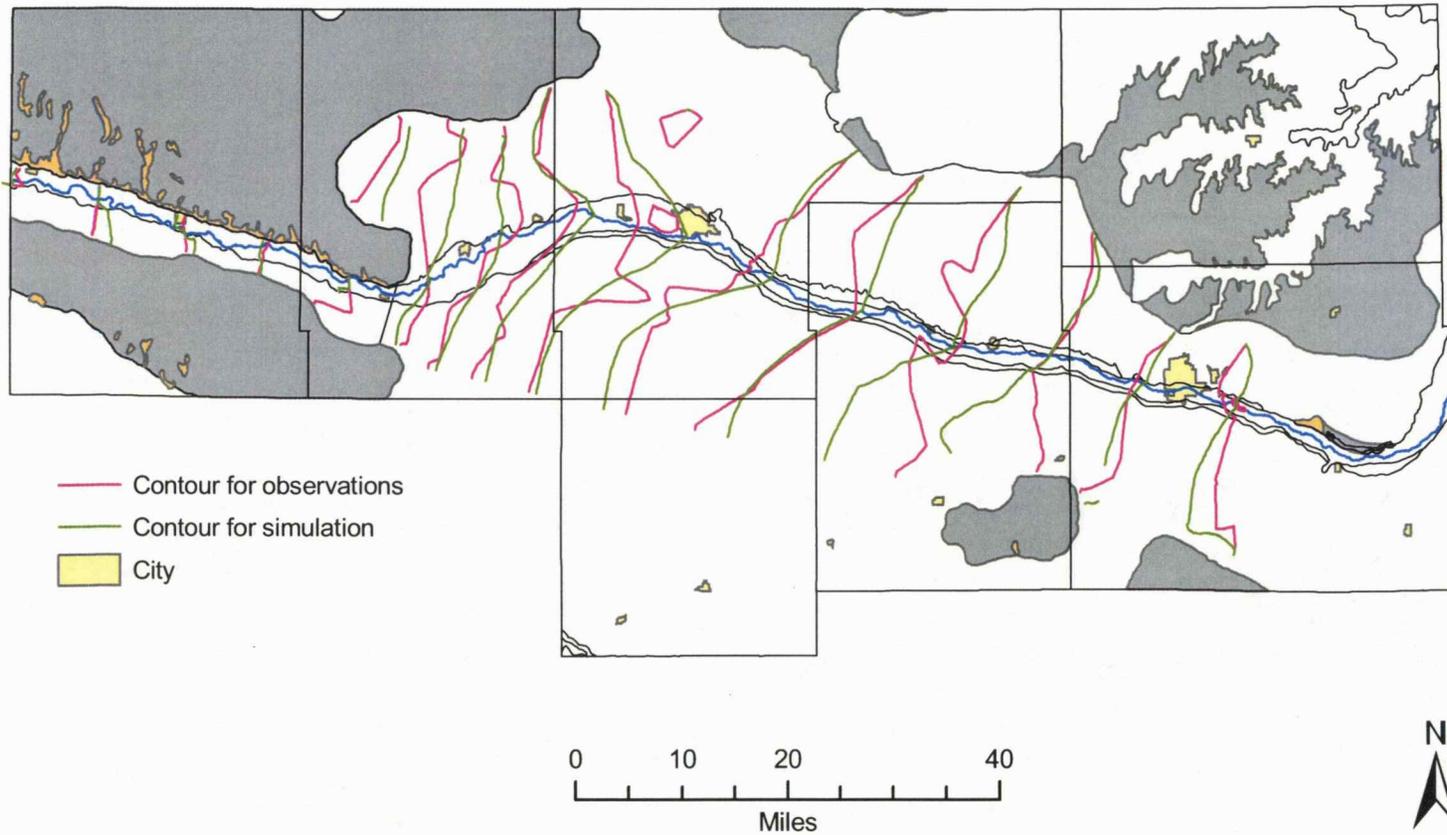


Figure 42. Comparison of contours based on observed and simulated water-level surfaces in model layer 2 for the steady-state simulation with water use reduced sufficiently to maintain average ground-water levels of the 1990's. The two contours near the Colorado border are for 1020 m and the two at the east side of the model area are for 740 m.

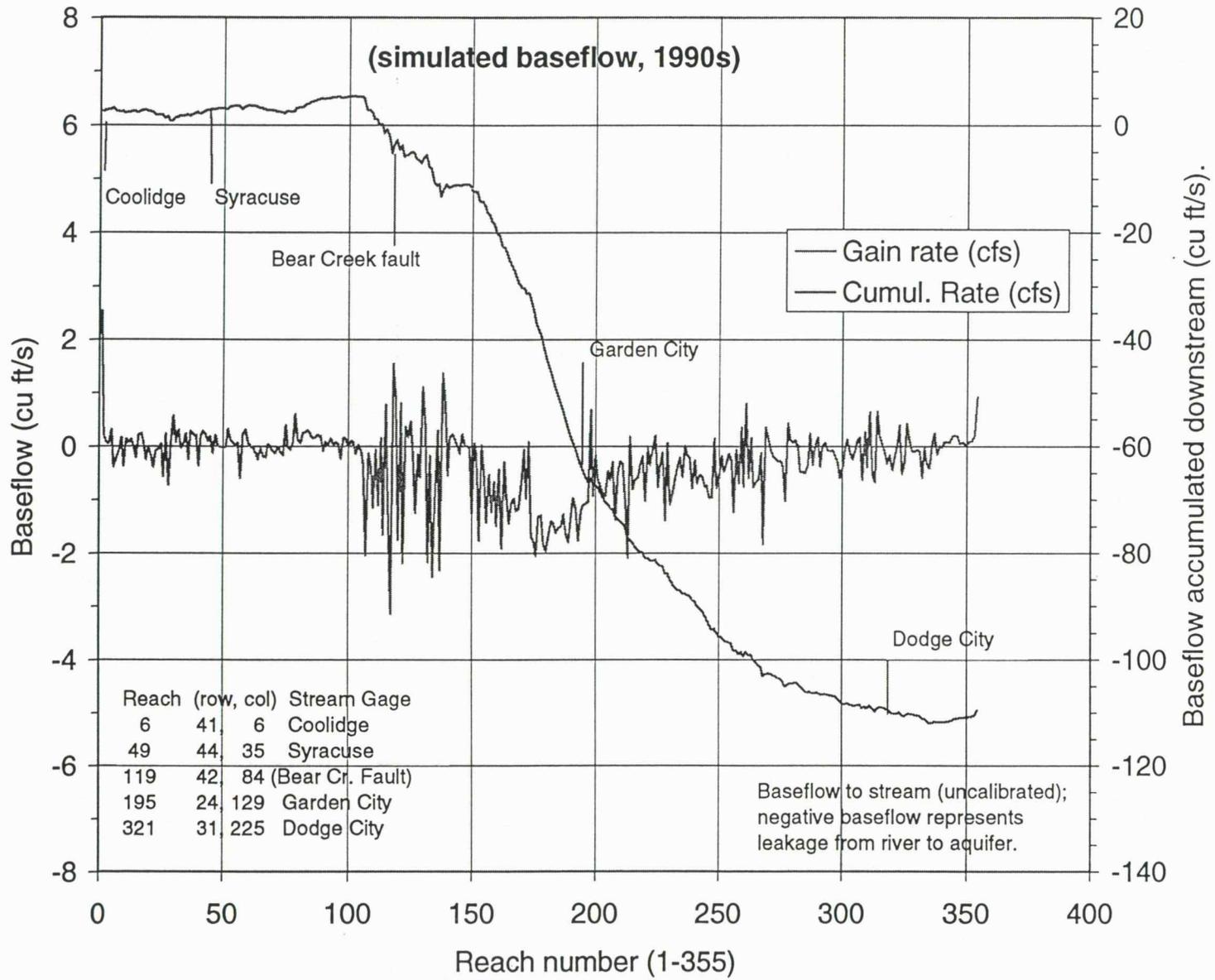


Figure 43. Baseflow (gains) and seepage (losses) along the Arkansas River for 1990's conditions with reduced water use (wc16n).

simulated flow losses greater, the simulation is comparatively a good representation of the average river-aquifer interactions during the 1990's.

An additional factor that should be considered when comparing simulated with actual changes in river flow is that the model used average conditions for the 1990's such that the river was assumed to flow through the entire corridor throughout the period. The water-level data used in the model span the time from January 1991 to January 2000, which is the calendar period 1991-1999 for river flow. During 1991 to mid-1995, the river was dry essentially all the time at Dodge City and had from low to no flow conditions at Garden City. From mid-1995 through 1999 the river contained moderate to substantial flows most of the time at Garden City and from mid-1996 through 1999 was usually flowing at Dodge City. The greatest annual flow loss (122,300 acre-ft) between Garden City and Dodge City was in 1995 even though the river flowed for only one month at Dodge City. In spite of the relatively large flows in the river during 1997-1999, the flow losses (72,800-78,400 acre-ft/yr) were substantially smaller than for 1995. The large variability in the river seepage is related to the amount and time of channel flow, the length of river channel with flow, the saturation of the alluvial aquifer, and the leakage rate from the alluvium to the High Plains aquifer. If the river were flowing constantly at an average rate, the amount of seepage might be expected to be greater than observed because river seepage would occur along the entire channel length all of the time. However, the fact that the largest flow loss (1995) was for the onset of appreciable flow after a dry period indicates that the alluvial aquifer was able to accept a much larger amount of river infiltration than during constant flow conditions through the river stretch. The small range in the observed flow loss between Garden City and Dodge City for 1977-1999, a period of nearly continuous flow at Dodge City, suggests that the leakage rate from the alluvium to the High Plains aquifer is a limiting factor in the amount of seepage allowed from the riverbed to the alluvium.

### **Forecasts of Salinity Movement (Particle Tracking)**

#### ***Early development conditions (circa 1940)***

Particle tracking for the 1940 simulation of ground-water flow was run to allow the particles to move until exiting at a grid cell or stopping at the edge of the model area to show the long-term paths if the system was assumed to approximate predevelopment conditions. Two sets of particle-track origins were used for the simulations, one with particles that started from the center of grid cells through which the Arkansas River passes and the other for particles originating in the center of selected grid cells along the major canals diverting river water for irrigation. The result of a MODPATH simulation was a set of points that move progressively farther from the starting location. A program was written to draw lines that connected the particle points to better show the particle path. The particle tracks for the 1940 simulations are displayed as two sets of figures, the first for the entire particle paths and the second for the particle tracking points for 40 years of flow time.

Figure 44 shows the entire particle paths that originate from the river nodes for the whole Arkansas River corridor. Figures 45-47 display the west, central, and east portions of

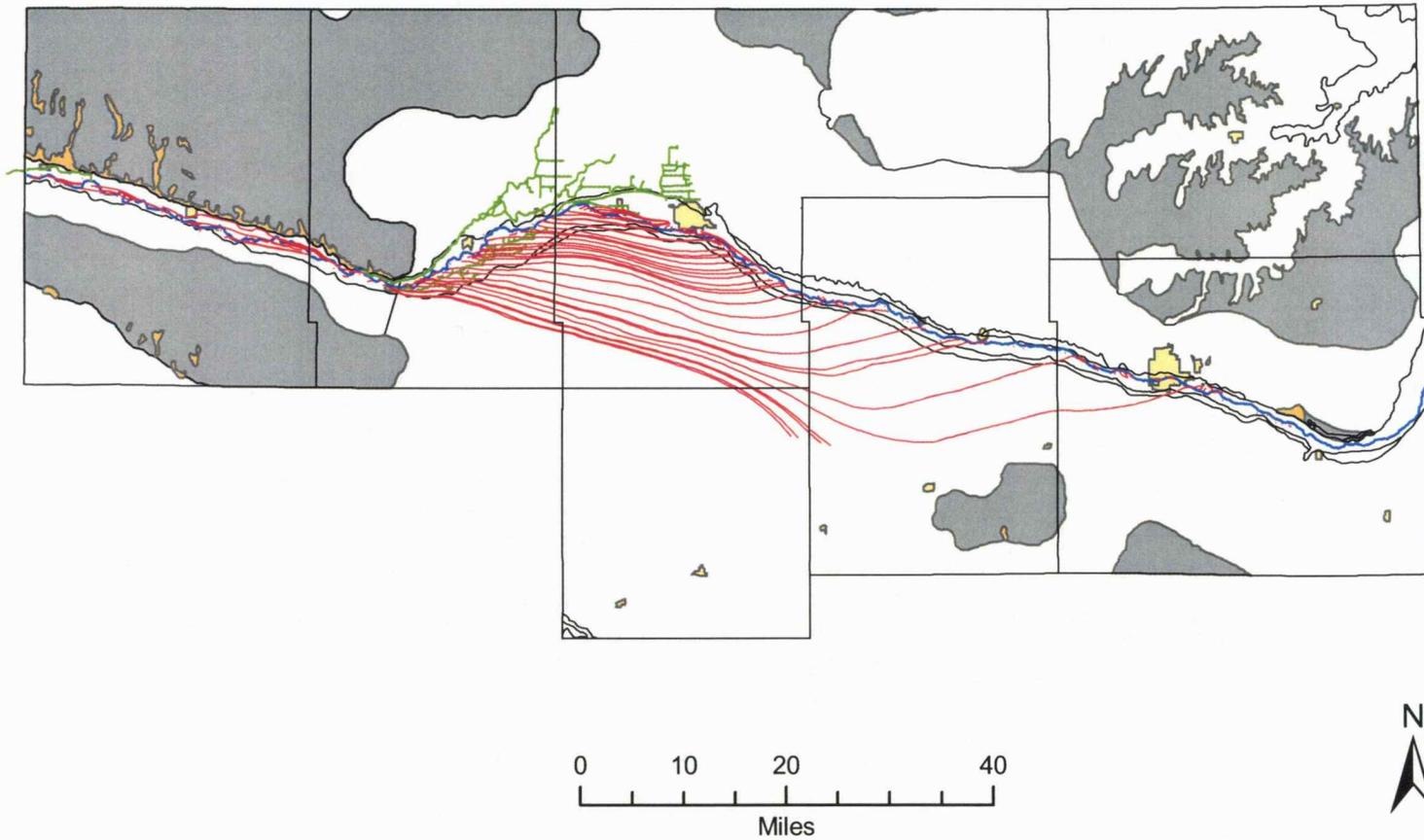


Figure 44. Particle path lines for the 1940 steady-state simulation with particle origins in grid cells along the Arkansas River in southwest Kansas. The particles were allowed to move until reaching points of termination.

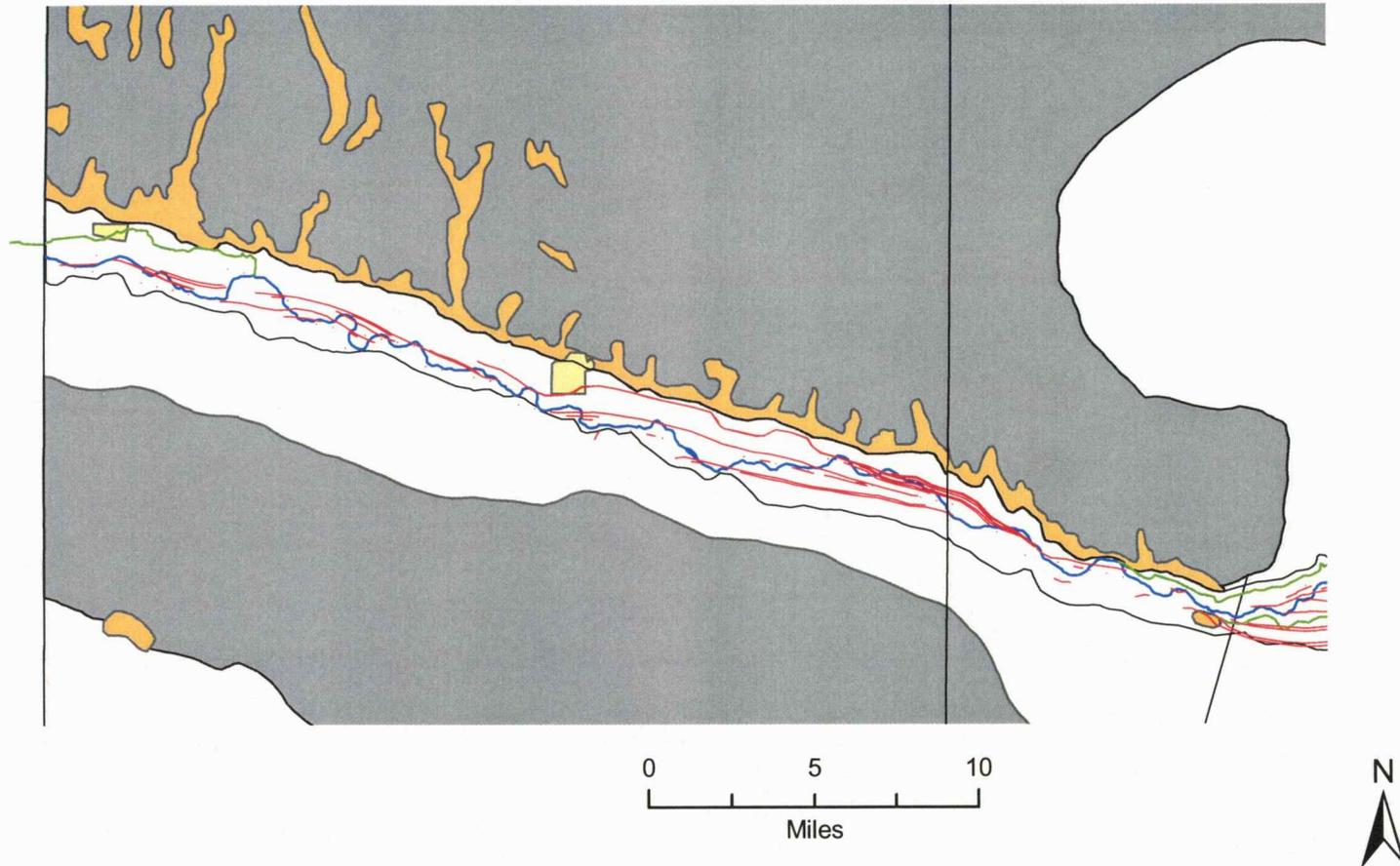


Figure 45. Particle path lines for the 1940 steady-state simulation with particle origins in grid cells along the Arkansas River in southwest Kansas. The particles were allowed to move until reaching points of termination. The area shown is an enlargement of the western third of Figure 44 and includes Hamilton County and western Kearny County.

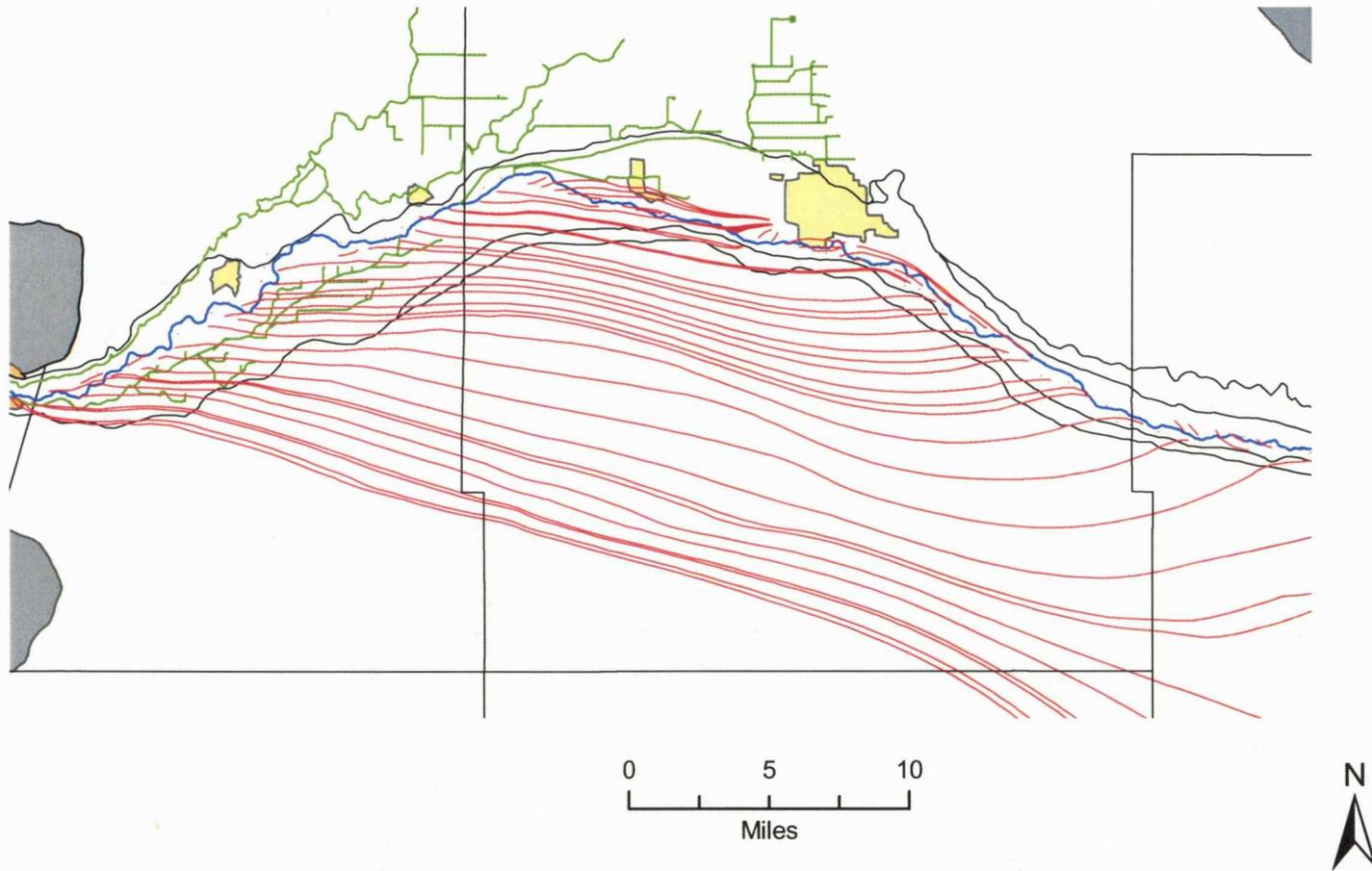


Figure 46. Particle path lines for the 1940 steady-state simulation with particle origins in grid cells along the Arkansas River in southwest Kansas. The particles were allowed to move until reaching points of termination. The area shown is an enlargement of the central third of Figure 44 and includes eastern Kearny County, southwest Finney County, western Gray County, and northern Haskell County.

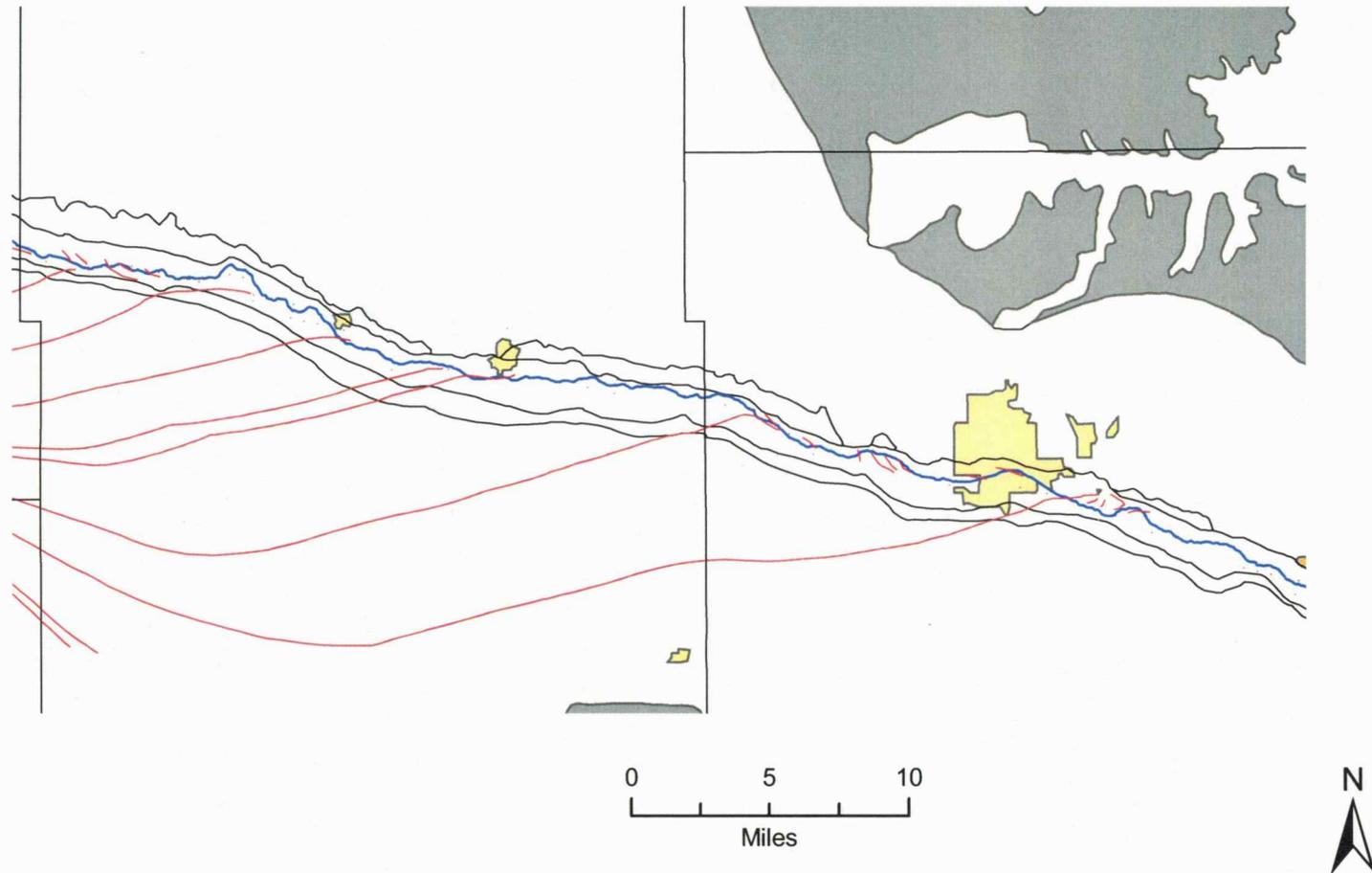


Figure 47. Particle path lines for the 1940 steady-state simulation with particle origins in grid cells along the Arkansas River in southwest Kansas. The particles were allowed to move until reaching points of termination. The area shown is an enlargement of the eastern third of Figure 44 and includes Gray County and western Ford County.

Figure 44 enlarged for easier viewing of detail. Some of the particles do not appear to start exactly at the river in the enlarged figures; the reason is that the centers of the river grid cells (each a half-mile on a side) do not fall precisely on the river line. The general pattern of particle movement indicates that the only particles that move from the river to the alluvial aquifer and then enter the High Plains aquifer originate along the east-northeast trending section of the river from the Bear Creek Fault zone to the Kearny-Finney county line. A few of the most western of these paths exit the model area at the southern boundary. Most of the flow paths reenter the river. The farther the particle origin is located to the east, the shorter is the particle path for those particles that flow through part of the High Plains aquifer.

The view of the western part of the river corridor exhibits particle paths that leave the river, flow within the Quaternary alluvial aquifer, and then reenter the river (Figure 45). The line across the river valley on the eastern side of Figure 45 represents the division between the alluvial trough in western Kearny County and the High Plains aquifer. The line is approximately the west side of the Bear Creek Fault zone; the center of the fault zone as indicated by a line for the fault on maps is about 3 miles farther to the east. Essentially none of the particles in Figure 45 flow within the older alluvial aquifer underlying the sand dunes. Not all of the particles originating in the river grid cells leave the river. The particles that do leave are from those cells that have a flow loss (the portions of the high-frequency line with negative baseflow in Figure 35). Many of the particles that do leave the river have short flow paths before reentering the river. Several paths are relatively long before reentering the river.

Similar to the western river corridor, not all of the particles in river nodes within the central corridor show flow paths and some paths are very short before reentering the river (Figure 46). Again, those paths that appear start from grid cells where the simulated baseflow is negative. The first particle paths that leave the alluvial aquifer and enter the High Plains aquifer south of the alluvium boundary start within the area overlying the Bear Creek Fault zone. None of the paths starting at river grid cells that enter the alluvial aquifer in Kearny County enter the High Plains aquifer north of the river valley. This fits the ground-water flow directions expected from the 1940 water-level surface mapped by McLaughlin (1943) for Kearny County. Particles that leave the river in Finney County flow various distances parallel to the general river direction within the alluvial aquifer; none of the paths enter the High Plains aquifer outside of the alluvial valley. Only a small percentage of the particles starting at river grid cells leave the river; those that do leave reenter the river after relatively short flow paths (Figure 46).

Figures 48-51 display the first 40 years of particle path travel times shown in Figures 44-47. Of particular note in these figures is that none of the particle paths originating at the river nodes leaves the boundaries of the alluvium, although a couple paths cross the edge of the recent alluvium and end near the boundary of the alluvial terrace deposits in westernmost Finney County.

Figures 52 and 53 show the long-term particle tracks for the 1940 steady-state simulation with origins at selected grid cells across which major diversion canals cross. Only the central river corridor is enlarged because there are only two paths in the west part and no

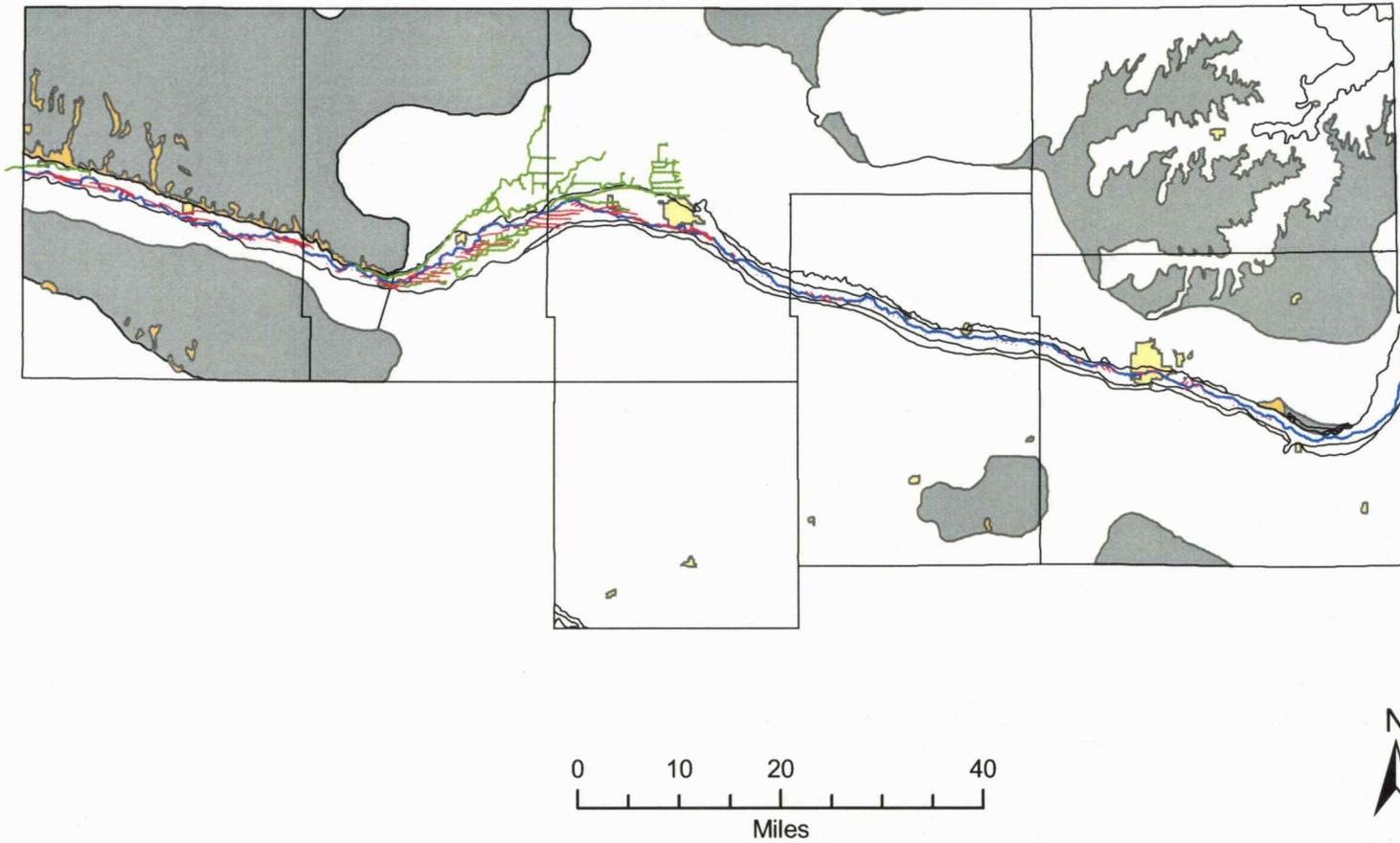


Figure 48. Particle path lines for the 1940 steady-state simulation with particle origins in grid cells along the Arkansas River in southwest Kansas. Simulated particle travel time was limited to the first 40 years of the path lines shown in Figure 44.

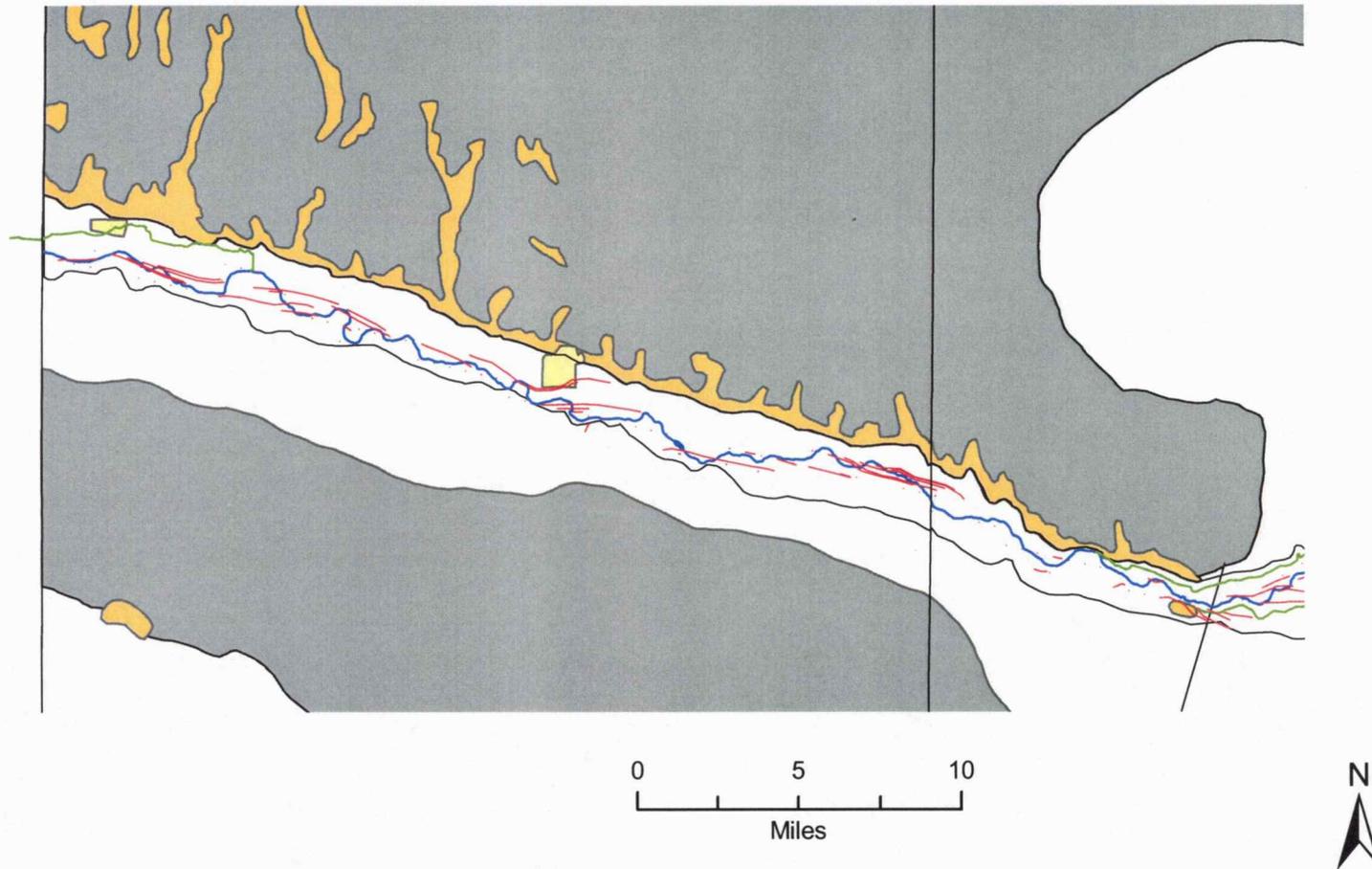


Figure 49. Particle path lines for the 1940 steady-state simulation with particle origins in grid cells along the Arkansas River in southwest Kansas. The area shown is an enlargement of the western third of Figure 48 and includes Hamilton County and western Kearny County. Simulated particle travel time was limited to the first 40 years of the path lines shown in Figure 45.

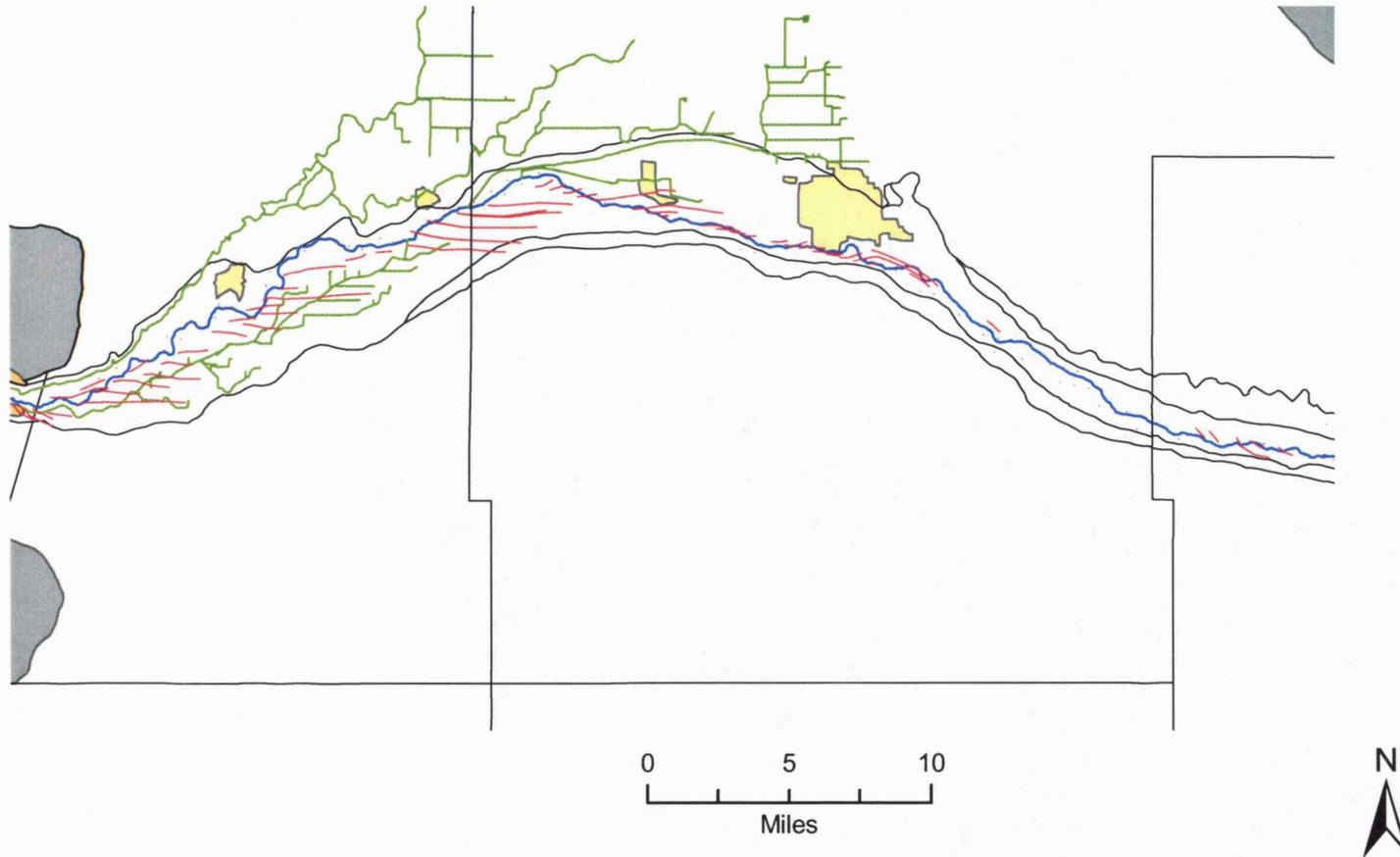


Figure 50. Particle path lines for the 1940 steady-state simulation with particle origins in grid cells along the Arkansas River in southwest Kansas. The area shown is an enlargement of the central third of Figure 48 and includes eastern Kearny County, southwest Finney County, and northwest Gray County. Simulated particle travel time was limited to the first 40 years of the path lines shown in Figure 46.

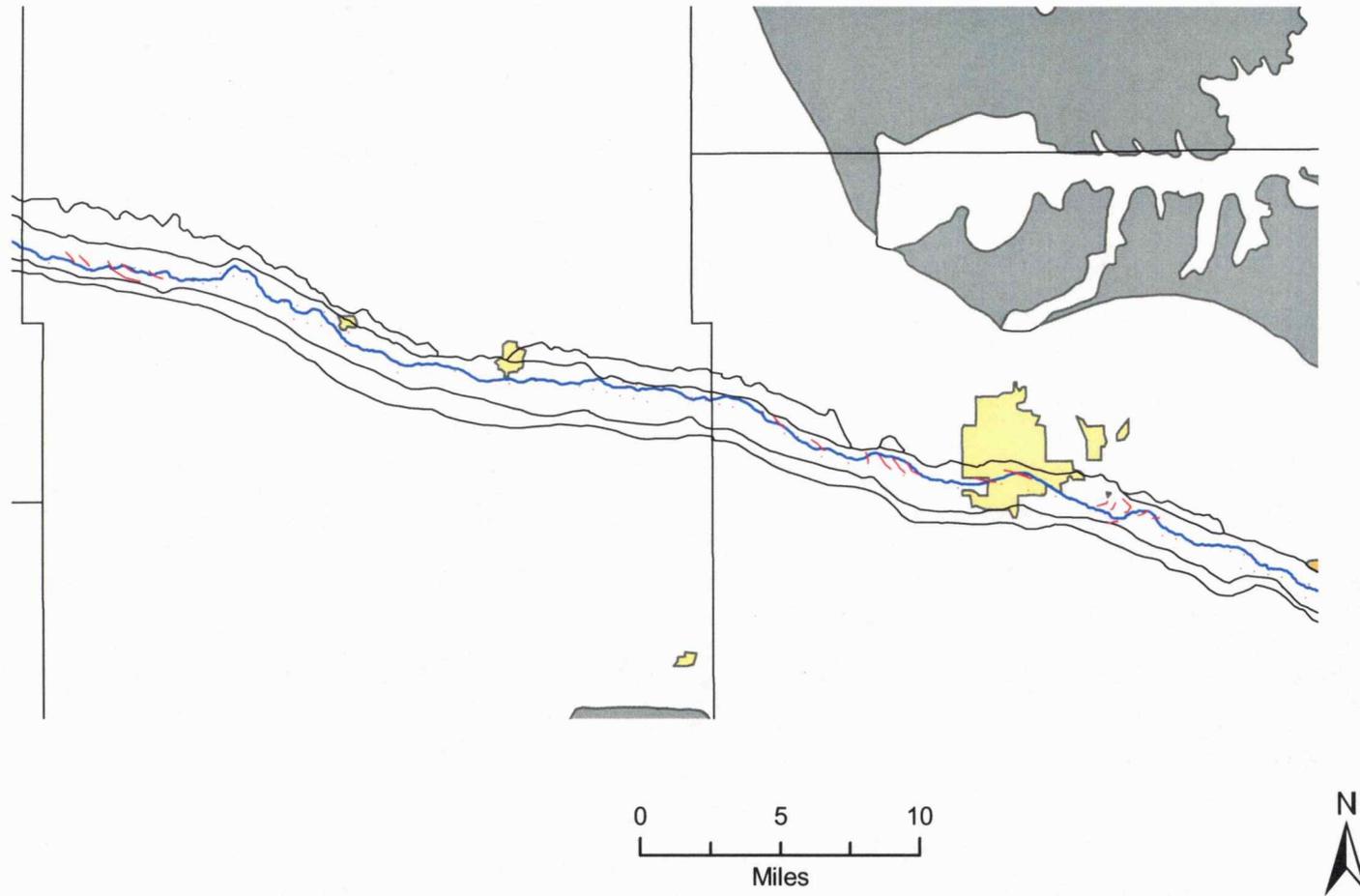


Figure 51. Particle path lines for the 1940 steady-state simulation with particle origins in grid cells along the Arkansas River in southwest Kansas. The area shown is an enlargement of the eastern third of Figure 48 and includes Gray County and western Ford County. Simulated particle travel time was limited to the first 40 years of the path lines shown in Figure 47.

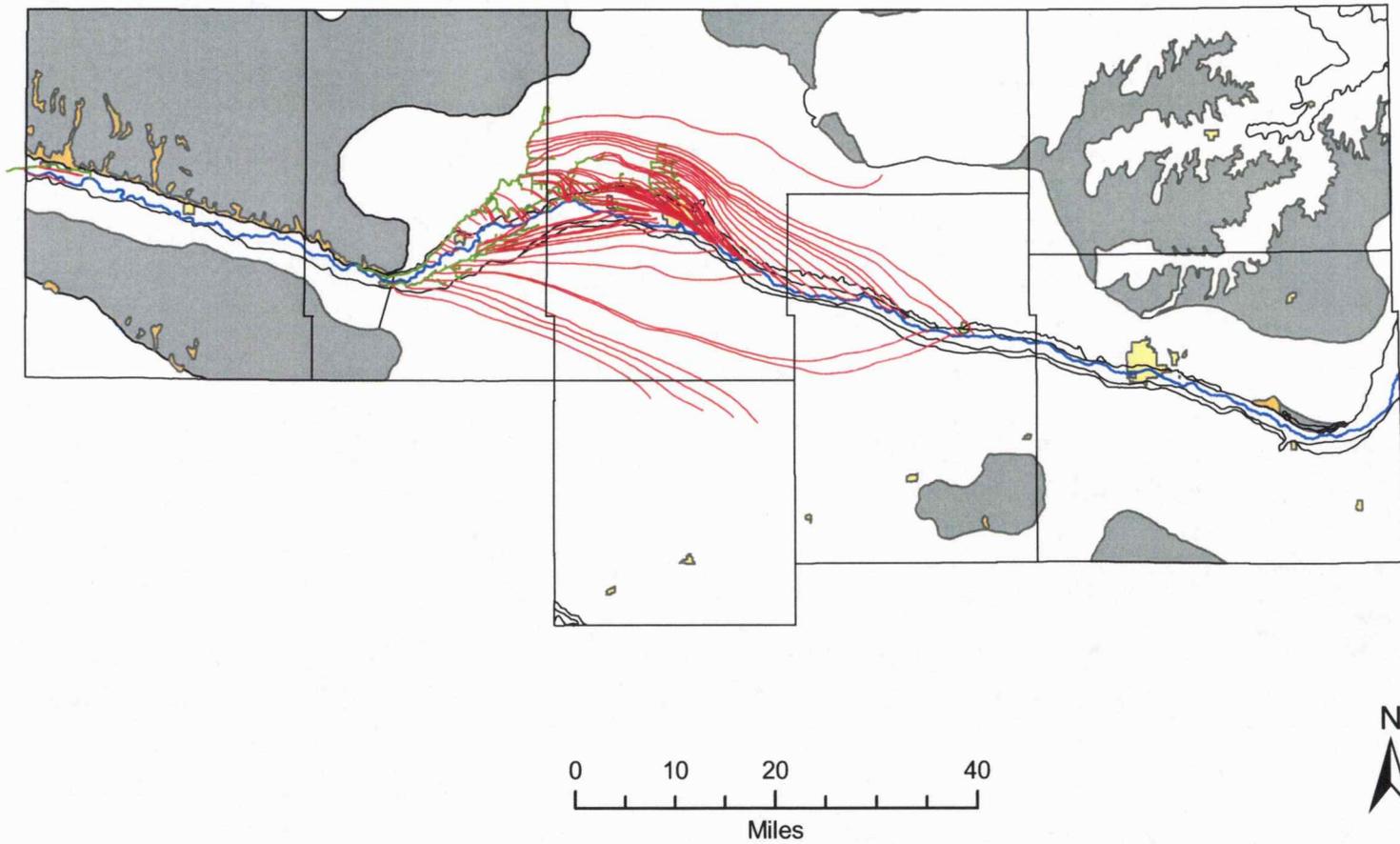


Figure 52. Particle path lines for the 1940 steady-state simulation with particle origins in selected grid cells along the diversion canals in southwest Kansas. The particles were allowed to move until reaching points of termination.

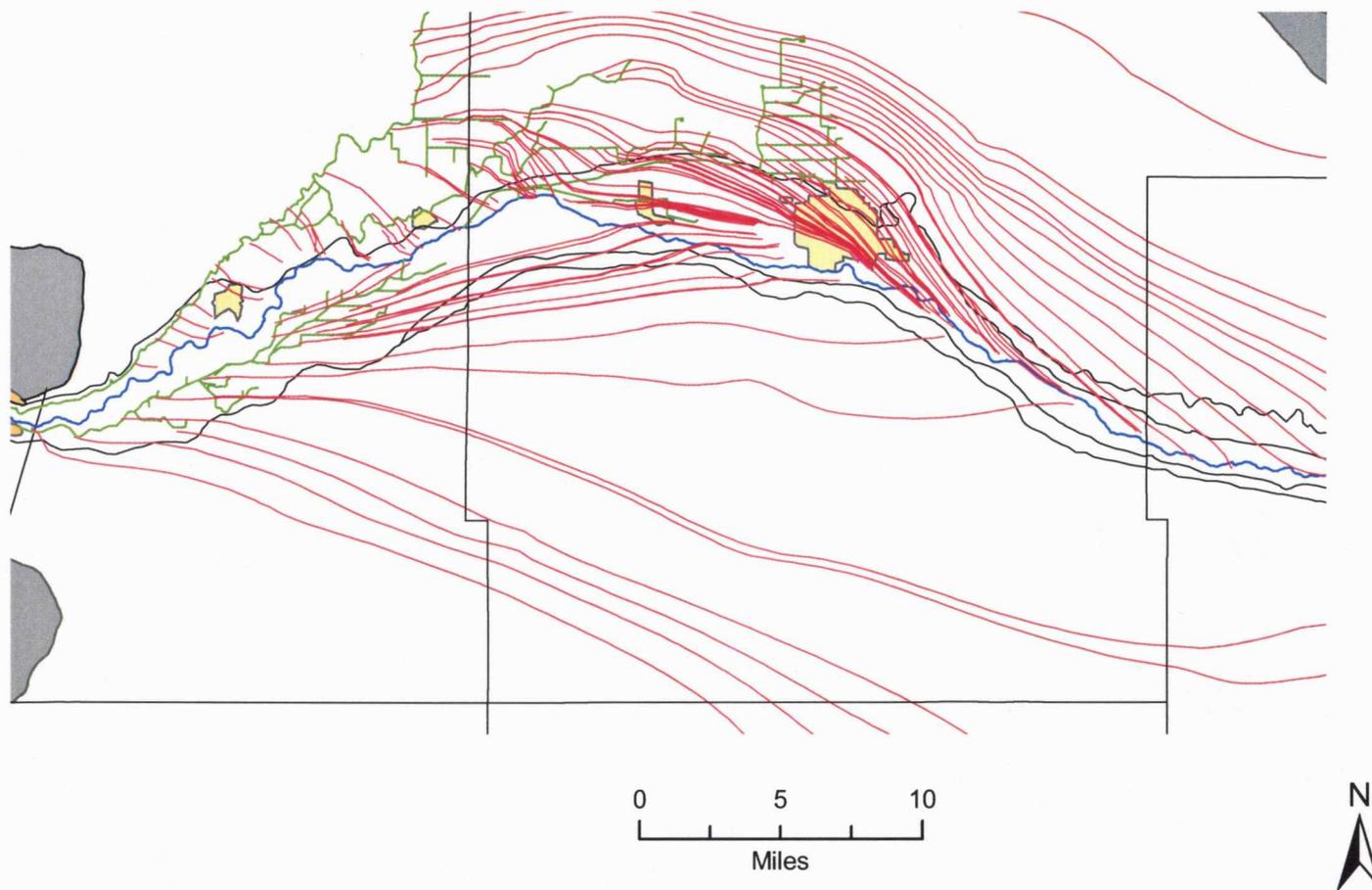


Figure 53. Particle path lines for the 1940 steady-state simulation with particle origins in selected grid cells along the diversion canals in southwest Kansas. The particles were allowed to move until reaching points of termination. The area shown is an enlargement of the central portion of Figure 52 and includes Kearny County, most of Finney County, and northwestern Gray County.

particle origins in the east portion of the river corridor. The two particle paths in western Hamilton County originating along the Frontier ditch remained within the Quaternary alluvial aquifer before entering the Arkansas River after a few miles travel. The particle tracks that start along the South Side canals produce a similar pattern as those particles that leave the river in Figures 44 and 46. A few of the particles flow to the southeast to the model boundary but most of the particles flow for various distances to the Arkansas River. In general, the farther the particle origin is located to the northeast along the South Side canals, the shorter is the flow path to the river. Particles starting from the Amazon and Great Eastern canals that lie at a latitude close to or south of the most northern latitude of the large bend in the Arkansas River in western Finney County have a much shorter path to the river in comparison with those farther to the north. The farther the track origin is located to the north, the longer is the track before joining the river. The most northern particle does not enter the river but flows to the east where it leaves the model area in the more thinly saturated portion of the High Plains aquifer.

Figures 54 and 55 exhibit the first 40 years of particle path travel times shown in Figures 52 and 53. In these figures, nearly all the flow paths from the South Side canals end within the boundaries of the alluvial aquifer and do not enter the High Plains aquifer outside the boundary. The tracks from the canals north of the river are generally shorter for those particles that start north of the alluvial valley than for those that begin within the valley.

The movement of particles from the Arkansas River and the location of the South Side canals in the eastern half of Kearny County indicate that water from the river and ground-water in the alluvial aquifer south of the river could enter the regional ground-water flow system in the High Plains aquifer during what are usually considered to be predevelopment conditions. If the 1940 ground-water levels were representative of conditions that occurred in this area before the start of diversions and ground-water pumping, ground water affected by river-aquifer interaction would have moved within the alluvial aquifer into the High Plains aquifer outside the alluvium in southeastern Kearny County. Early data indicate that ground-water was very fresh in the High Plains aquifer underlying the alluvial aquifer in the river corridor. Present data show that the water in the High Plains aquifer is still very fresh in the parts of Kearny and Finney counties to the south of the Arkansas River and outside the ends of pathlines originating from the river and the diversion canals (Whittemore, 2000b). Holmes (in McLaughlin, 1943) reports an analysis of shallow ground water from the High Plains aquifer that is located about 2 miles east (along the direction of ground-water flow) of the alluvial aquifer boundary. The water was very fresh and contained sulfate and TDS concentrations of 64 and 254 mg/L, respectively. The sulfate concentration was somewhat greater than the less than 50 mg/L expected in the deeper portions of the High Plains aquifer such as found in wells at Lakin in 1902 (Parker, 1911). The somewhat greater sulfate content in the water produced by the well east and south of the alluvial valley fits the general flow of ground water with even greater sulfate and TDS contents in the alluvial aquifer towards and into the shallow part of the High Plains aquifer to the west of this well. However, the water in the alluvial aquifer that migrated to the east could not have been as saline as observed from 1940 to the present because otherwise the salinity of the water in the shallow part of the High Plains aquifer 2 miles to the east would have been expected to be much greater. Assuming similar patterns of

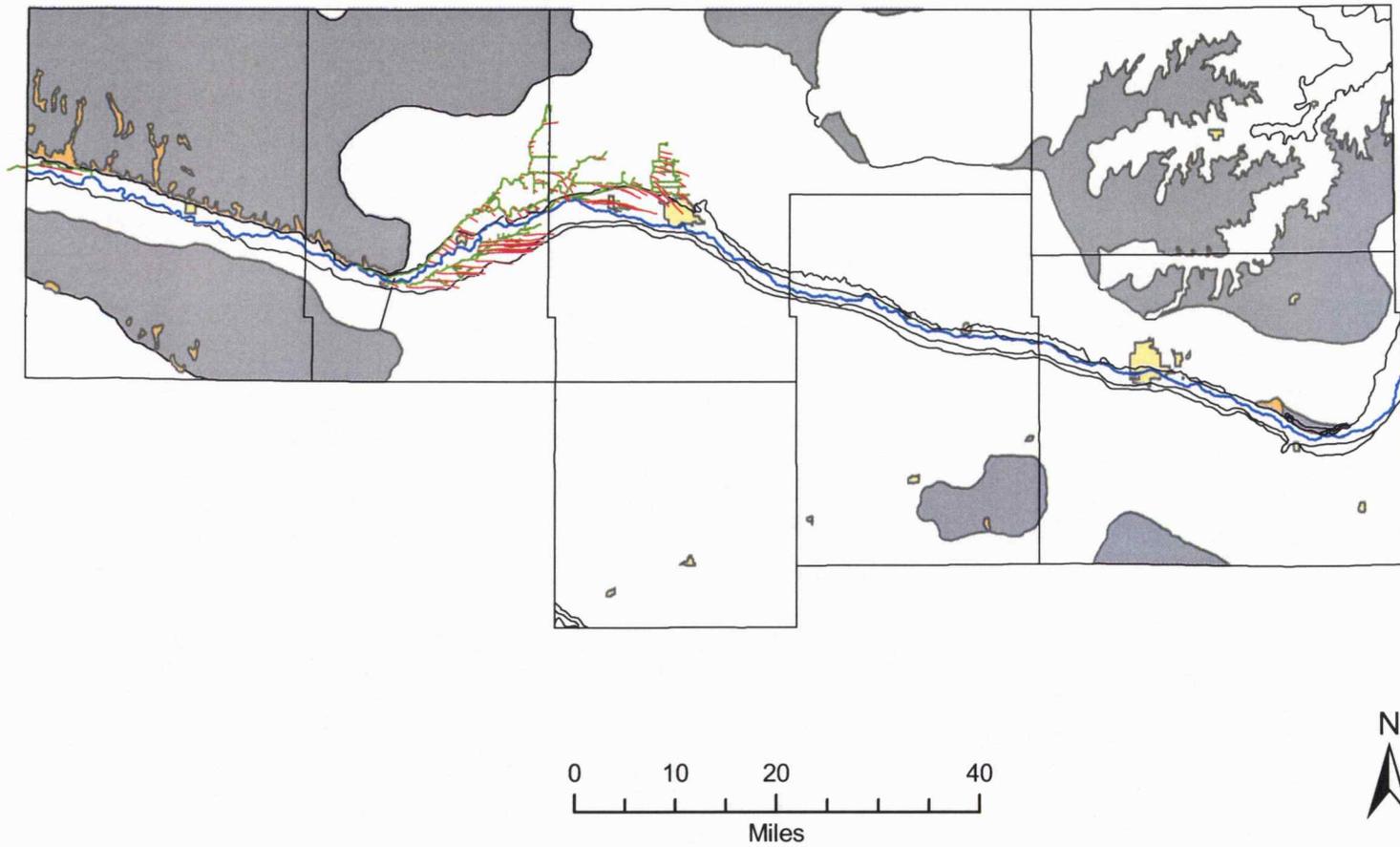


Figure 54. Particle path lines for the 1940 steady-state simulation with particle origins in selected grid cells along the diversion canals in southwest Kansas. Simulated particle travel time was limited to the first 40 years of the path lines shown in Figure 52.

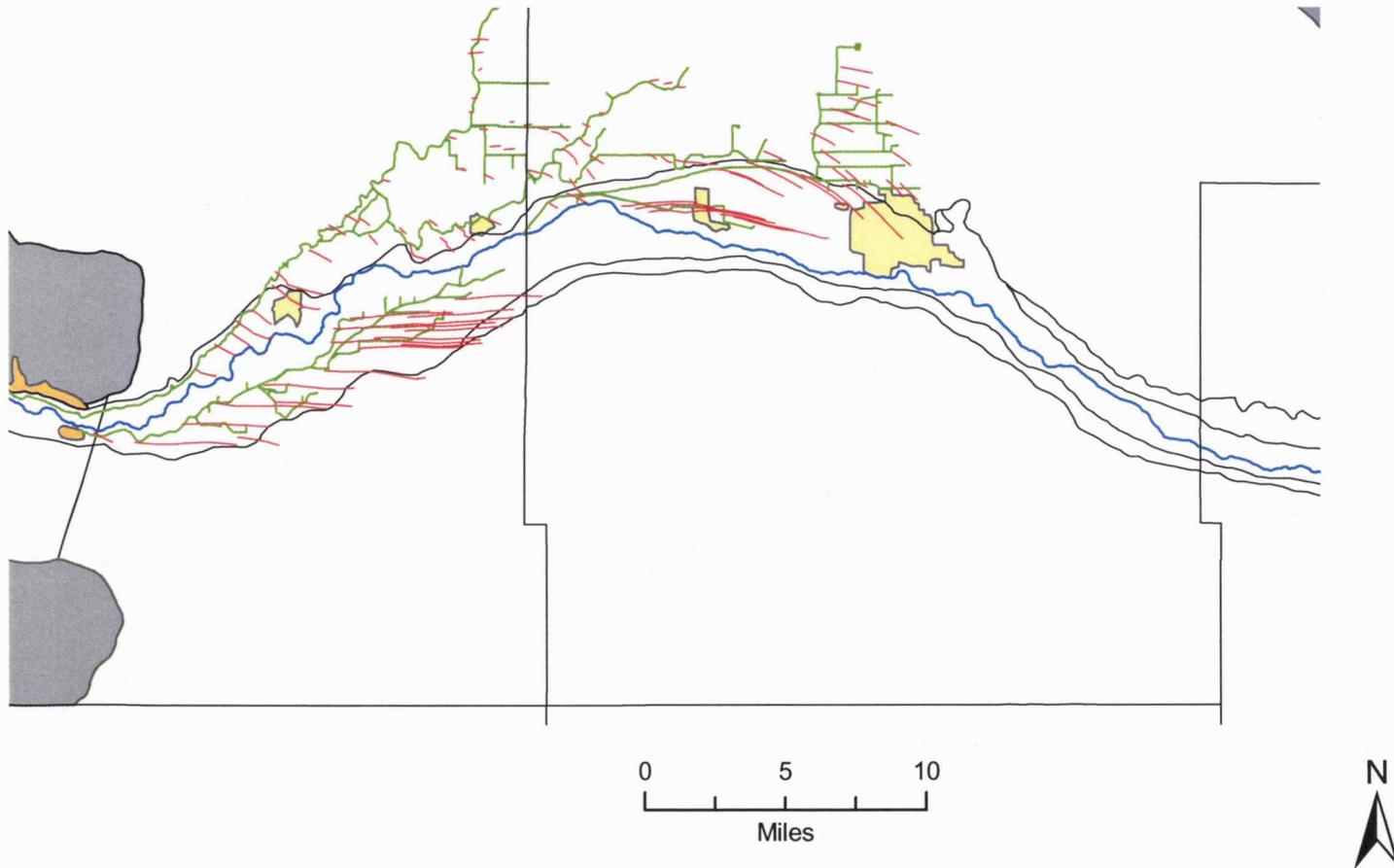


Figure 55. Particle path lines for the 1940 steady-state simulation with particle origins in selected grid cells along the diversion canals in southwest Kansas. The area shown is an enlargement of the central portion of Figure 54 and includes Kearny County, most of Finney County, and northwestern Gray County. Simulated particle travel time was limited to the first 40 years of the path lines shown in Figure 53.

particle movement for predevelopment conditions as in 1940, this observation indicates that the salinity of the Arkansas River was appreciably less before substantial irrigation diversions began or that only a small portion of Arkansas River water entered the alluvial aquifer south of the river in eastern Kearny County before diversions.

The increase in sulfate concentration in the deep portion of the High Plains aquifer at the location of the 1940 well described above that was 2 miles east of the alluvium boundary in Kearny County is now approximately 100 mg/L (Whittemore and Schloss, 2000). This fits the movement of saline water from the alluvial aquifer underlying the South Side ditch area towards the east along the particle pathlines during the more than 100 years that the ditches have been in operation. The salinization of the High Plains aquifer north of the river and underlying the ditch service area east of the Amazon canal in eastern Kearny and western Finney counties fits the flow paths in the 1940 simulation. However, declines in water levels after the 1940's greatly increased the downward movement of the salinity into the aquifer. The salinization of the High Plains aquifer is further discussed in the section below on the simulations based on the 1990's conditions.

### ***Projections from 1990's conditions***

#### ***Forty-year transient simulation***

Particle paths were generated for the 40-year transient simulation starting with the average 1990's conditions and with particle origins at river grid cells (Figures 56-59). Similar to the enlarged illustrations of the 1940's paths, Figures 57-59 portray the west, central, and east portions of Figure 56. Due to the very large size of the computer files for this run, the number of particle origins was reduced to 1/3 of the total river nodes for simulations for the entire river corridor in order to process the particle points and generate the pathlines. The simulation was run for particle origins at all of the river nodes along the central portion of the river corridor to illustrate detail in this area.

The particle paths for the 40-year transient simulation based on the 1990's conditions (Figures 56-59) are different from the tracks for the 1940 steady-state simulation with origins at river nodes (Figures 48-51). Although the number of particle origins along the west corridor for Figure 57 is 1/3 of those for Figure 49, there are about as many paths. If the full number of river nodes were used as starting positions for the particle paths, there would have been more paths with viewable lines in the 1990's transient than in the 1940 steady-state simulation. This would result from the greater number of grid cells with flow losses than in the 1990's than in the 1940 simulation.

The particle tracks for the 1990's model that appear on the south side of the Arkansas river in the alluvial valley of Hamilton and western Kearny County (Figure 57) generally parallel the river and valley margins as do the tracks for the 1940 model (Figure 49). Similar to the 1940 figure, the particle paths generally remain within the recent alluvial valley and do not have substantial flow paths within the alluvial trough underlying the sand dunes to the south of the floodplain. In contrast, many of the particle paths in the alluvial aquifer on the

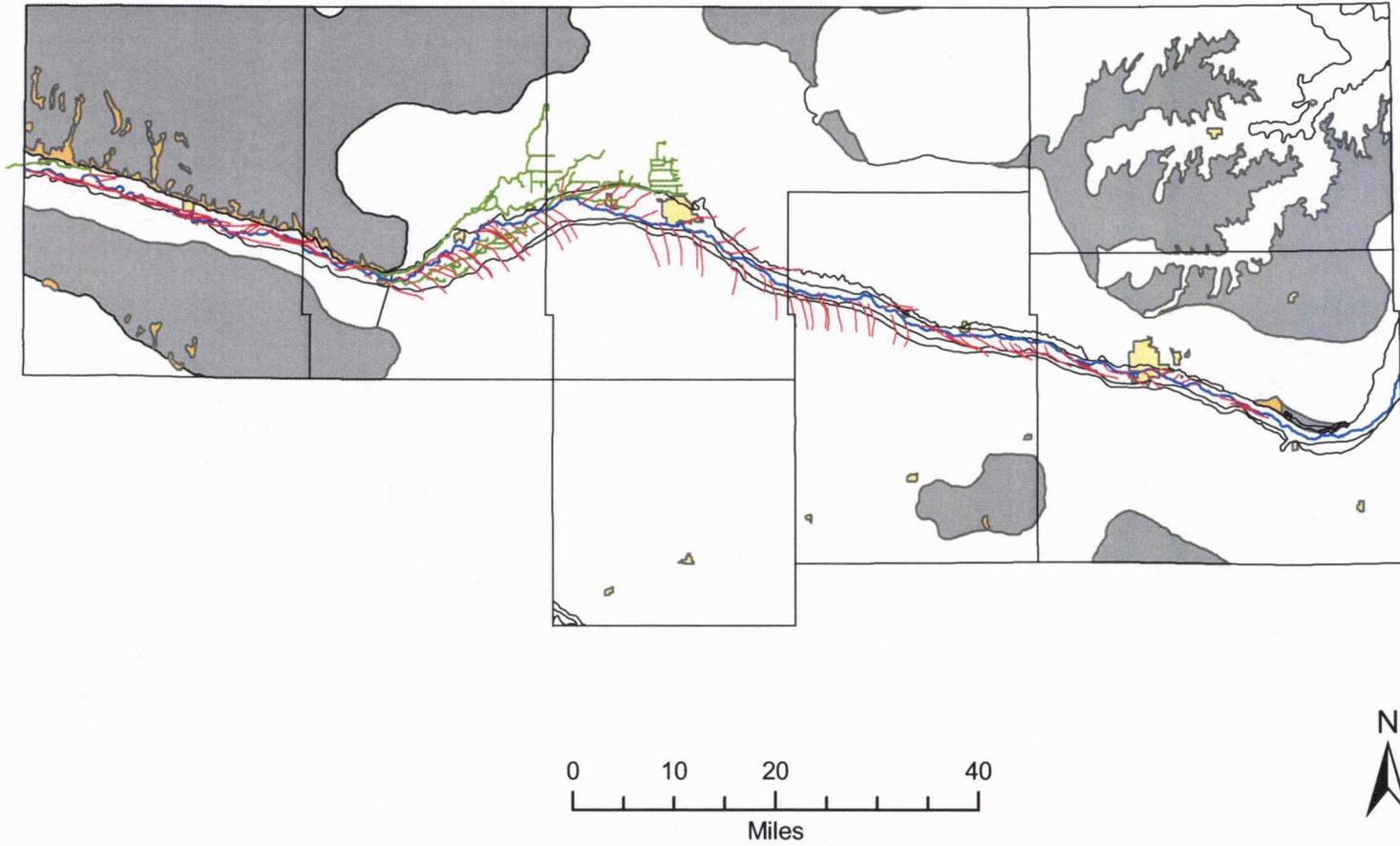


Figure 56. Particle path lines for the 40-year transient simulation based on average 1990's conditions with particle origins in 1/3 of the grid cells along the Arkansas River in southwest Kansas.

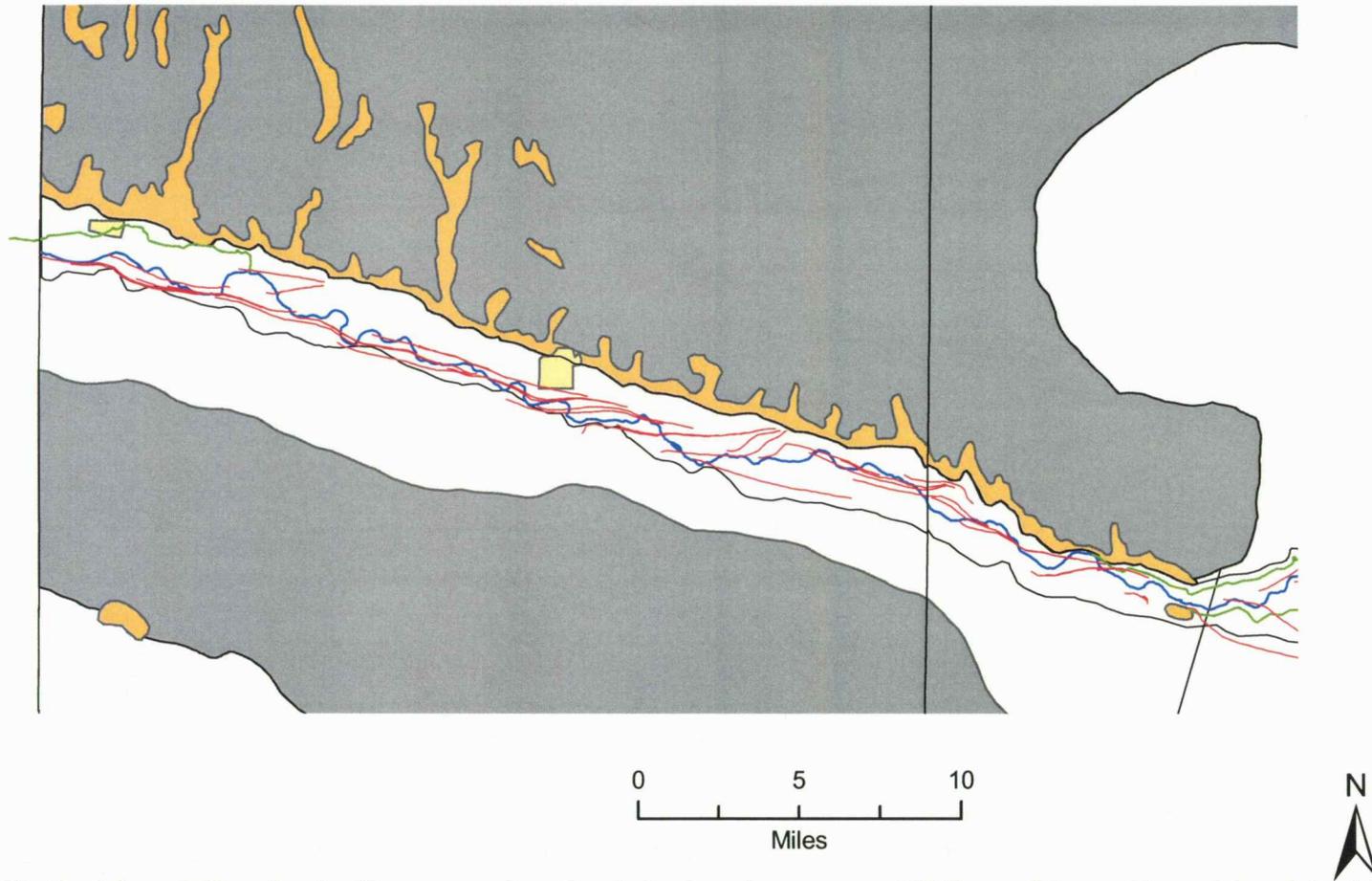


Figure 57. Particle path lines for the 40-year transient simulation based on average 1990's conditions with particle origins in 1/3 of the grid cells along the Arkansas River in southwest Kansas. The area shown is an enlargement of the western third of Figure 56 and includes Hamilton County and western Kearny County.

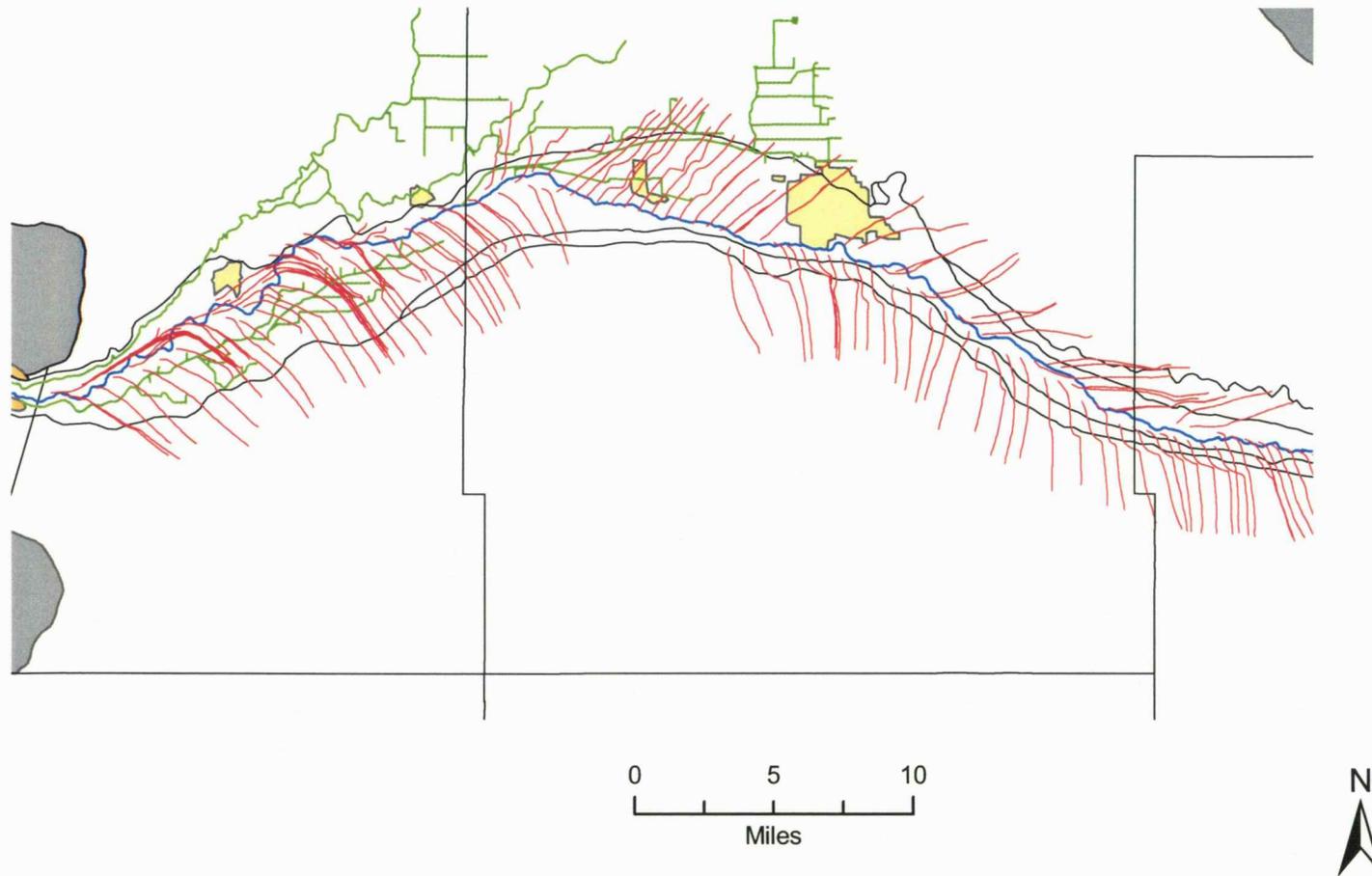


Figure 58. Particle path lines for the 40-year transient simulation based on average 1990's conditions with particle origins in all of the grid cells along the Arkansas River in southwest Kansas. The area shown is an enlargement of the central portion of Figure 56 and includes eastern Kearny County, southwest Finney County, and part of northwest Gray County.

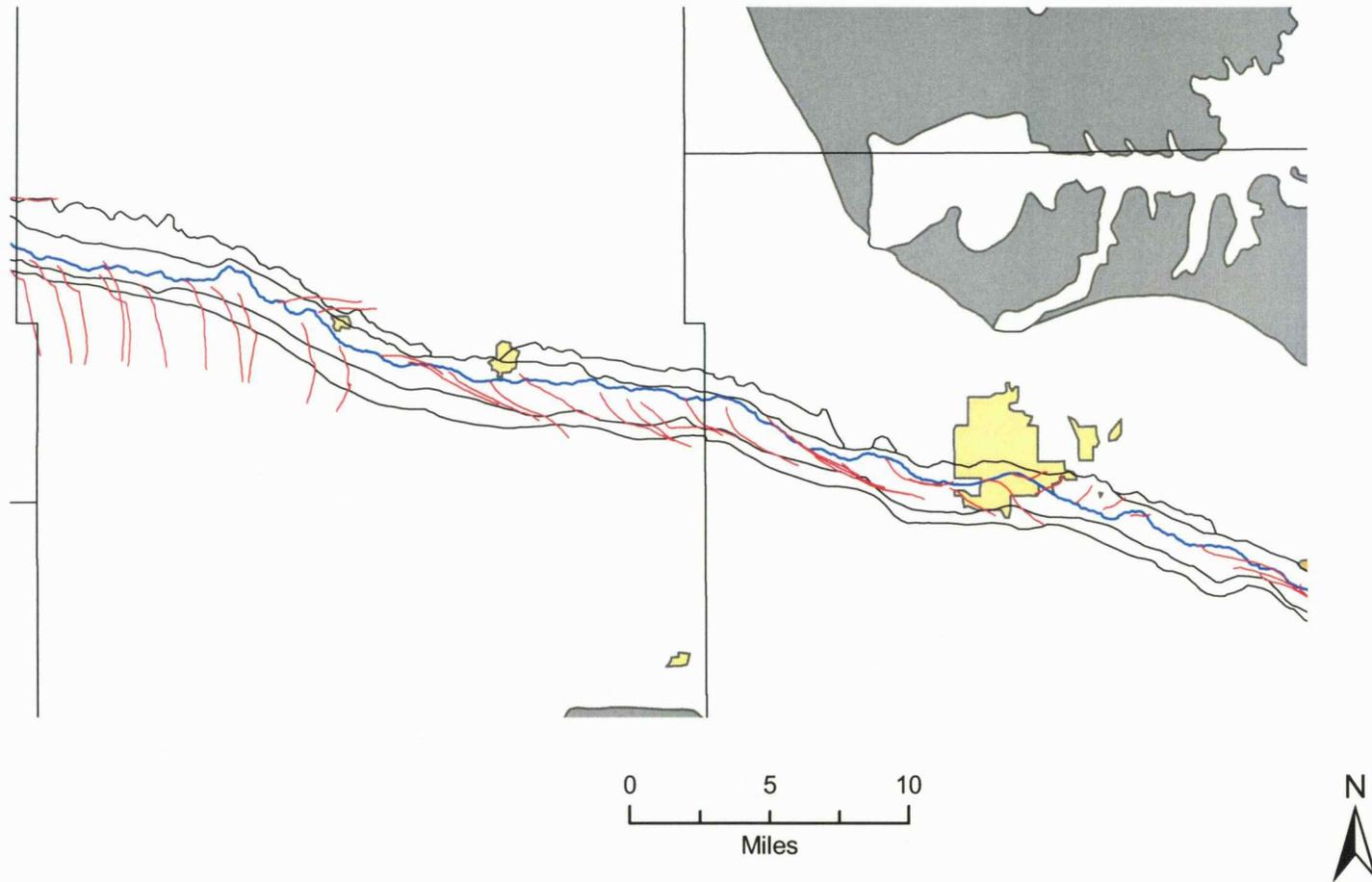


Figure 59. Particle path lines for the 40-year transient simulation based on average 1990's conditions with particle origins in 1/3 of the grid cells along the Arkansas River in southwest Kansas. The area shown is an enlargement of the eastern third of Figure 56 and includes Gray County and northwest Ford County.

north side of the river move away from the river, probably due to pumping effects on ground-water levels.

The particle tracks in the central corridor for the 1990's transient simulation (Figure 58) are generally longer and have substantially different directions from those in the 1940 model (Figure 50). Nearly all of the 1990's model paths that start at river nodes in the eastern half of Kearny County move across the area of the alluvial aquifer in a southeast direction. Many of these also enter the High Plains aquifer along the southern margin of the alluvial valley. In general, the farther to the east of the Bear Creek Fault zone, the greater the southerly component of the path direction. The few particle tracks that are on the north side of the river move in a direction parallel to the river.

In westernmost Finney County, the particles originating at the river shift from a southeastern flow path to a northeastern direction (Figure 58). This indicates that the hydraulic head gradient to the north of the river is greater than to the south in this area. This may partially result from the change from the east-northeast flow direction of the river near the Kearny-Finney county line to the east-southeast direction farther downstream, a direction more similar to that of the regional ground-flow. There are a large number of wells in the High Plains aquifer with water rights to the north of the Arkansas River along this section. Although there are also a large number of wells in the High Plains aquifer south of this river stretch, there are some areas where there are few wells underlying the sand dunes and the land use is still grassland. Thus, the combined effect of a greater number of wells close to the Arkansas river to the north in comparison with an overall smaller density of wells just to the south in this section may be enough to create the greater head gradient just north of the river.

The movement to the north rather than to the south along this corridor section may explain why the High Plains aquifer still contains freshwater just to the south of the river from Holcomb to half way to Garden City (Whittemore and Schloss, 2000). Many of the particle paths that move north of the river end in the High Plains aquifer north of the alluvial valley. The northeast path direction indicates the potential for contamination of the High Plains aquifer in the Holcomb area that presently includes some fresh ground water. However, the saline water from the river is retarded in its areal vertical migration to the High Plains aquifer because clay layers of substantial thickness underlie the alluvium in the Holcomb area. The direction of movement north of the river predicted from the 1990's conditions contrasts greatly with the particle paths for the 1940 conditions (Figure 50) for which the tracks from westernmost Finney County to Garden City remained within the alluvial valley and close to the river.

Just west of Garden City, particle paths that move to the south of the river again appear (Figure 58). These tracks move substantial distances into the High Plains aquifer south of the alluvial aquifer. Both northeast and south moving tracks occur along the river from Garden City to the Finney-Gray county line. The slight change in direction about 1/3 of the distance from the river to the end of some of the paths to the south is related to movement from the edge of the alluvial aquifer into the High Plains aquifer. The south moving tracks fit the migration of saline water into the High Plains aquifer south of Garden City such as

recently observed in the two most northern wells of the sand hills municipal well field of Garden City (Whittemore, 2000b; Whittemore and Schloss, 2000).

From western Gray County to the end of the modeled area east of Dodge City, most of the particle paths for the transient simulation starting from the Arkansas River move south of the river (Figures 58 and 59). The tracks change direction from predominantly to the south with a small eastward component in western Gray County to an east-southeast direction in Ford County. This change also shows that the farther to the east along the river corridor in Gray and Ford counties, the smaller is the distance the particles travel into the High Plains aquifer south of the alluvial valley. Nearly all the particle paths remain within the boundaries of the Quaternary alluvium in Ford County. These path observations generally fit the pattern of increases in sulfate concentration above 50 mg/L in the High Plains aquifer at the southern edge of the alluvial valley boundary in Gray and Ford Counties (Whittemore and Schloss, 2000). Two of the particles track into the High Plains aquifer north of the river in central Gray County near Ingalls, and a few particles move to the north of the river on the eastern side of Dodge City (Figure 59). The map of sulfate content for the High Plains aquifer also shows some movement of higher concentrations into these areas (Whittemore and Schloss, 2000).

The pattern of most pathline directions semi-parallel to the Arkansas River and locations within the boundaries of the alluvial valley from eastern Gray County through western Ford County (Figure 59) fits the general distribution of historic water-level declines and well distribution in this region. The historic declines in ground-water levels are substantially smaller in the region than to the west. The average head gradients in the 1990's outwards from the river are generally not as steep as to the west. The movement of a couple pathlines to the northeast near Ingalls, of most pathlines to the east-southeast in eastern Gray County and westernmost Ford County and towards the northeast and east on the east side of Dodge City all fit the relative density distribution of wells with water rights in or near the river valley.

Particle paths were also generated for the 40-year transient simulation starting with the average 1990's conditions but with particle origins along the 500 mg/L isolines of sulfate concentration for the alluvial trough in Hamilton and western Kearny counties and the High Plains aquifer (Figures 60-63) based on Plate B in Whittemore and Schloss (2000). These particles start within either the High Plains aquifer or the alluvial aquifer of the bedrock trough west of the Bear Creek Fault zone. Figure 60 displays the results for the entire corridor whereas Figures 61-63 illustrate the particle paths for the enlarged west, central, and east portions of the corridor.

The 500 mg/L sulfate isoline in the west part of the river corridor parallels most of the southern boundary of the Quaternary alluvium (Figure 61). The sulfate content of the ground water in the Quaternary alluvium is greater than 2,000 mg/L in Hamilton County and usually between 1,500 and 2,000 in Kearny County (Plates A and C in Whittemore and Schloss, 2000). Most of the particle paths that start from the 500 mg/L sulfate isoline in Hamilton County track parallel to the general direction of the boundary between the floodplain and alluvial deposits underlying the sand dunes to the south. The bend in the sulfate contour into

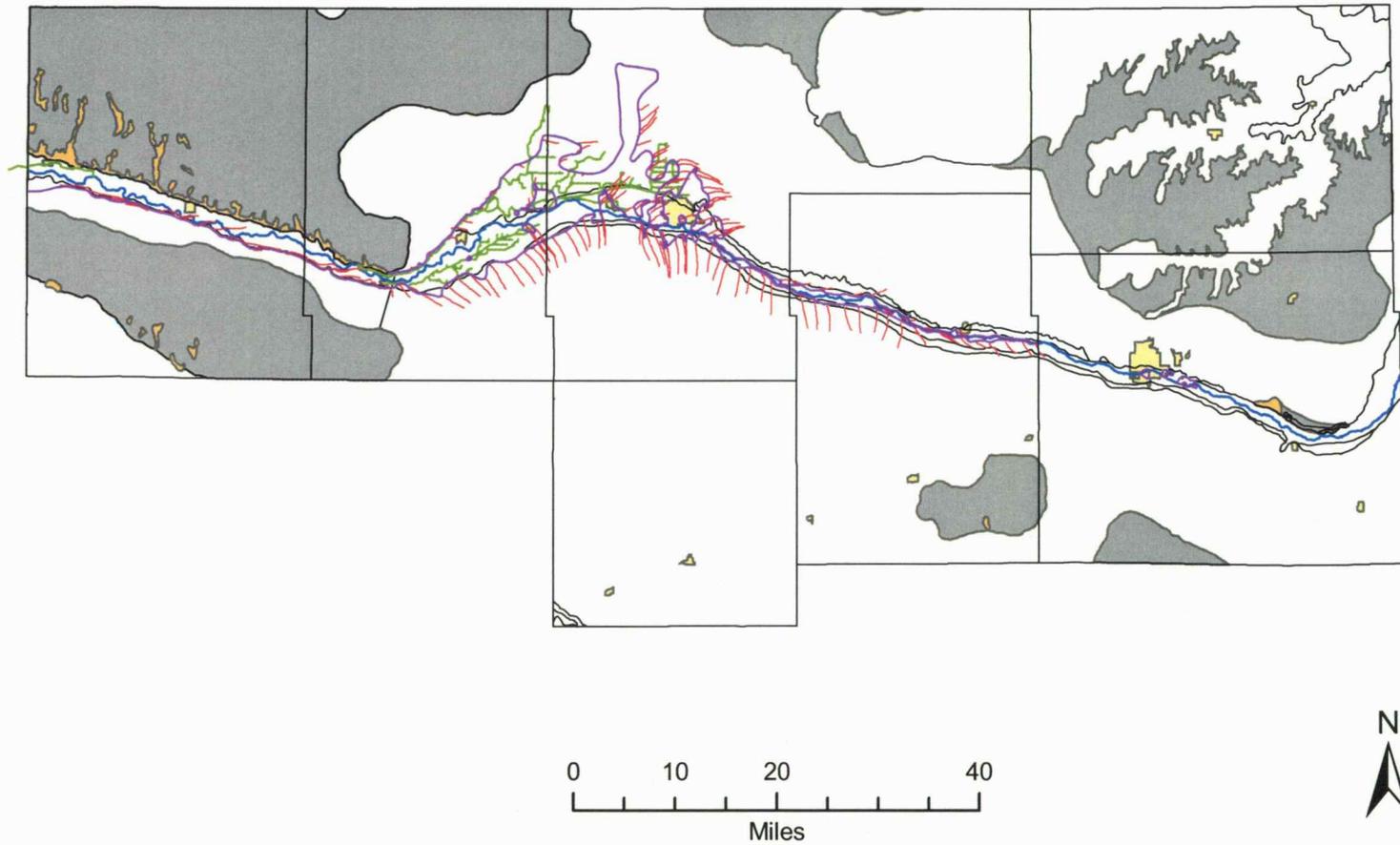


Figure 60. Particle path lines for the 40-year transient simulation based on average 1990's conditions with particle origins in selected grid cells along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer in southwest Kansas.

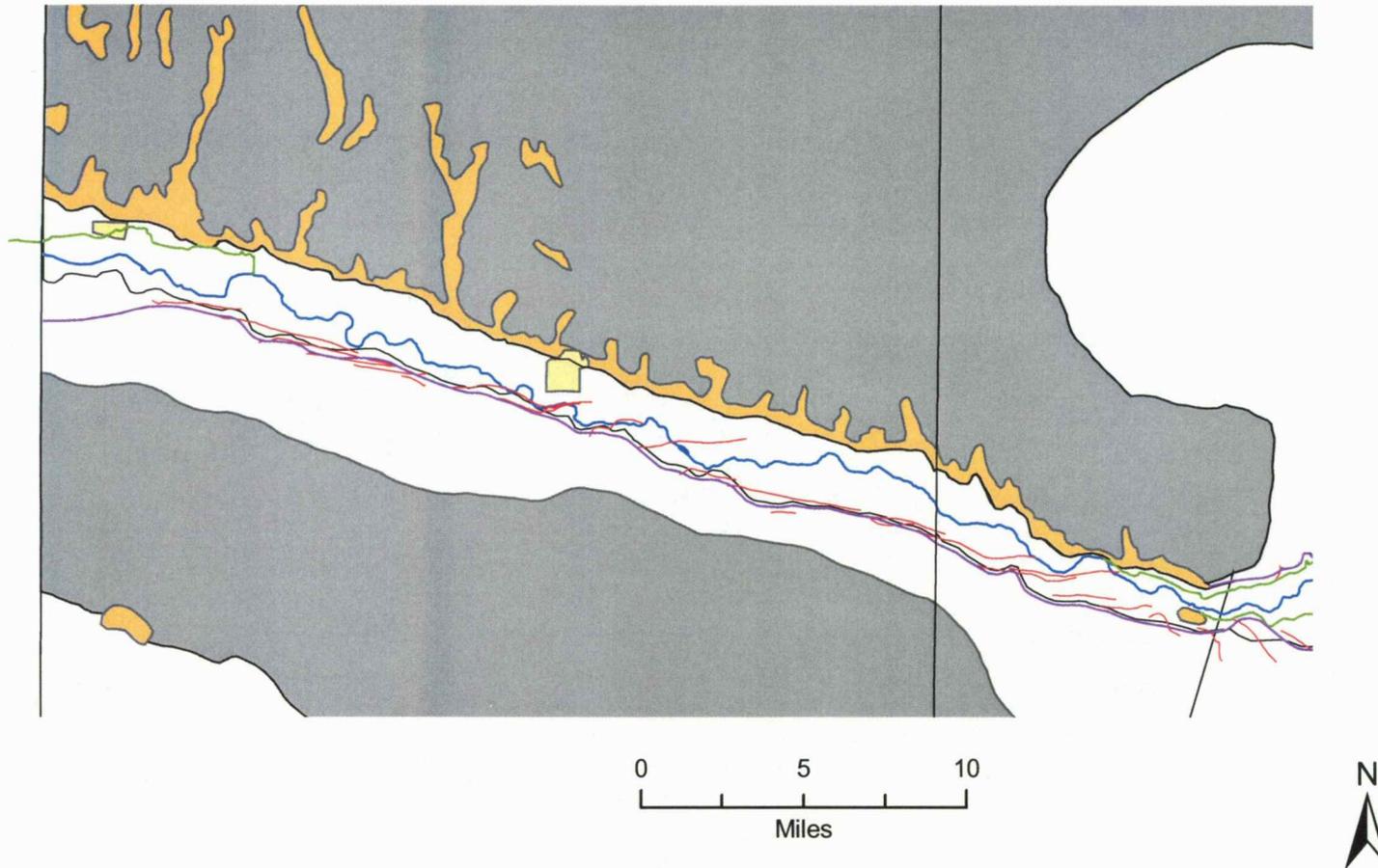


Figure 61. Particle path lines for the 40-year transient simulation based on average 1990's conditions with particle origins in selected grid cells along the 500 mg/L isoline for sulfate concentration in the alluvial aquifer underlying the sand dunes south of the Arkansas River floodplain and in the High Plains aquifer. The area shown is an enlargement of the western third of Figure 60 and includes Hamilton County and western Kearny County.

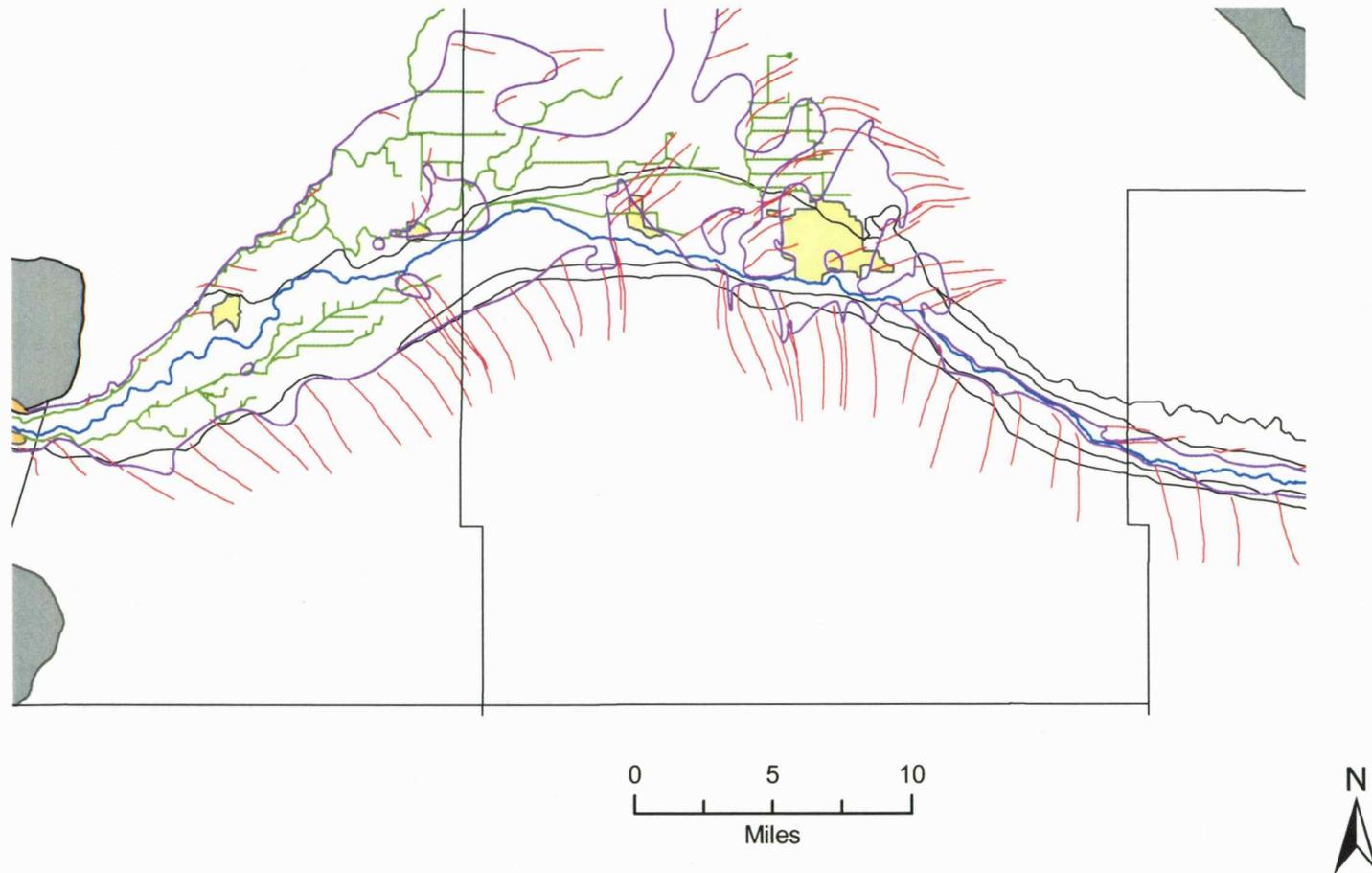


Figure 62. Particle path lines for the 40-year transient simulation based on average 1990's conditions with particle origins in selected grid cells along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer. The area shown is an enlargement of the central portion of Figure 60 and includes eastern Kearny County, western Finney County, and part of northwest Gray County.

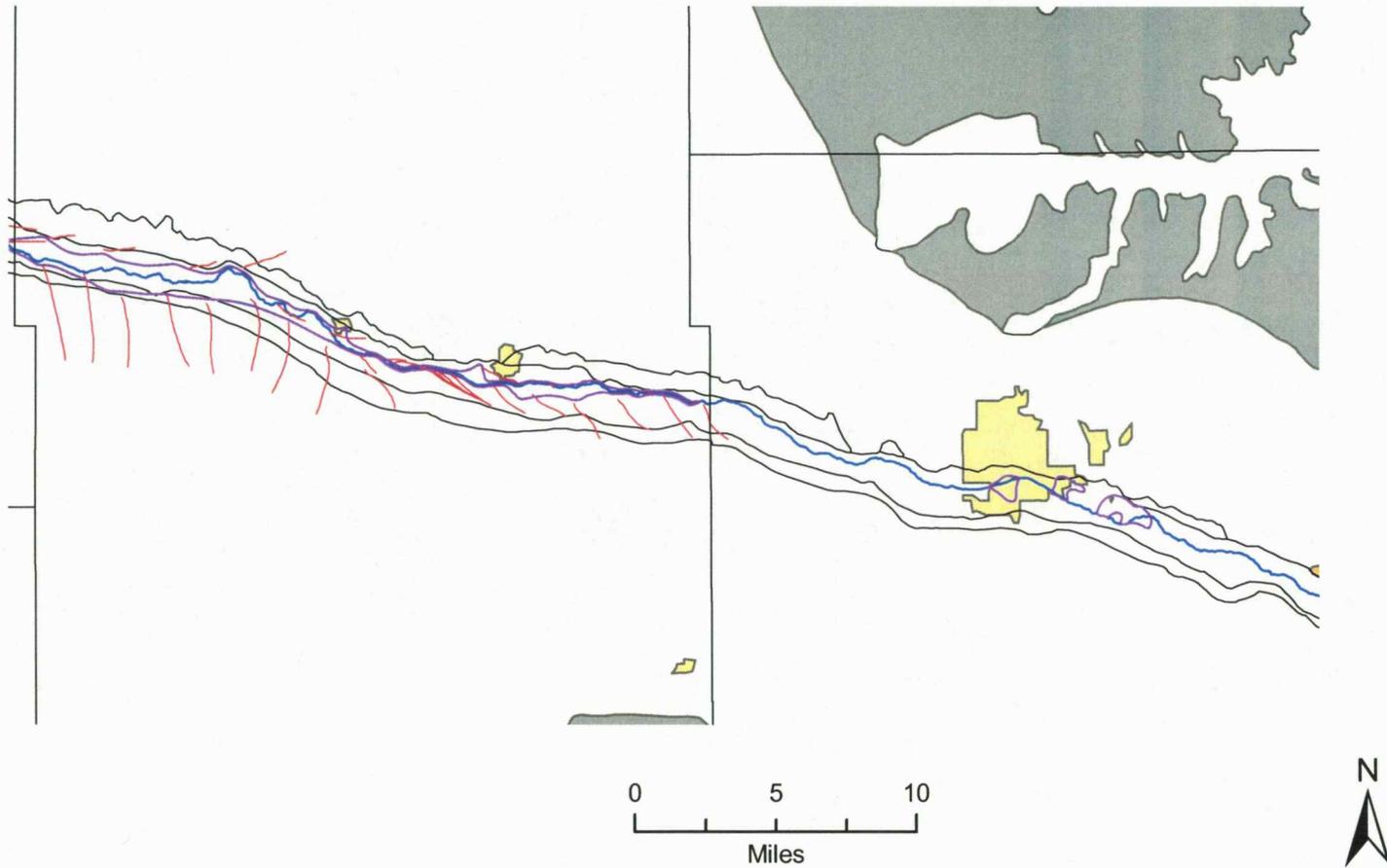


Figure 63. Particle path lines for the 40-year transient simulation based on average 1990's conditions with particle origins in selected grid cells along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer. The area shown is an enlargement of the eastern third of Figure 60 and includes Gray County and northwest Ford County.

the older alluvium near the Colorado-Kansas border is either related to movement of saline ground water down the valley from Colorado or diversion of saline river water for irrigation into this area. This small area of saline ground water could be expected to move further down the valley in the future.

In western Kearny County, the particles starting at the 500 mg/L sulfate isoline begin to move away from the isoline towards the east-southeast the closer the particle origins are to the Bear Creek Fault zone (Figure 61). The particle paths originating from the sulfate isoline south of the Arkansas River trend towards the southeast in the High Plains aquifer in eastern Kearny County (Figure 62). The paths along the southern sulfate isoline shift to a nearly south direction from near Holcomb to the Finney-Gray county line. Because the particles start within the High Plains aquifer there are no sudden bends in the paths as for some particles that originated from the river and flowed through the alluvium before entering the High Plains aquifer (Figures 58 and 59). The particle paths starting along the 500 mg/L sulfate isoline in eastern Kearny County north of the river are relatively short. North of the river in Finney County, most of the particle path directions are towards either the northeast or the east-northeast. The particle origins were selected before the MODPATH calculations were run. Thus, some of the particles move from the 500 mg/L isoline into areas of higher sulfate concentration. In general, this does not mean that the water will be come less saline in that area. The results indicate that additional starting locations of particles could be selected for MODPATH computations to show how saline waters will move into some of the small areas of fresher ground waters in Figure 62.

The 500 mg/L sulfate isolines for the High Plains aquifer in Finney County extend to near the Gray-Ford county boundary near the Arkansas River (Figure 62). Some of the particles traveling from locations that underlie the alluvial aquifer in Gray County have shorter pathlines than those particles originating from the river (Figure 59). The reason is that some particles that start at the river travel in the alluvial aquifer before entering the High Plains aquifer. The greater hydraulic conductivity of parts of the alluvium than the High Plains aquifer explains the longer path length. Thus, although the particles originating from the sulfate concentration isoline start farther away from the Arkansas River, the end of the pathline may not be at a much different location outside the alluvial valley than a pathline from the river.

#### *Solution for steady-state equilibrium for 1990's water use*

Particle paths were calculated for 40 years in MODPATH based on the solution imported from the steady-state simulation that held 1990's water use constant. The solution was based on specified-flux conditions along the southern boundary of the model, and resulted in the water-level surface shown in Figure 40. Particle pathlines were generated for positions starting from the Arkansas River and from the 500 mg/L sulfate concentration isolines as described for the transient case above. Figures 64-67 display the results for the particle origins at the Arkansas River and Figures 68-71 depict the pathlines that start at the 500 mg/L sulfate isoline in the alluvial trough west of the Bear Creek Fault zone and in the High Plains aquifer. All of the river grid cells were used for particle origins for the steady-state case in

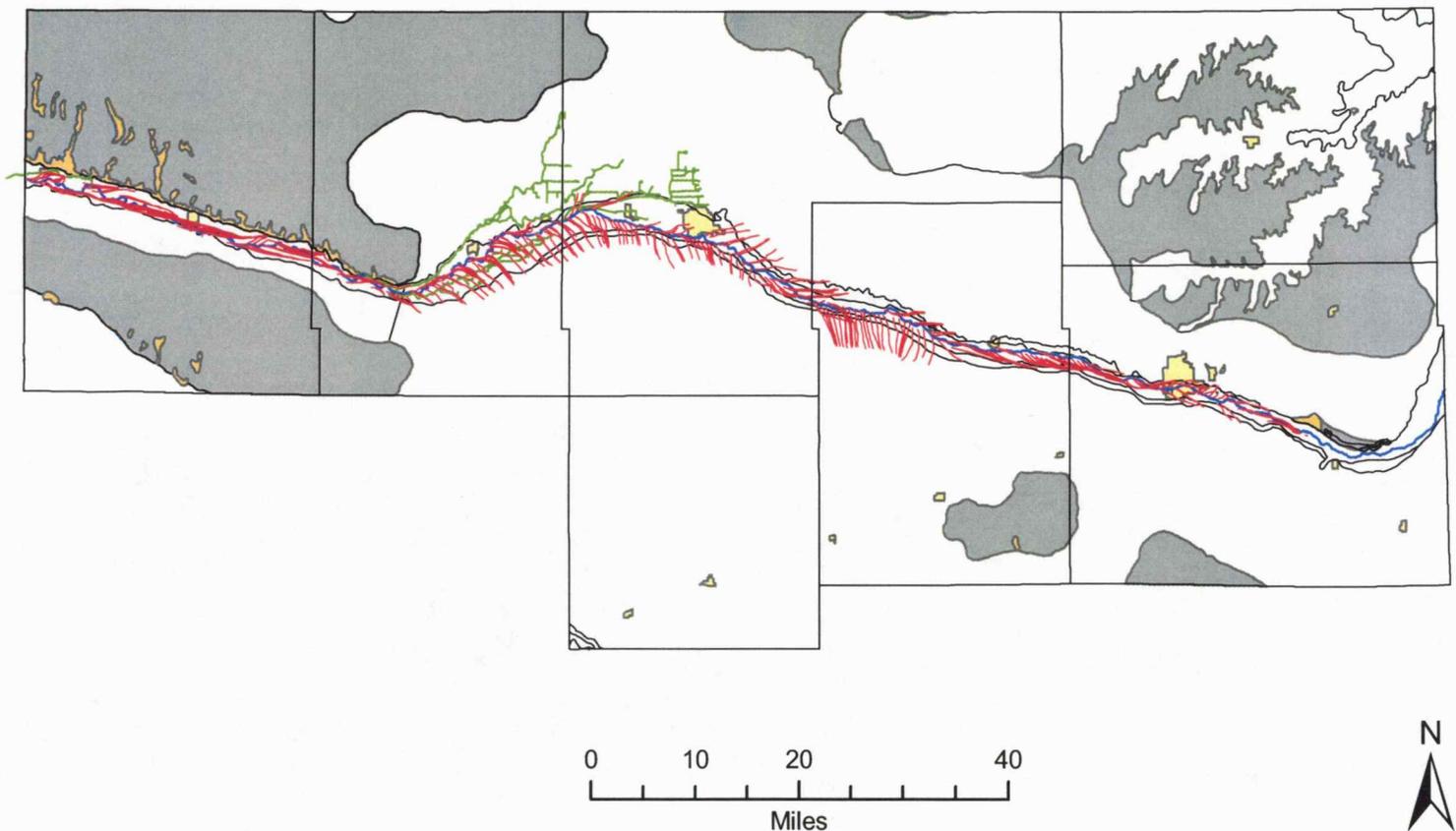


Figure 64. Particle path lines for a 40-year travel time for the steady-state simulation based on average 1990's water use with particle origins in the grid cells along the Arkansas River in southwest Kansas.

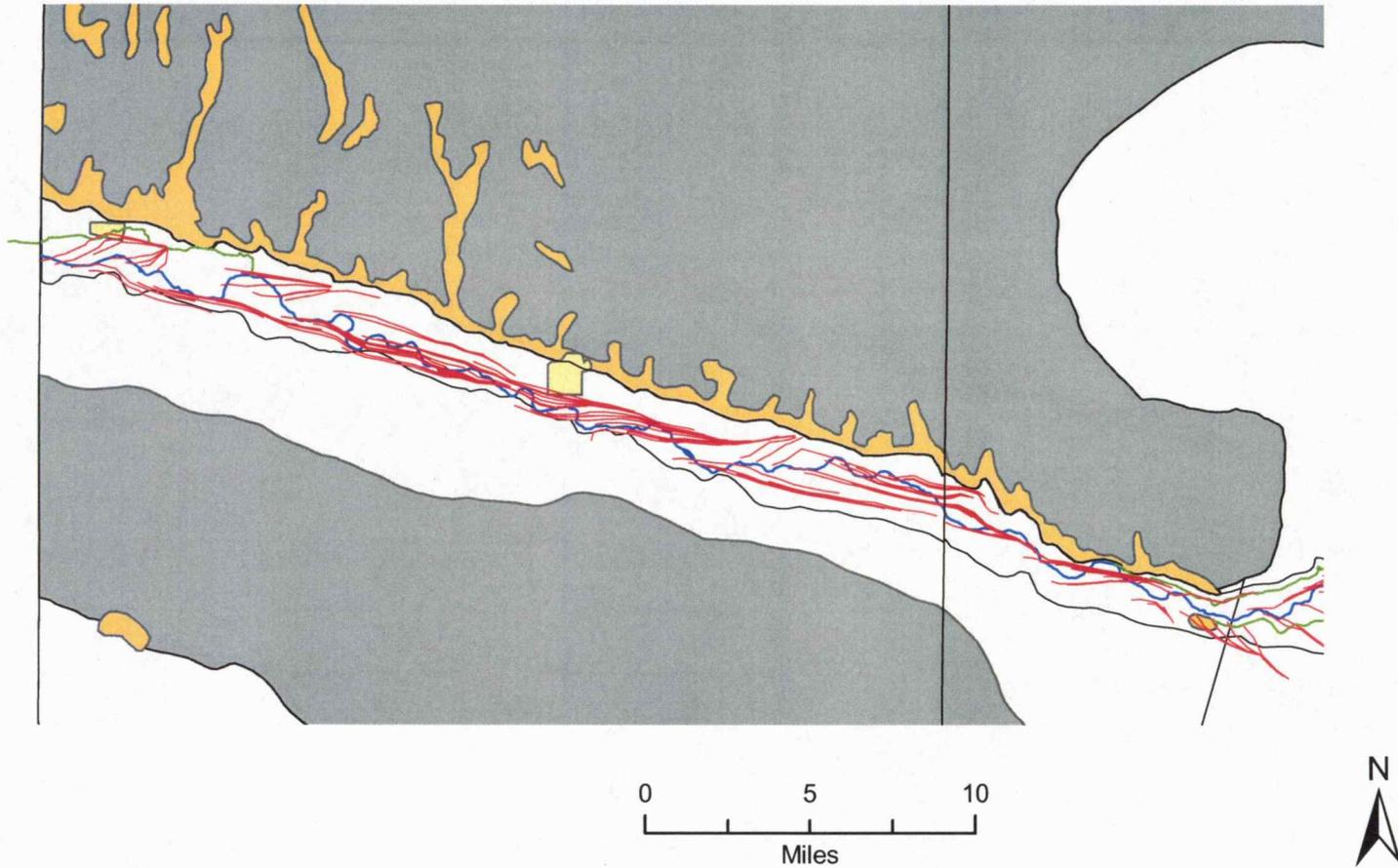


Figure 65. Particle path lines for a 40-year travel time for the steady-state simulation based on average 1990's water use with particle origins in the grid cells along the Arkansas River in southwest Kansas. The area shown is an enlargement of the western third of Figure 64 and includes Hamilton County and western Kearny County.

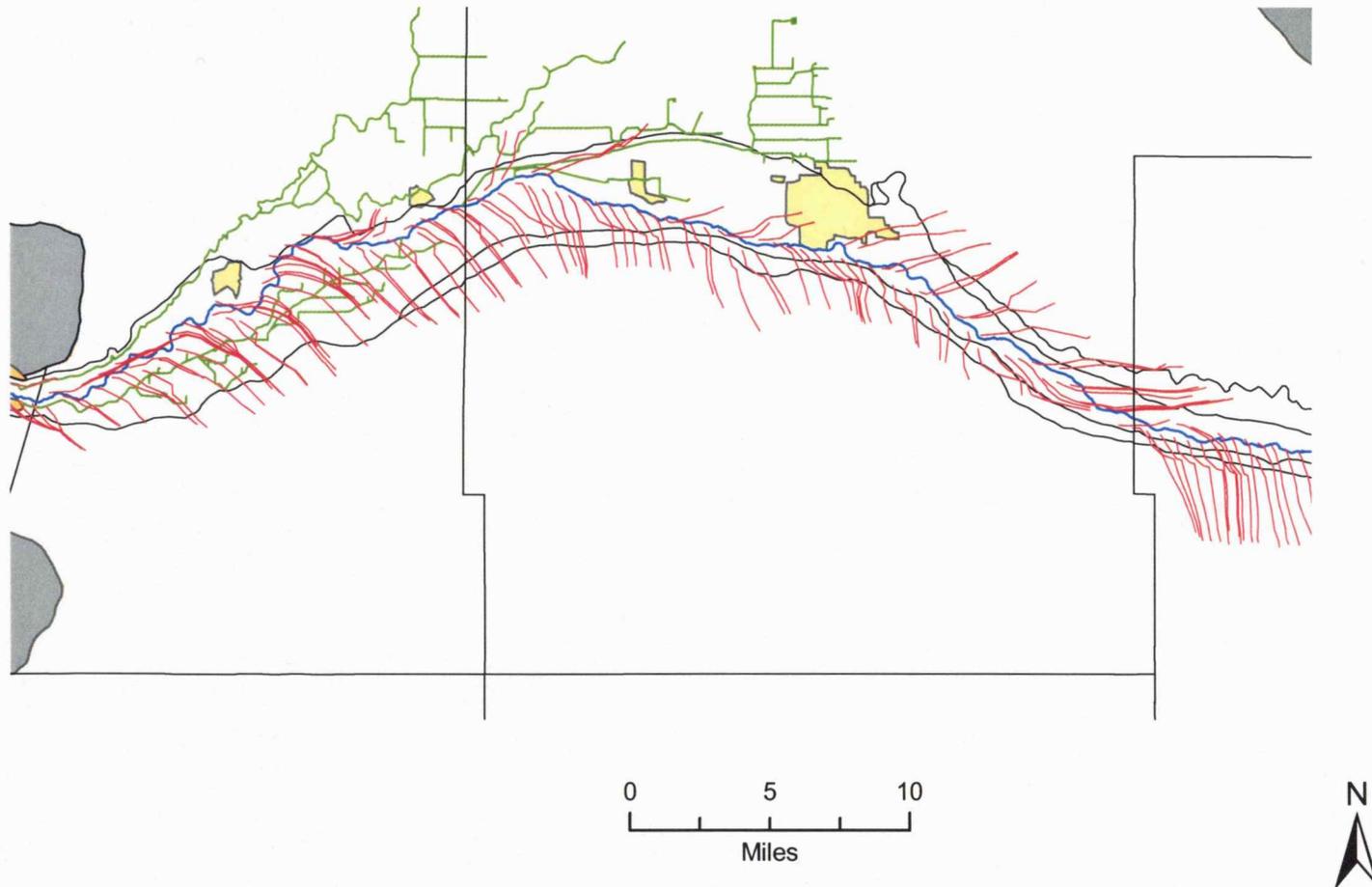


Figure 66. Particle path lines for a 40-year travel time for the steady-state simulation based on average 1990's water use with particle origins in the grid cells along the Arkansas River in southwest Kansas. The area shown is an enlargement of the central portion of Figure 64 and includes eastern Kearny County, southwest Finney County, and the edge of northwest Gray County.

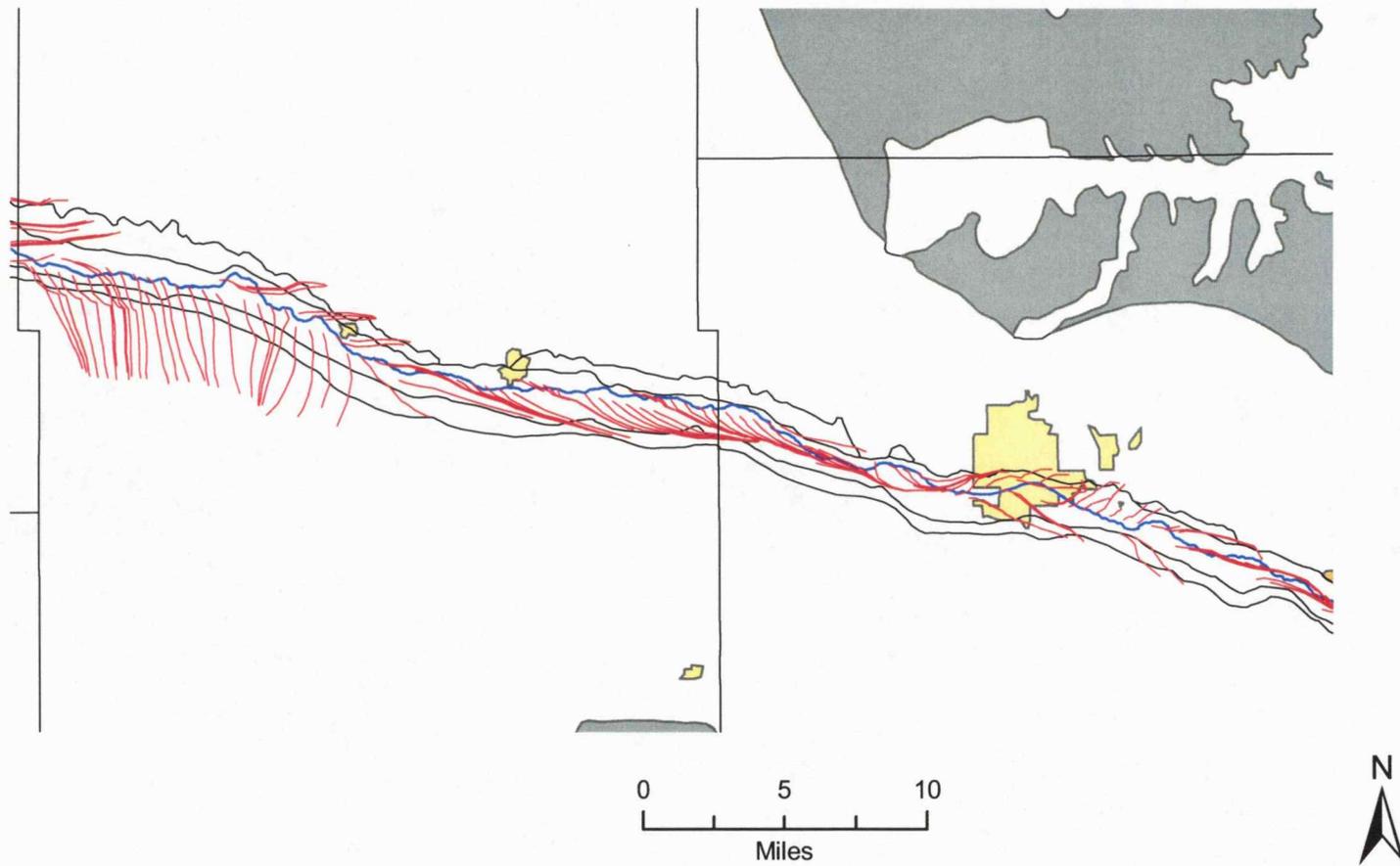


Figure 67. Particle path lines for a 40-year travel time for the steady-state simulation based on average 1990's water use with particle origins in the grid cells along the Arkansas River in southwest Kansas. The area shown is an enlargement of the eastern third of Figure 64 and includes Gray County and northwest Ford County.

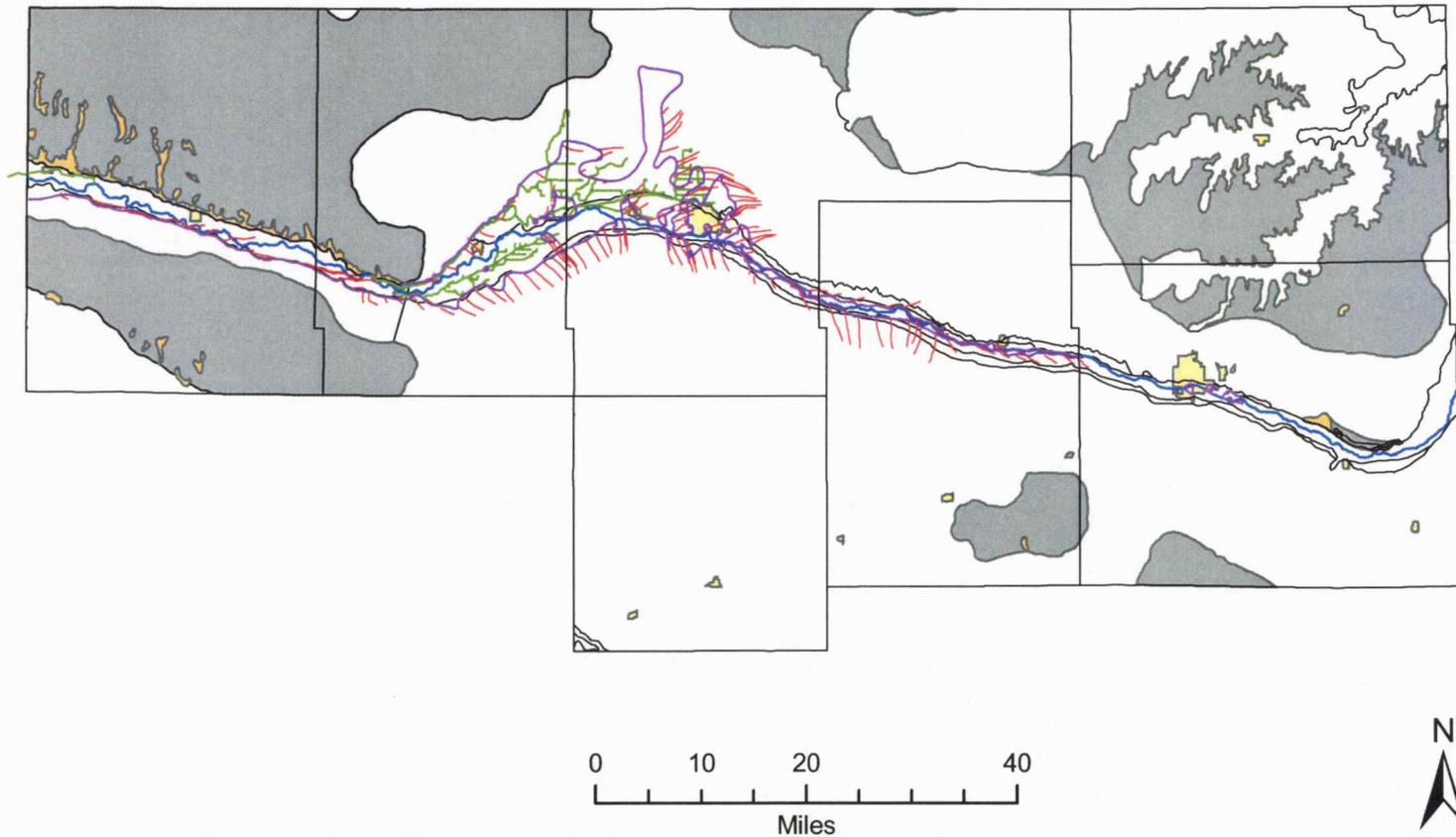


Figure 68. Particle path lines for a 40-year travel time for the steady-state simulation based on average 1990's water use with particle origins in selected grid cells along the 500 mg/L isoline for sulfate concentration in the alluvial paleovalley and the High Plains aquifer in southwest Kansas.

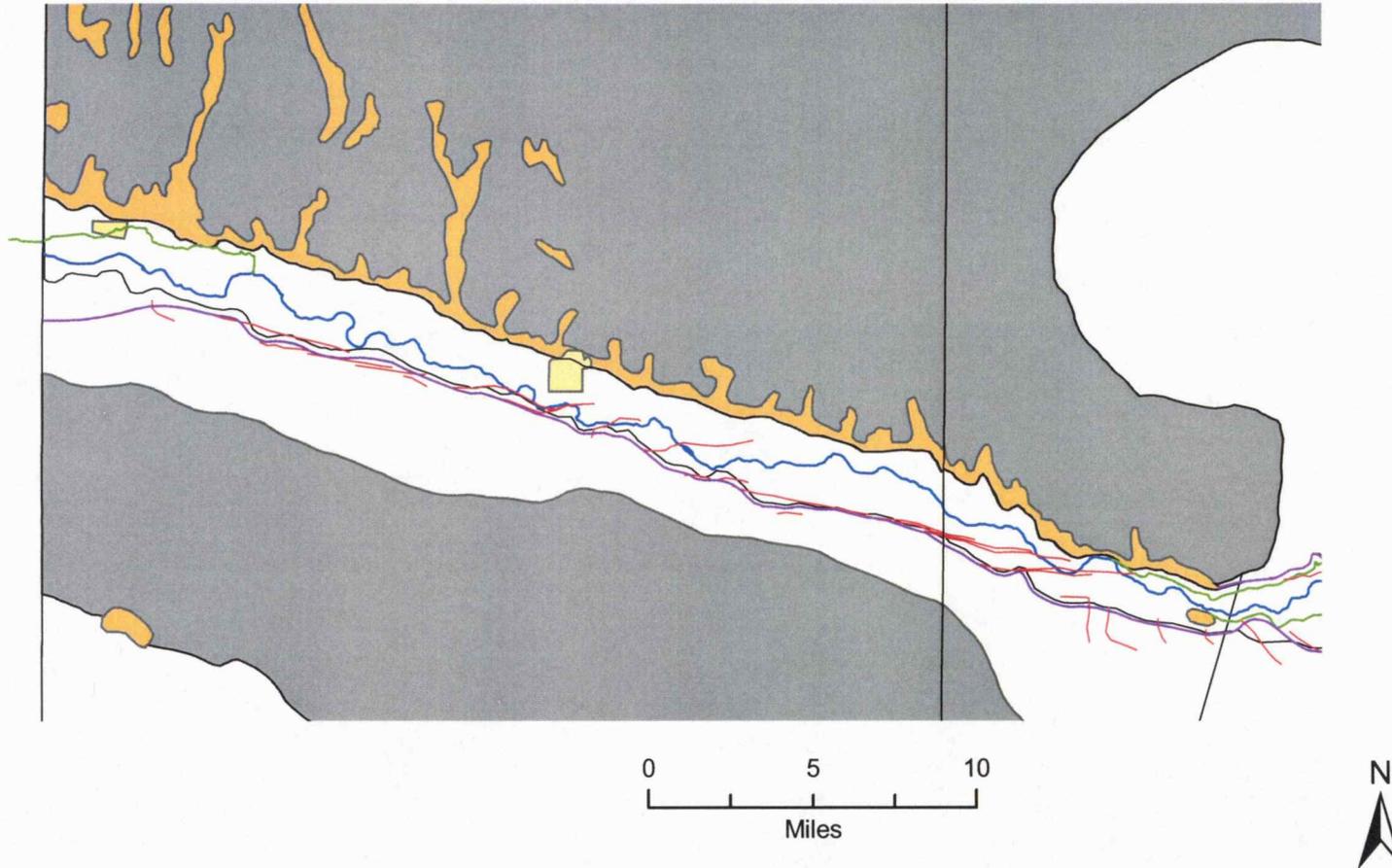


Figure 69. Particle path lines for a 40-year travel time for the steady-state simulation based on average 1990's water use with particle origins in selected grid cells along the 500 mg/L isoline for sulfate concentration in the alluvial aquifer underlying the sand dunes south of the Arkansas River floodplain and in the High Plains aquifer. The area shown is an enlargement of the western third of Figure 68 and includes Hamilton County and western Kearny County.

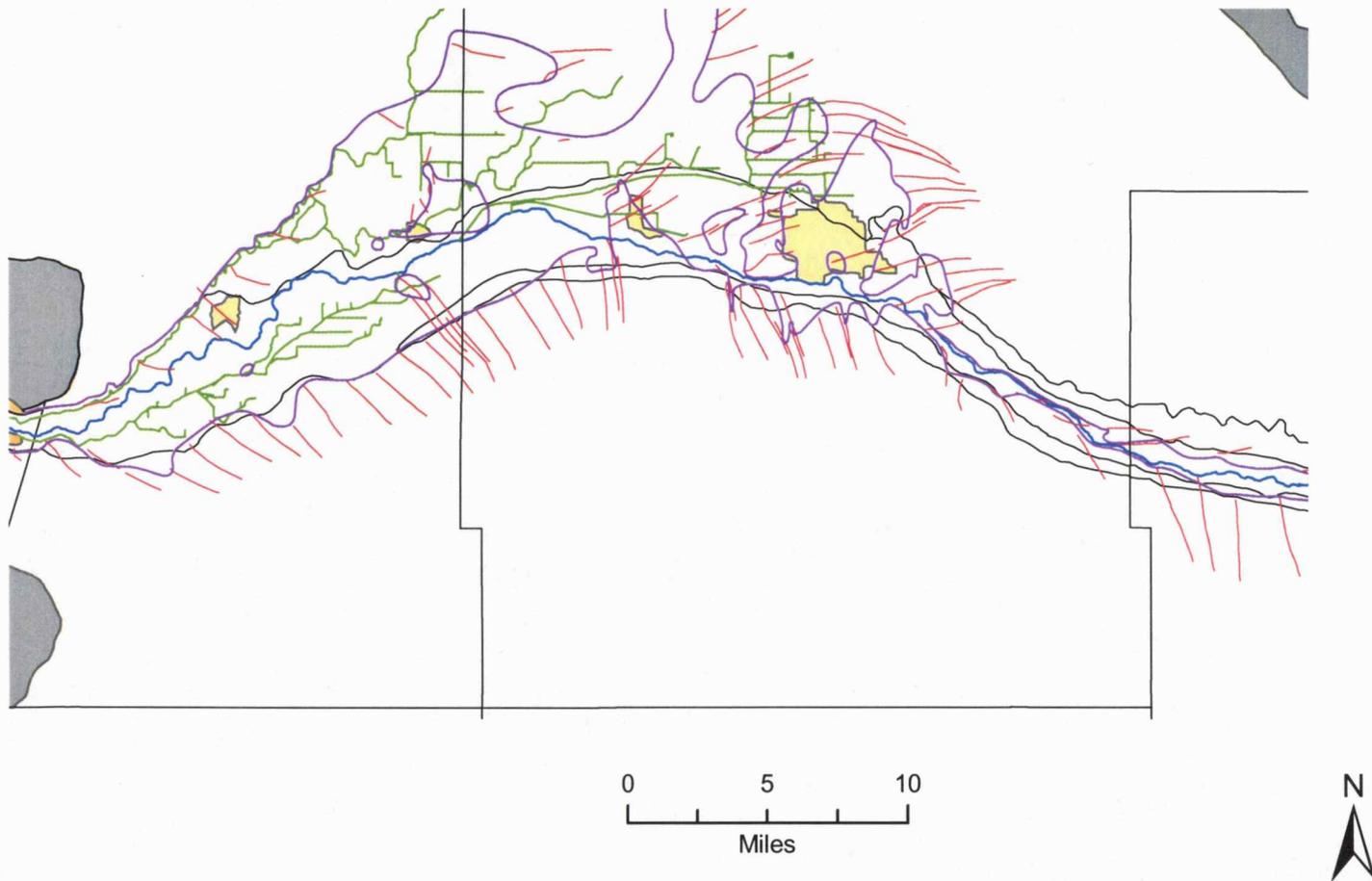


Figure 70. Particle path lines for a 40-year travel time for the steady-state simulation based on average 1990's water use with particle origins in selected grid cells along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer. The area shown is an enlargement of the central portion of Figure 68 and includes eastern Kearny County, western Finney County, and part of northwest Gray County.

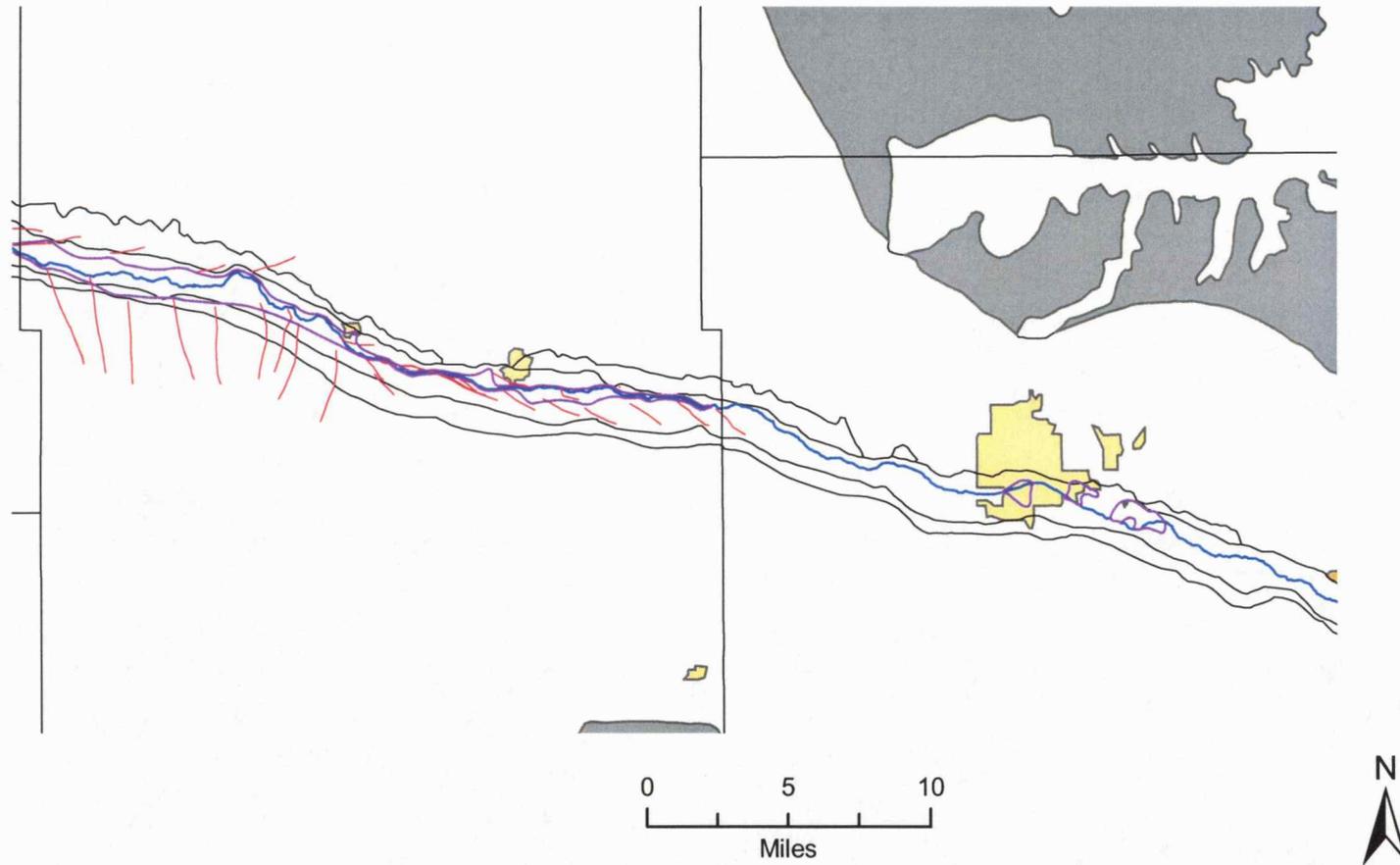


Figure 71. Particle path lines for a 40-year travel time for the steady-state simulation based on average 1990's water use with particle origins in selected grid cells along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer. The area shown is an enlargement of the eastern third of Figure 68 and includes Gray County and northwest Ford County.

comparison with a subset of the river nodes for the transient case, because the number of particle positions generated by the steady-state simulation were substantially fewer than for the transient model. Thus, there are many more particle paths shown in Figures 64, 65, and 67 than for Figures 56, 57, and 59.

In general, the particle pathlines for the imported steady-state solution are similar to those for the 40-year transient model based on 1990's conditions. However, one difference is that some of the pathlines for particles tracking to the south of the Arkansas River into or within the High Plains aquifer are somewhat longer for the 40-year transient case (both river node and sulfate isoline origins) than for the steady-state solution for 1990's water use. The other notable difference is the shift of particle paths that tracked towards the northeast from river node origins in the 40-year transient simulation to a south pathline direction in the steady-state model in the area from west to east of Holcomb in western Finney County.

#### *Steady-state solution for constant 1990's water-level conditions*

Pathlines for the steady-state case in which water use was reduced to maintain the average 1990's ground-water levels are displayed in Figures 72-75 for particles starting in the alluvial aquifer along the Arkansas River and in Figures 76-79 for particles originating in the High Plains aquifer along the 500 mg/L sulfate isoline. The pathlines for the western part of the model area (Figure 73) remain within the Quaternary alluvial valley and have directions that generally parallel the river valley similar to the pathlines in Figure 57 (the 40-year transient simulation based on 1990's water use) and in Figure 65 (the 40-year travel time from the steady-state case based on 1990's water use). The pathlines are, however, generally straighter in Figure 73 than in Figures 57 and 65, reflecting the smaller influence of grid cells as pumping sinks. The longest pathlines in Figure 73 are about the same length as the longest in Figures 57 and 65 but there are fewer pathlines in Figure 73 with short lengths, again reflecting the smaller influence of pumping sinks in some grid cells.

The greatest differences in the pathlines between the simulation for constant 1990's water levels and the 40-year transient and steady-state solutions for 1990's water use appear in the central section of the model area from eastern Kearny County to western Gray County. Most of the pathlines in the central area for the steady-state case for constant water levels (Figure 74) are substantially shorter than for pathlines in the same area from the simulations for constant 1990's water use (Figures 58 and 66). Thus, whereas many of the pathlines for the Figures 58 and 66 extend substantially into the High Plains aquifer, most of the pathlines in Figure 74 remain within the boundaries of the alluvial aquifer. The movement of the pathlines to the north of the river in western Finney County in Figure 74 is similar to the pattern for the transient simulation for 1990's water use (Figure 58). As described earlier, most of the pathlines in the Holcomb region from the steady-state case for 1990's water use (Figure 66) move to the south of the river in contrast to the pathlines in this area in Figure 58 (and also Figure 74). The area with the greatest change in the pathline directions is from Garden City to western Gray County. The pathlines in this area of Figure 74 tend not to move away from the Arkansas River with as great an angle as in Figures 58 and 66. The results indicate the impact of the smaller hydraulic-head gradients (that would occur from reduction

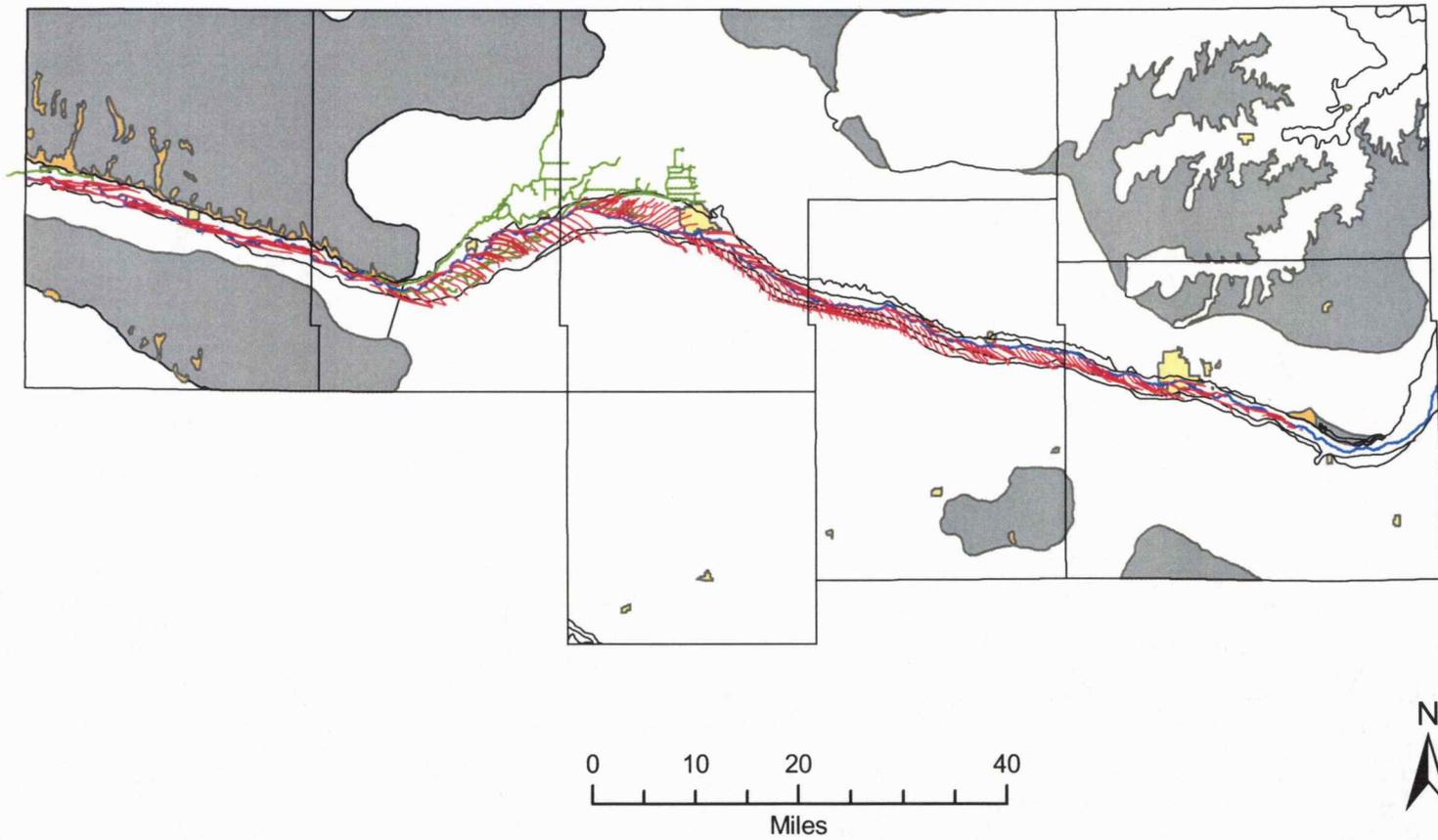


Figure 72. Particle path lines for a 40-year travel time for the steady-state simulation with reduced irrigation water use to maintain average 1990's ground-water levels. Particles start in the grid cells along the Arkansas River in southwest Kansas.

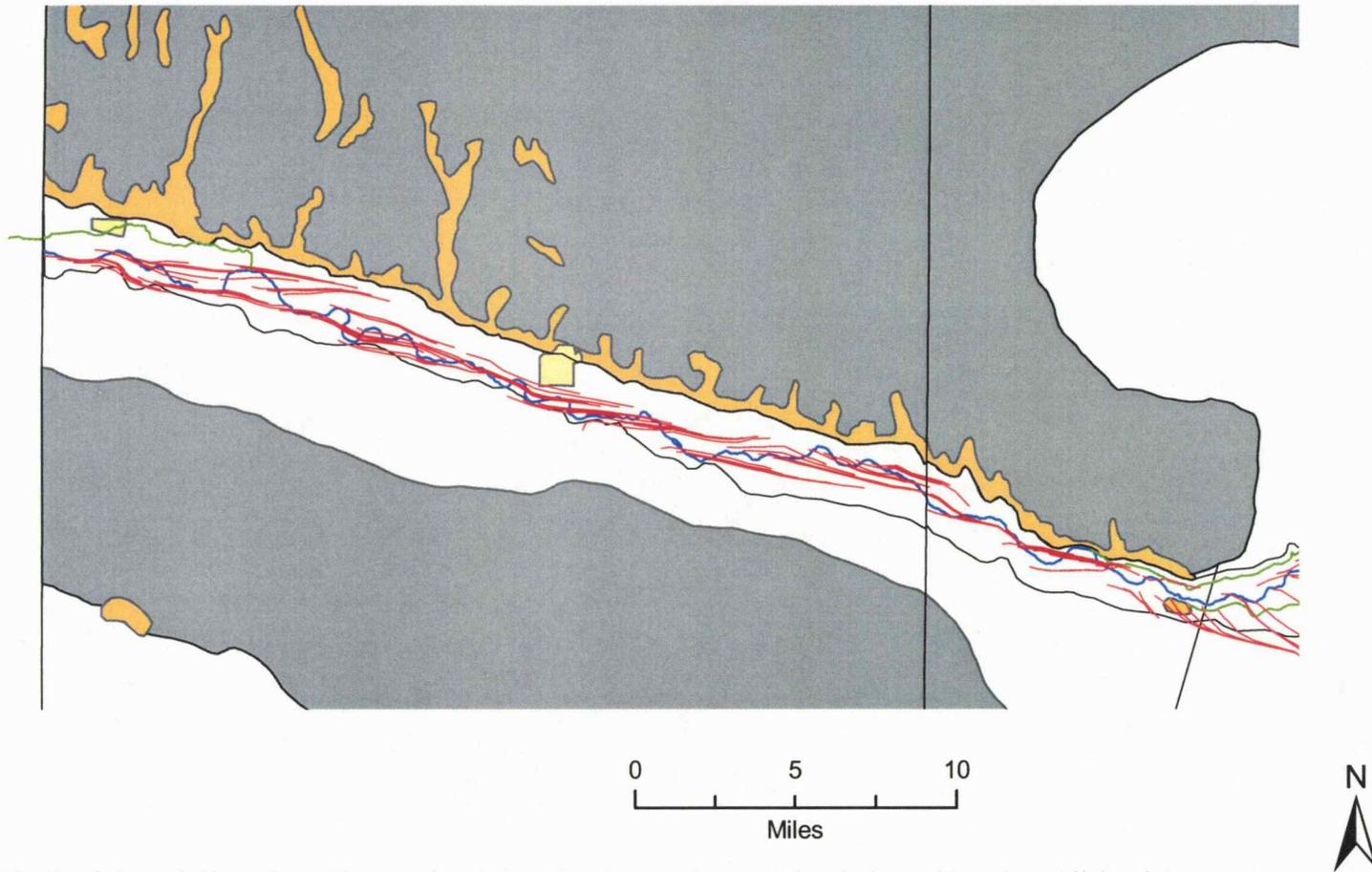


Figure 73. Particle path lines for a 40-year travel time for the steady-state simulation with reduced irrigation water use to maintain average 1990's ground-water levels. Particles start in the grid cells along the Arkansas River in southwest Kansas. The area shown is an enlargement of the western third of Figure 72 and includes Hamilton County and western Kearny County.

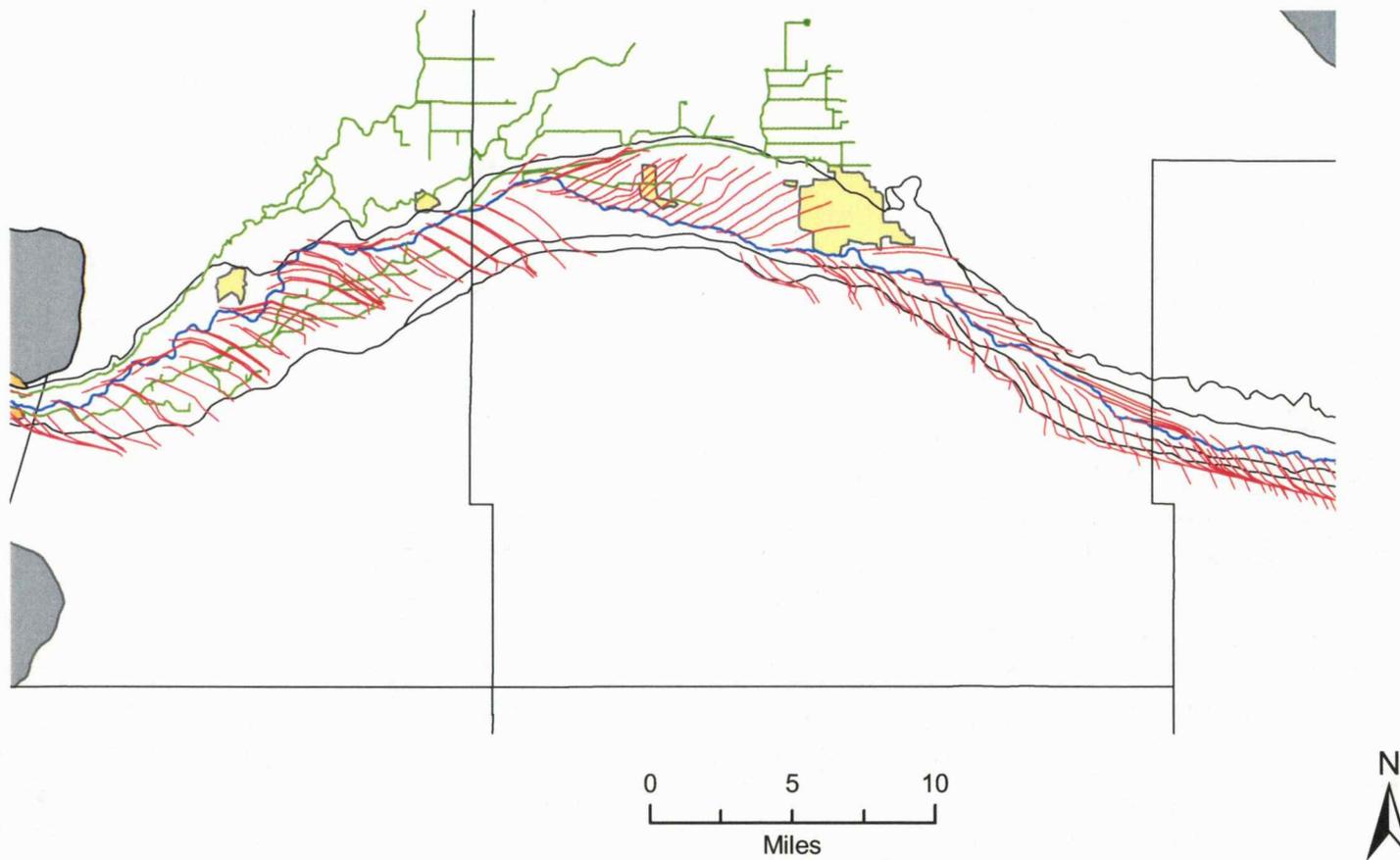


Figure 74. Particle path lines for a 40-year travel time for the steady-state simulation with reduced irrigation water use to maintain average 1990's ground-water levels. Particles start in the grid cells along the Arkansas River in southwest Kansas. The area shown is an enlargement of the central portion of Figure 72 and includes eastern Kearny County, southwest Finney County, and the edge of northwest Gray County.

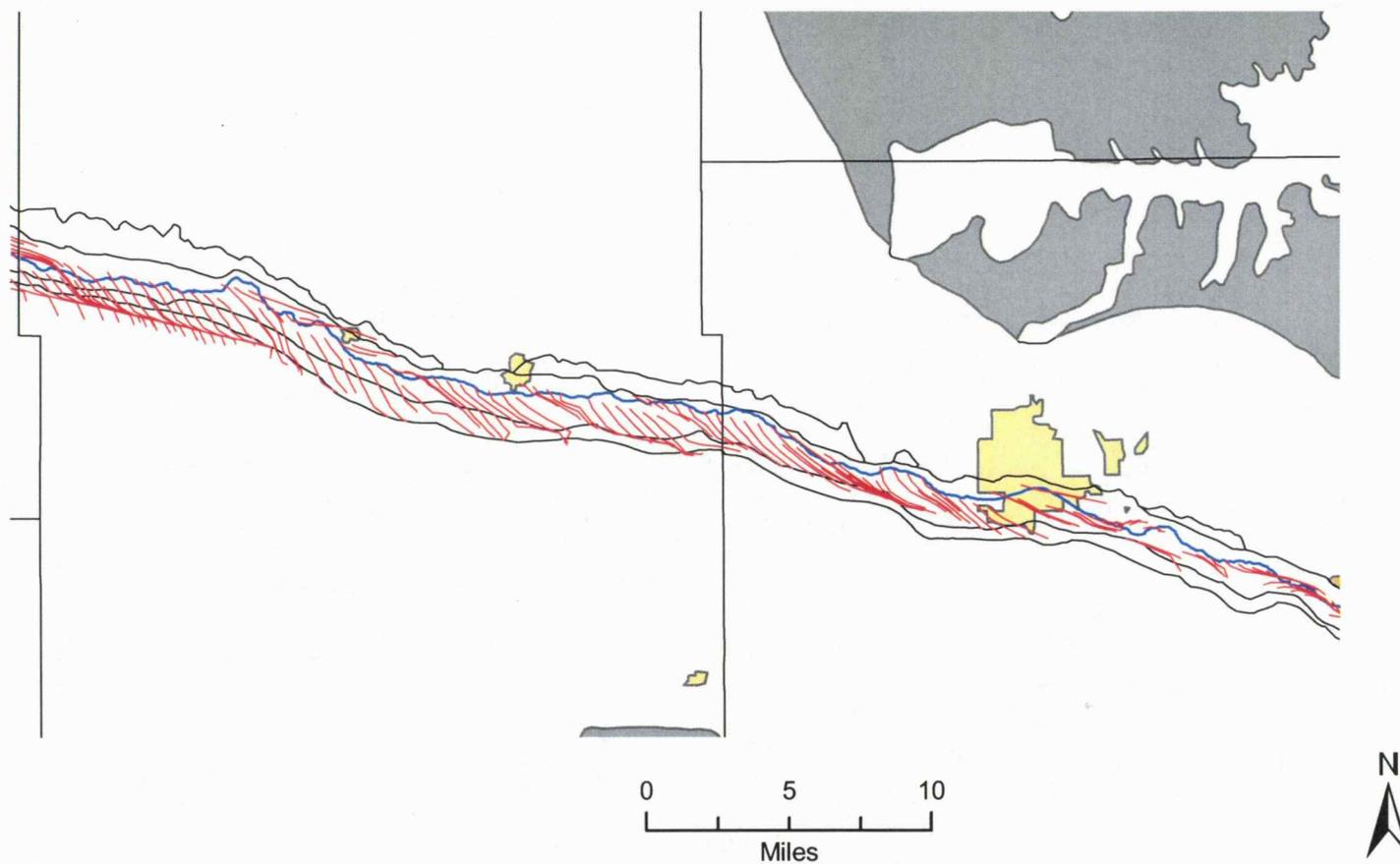


Figure 75. Particle path lines for a 40-year travel time for the steady-state simulation with reduced irrigation water use to maintain average 1990's ground-water levels. Particles start in the grid cells along the Arkansas River in southwest Kansas. The area shown is an enlargement of the eastern third of Figure 72 and includes Gray County and northwest Ford County.

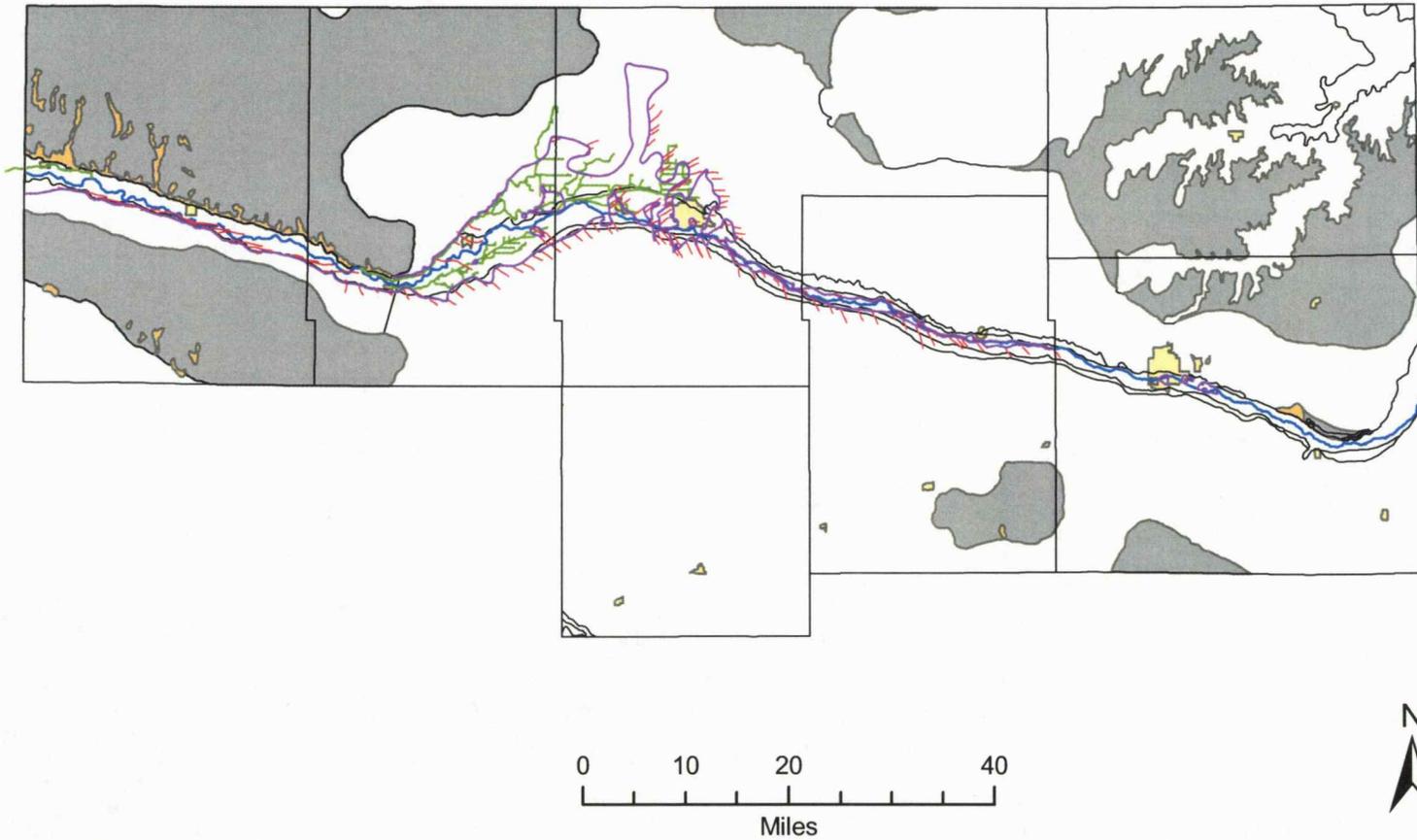


Figure 76. Particle path lines for a 40-year travel time for the steady-state simulation with reduced irrigation water use to maintain average 1990's ground-water levels. Particles start in selected grid cells along the 500 mg/L isoline for sulfate concentration in the alluvial paleovalley and the High Plains aquifer in southwest Kansas.

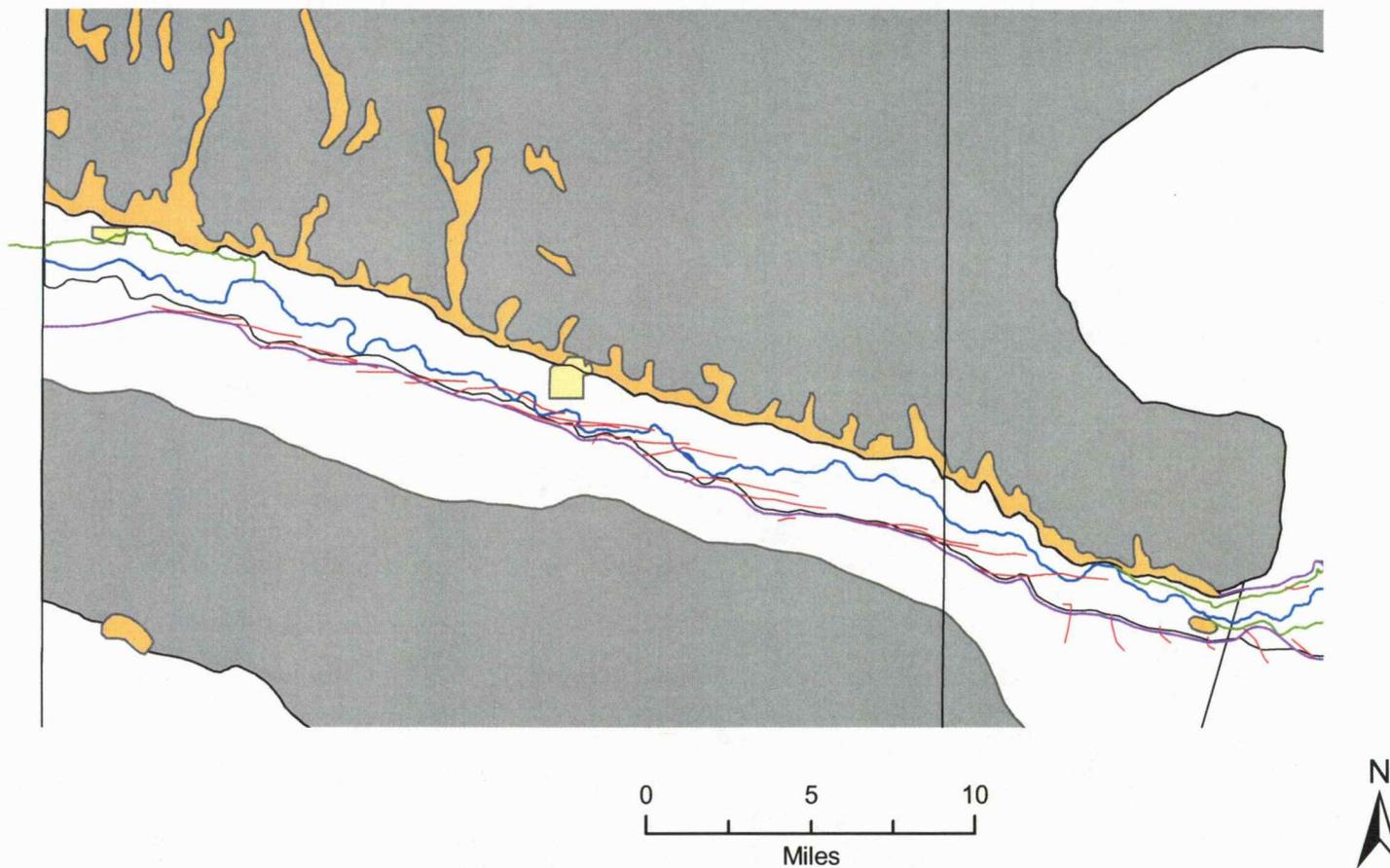


Figure 77. Particle path lines for a 40-year travel time for the steady-state simulation with reduced irrigation water use to maintain average 1990's ground-water levels. Particles start in selected grid cells along the 500 mg/L isoline for sulfate concentration in the alluvial aquifer underlying the sand dunes south of the Arkansas River floodplain and in the High Plains aquifer. The area shown is an enlargement of the western third of Figure 76 and includes Hamilton County and western Kearny County.

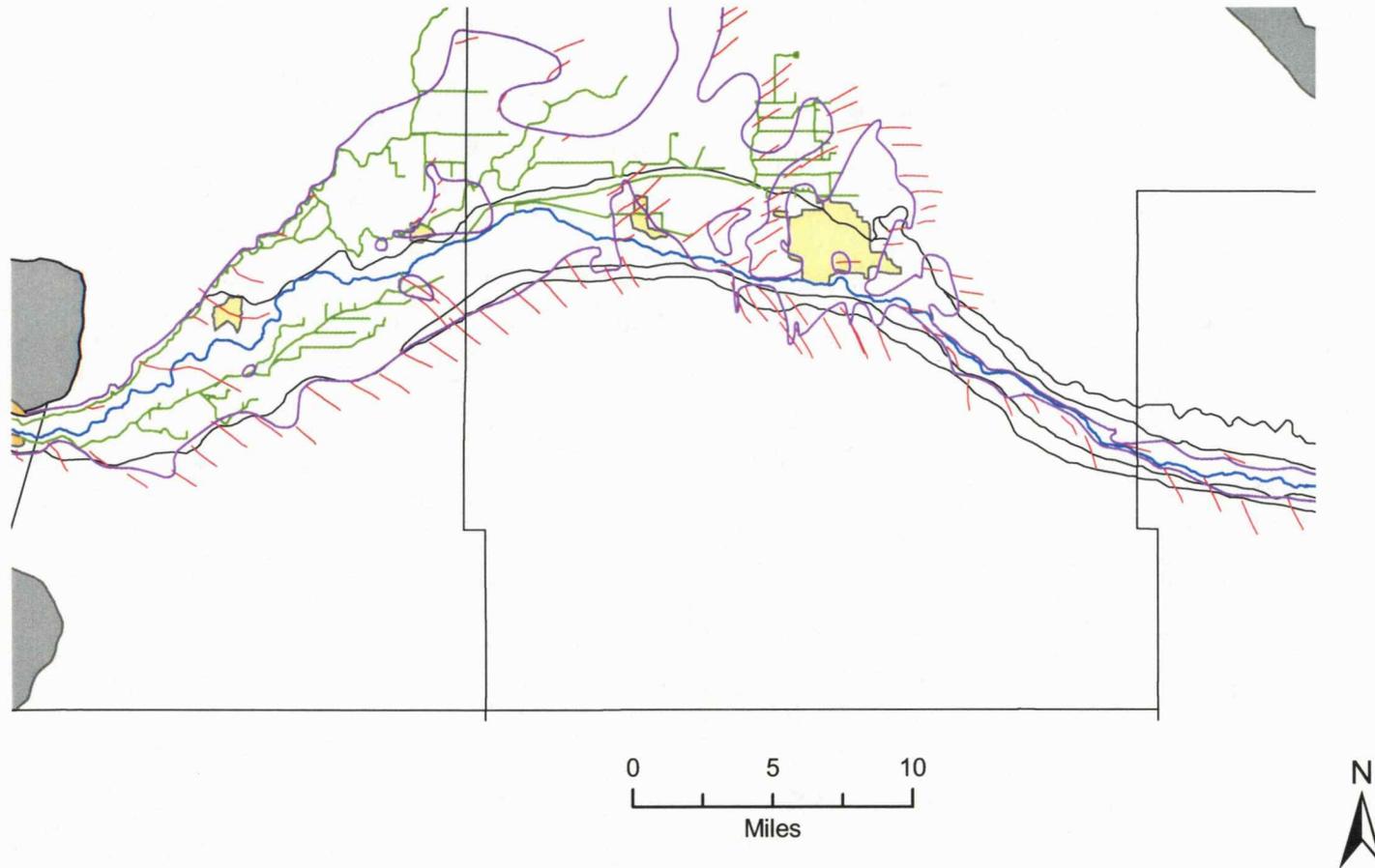


Figure 78. Particle path lines for a 40-year travel time for the steady-state simulation with reduced irrigation water use to maintain average 1990's ground-water levels. Particles start in selected grid cells along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer. The area shown is an enlargement of the central portion of Figure 76 and includes eastern Kearny County, western Finney County and part of northwest Gray County.

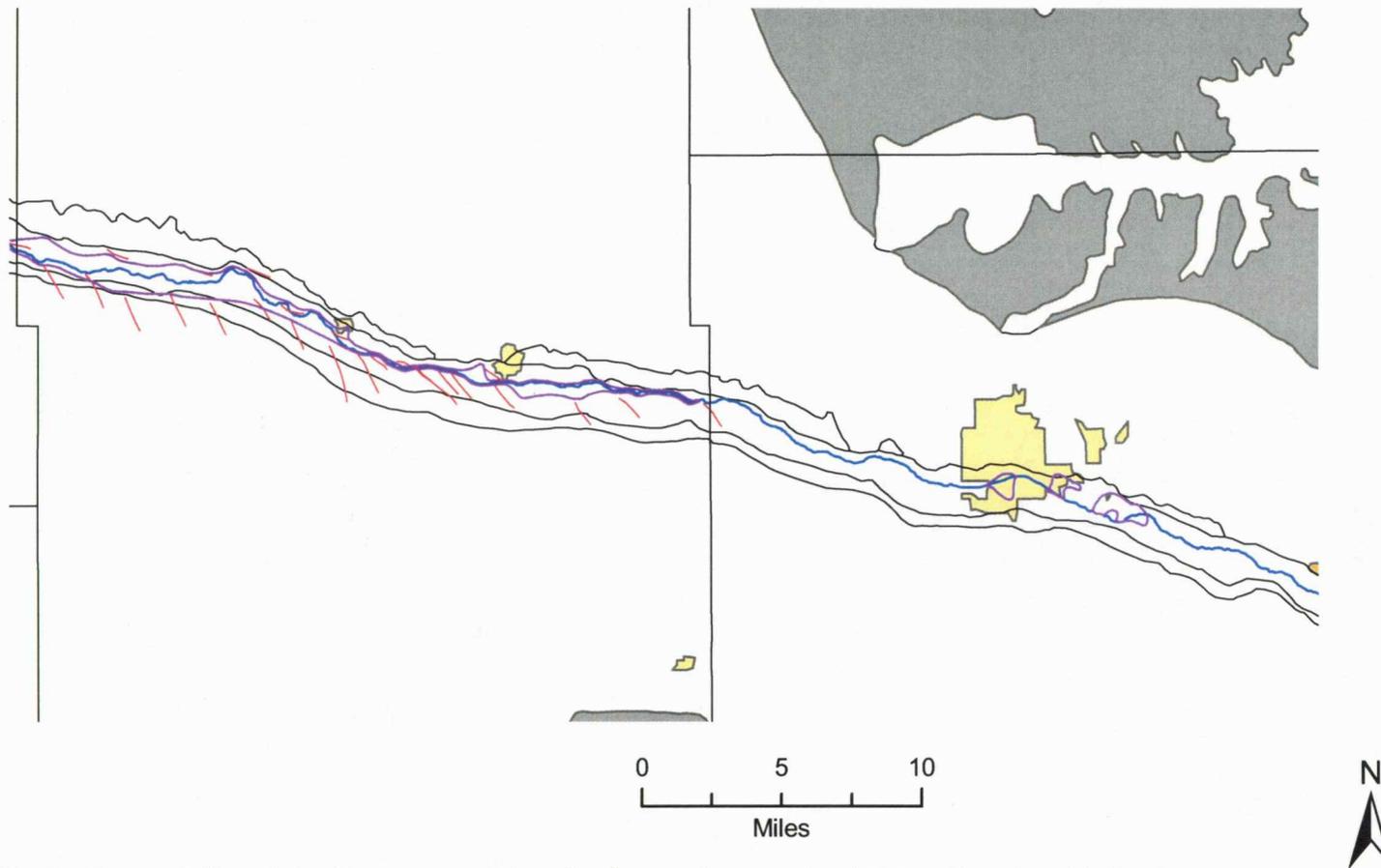


Figure 79. Particle path lines for a 40-year travel time for the steady-state simulation with reduced irrigation water use to maintain average 1990's ground-water levels. Particles start in selected grid cells along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer. The area shown is an enlargement of the eastern third of Figure 76 and includes Gray County and northwest Ford County.

of pumping to maintain 1990's water levels) on pathlines in comparison to the effect of steeper gradients that would occur in some regions if 1990's pumping continued.

The general patterns in the pathlines for the steady-state case based on reduced pumping (Figure 75) in eastern Gray County and western Ford County are generally similar to those for the pathlines for the simulations with continued 1990's water use (Figures 59 and 67). As for the western portion of the model area, the pathlines from the reduced pumping simulation (Figure 75) tend to be more parallel to the river than for the other simulations (Figures 59 and 67). The shorter pathlines that move to the northeast on the east side of Dodge City in Figures 59 and 67 are not present in Figure 75, reflecting the reduction in pumping from wells in that area.

The results for particle tracking from the simulation with reduced pumping with particle origins along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer are shown in Figures 76-79. In general, the comparisons of the pathlines for this simulation with those for the transient and steady-state cases based on 1990's water use are similar to the descriptions above for particles starting at the river grid cells. In the western part of the model area, the pathlines for the reduced pumping case are either parallel to the boundary between the Quaternary alluvial aquifer and the sand dune area or move at a small angle towards the Arkansas River, a pattern similar for the simulated pathlines for 1990's water use (Figures 61 and 69). A few pathlines in the Syracuse area for the simulations using 1990's water use move towards the northeast across the river; these are not present in the simulation for reduced water use case, probably as a result of the reduced pumping in the area.

Nearly all the pathlines originating from the 500 mg/L sulfate isoline for the steady-state case with reduced water use in the central model region (Figure 78) are shorter than those for the 1990's water use simulations (Figures 62 and 70). The pathline directions are relatively similar for all the cases except for the area from near Garden City to western Gray County, where the pathlines south of the river are generally to the south-southeast for the reduced pumping simulation (Figure 78) in comparison to the south for the 1990's pumping simulations (Figures 62 and 70), and typically to the east north of the river in Figure 78 compared to east-northeast in Figures 62 and 70. The length and direction of the particle paths starting from the 500 mg/L sulfate isoline in eastern Gray County are relatively similar for all three different simulations (Figures 62, 70, and 79).

#### Comparison of particle paths for 1990's simulations

The particle paths calculated for the 40-year transient simulation and the steady-state solution in which 1990's water levels were maintained represent extremes in the possible future movement of water and salinity in the river corridor. To facilitate comparison of the pathlines for these 1990's simulations in selected areas, particle tracks for the two simulations were placed on four figures, two each for the Lakin region and two each for the Garden City region. Figures 80 and 81 compare the pathlines for origins in grid cells along the Arkansas River from the 1990's transient and steady-state simulations. Figures 82 and 83 compare the pathlines for origins in grid cells along the 500 mg/l isoline for sulfate concentration from the

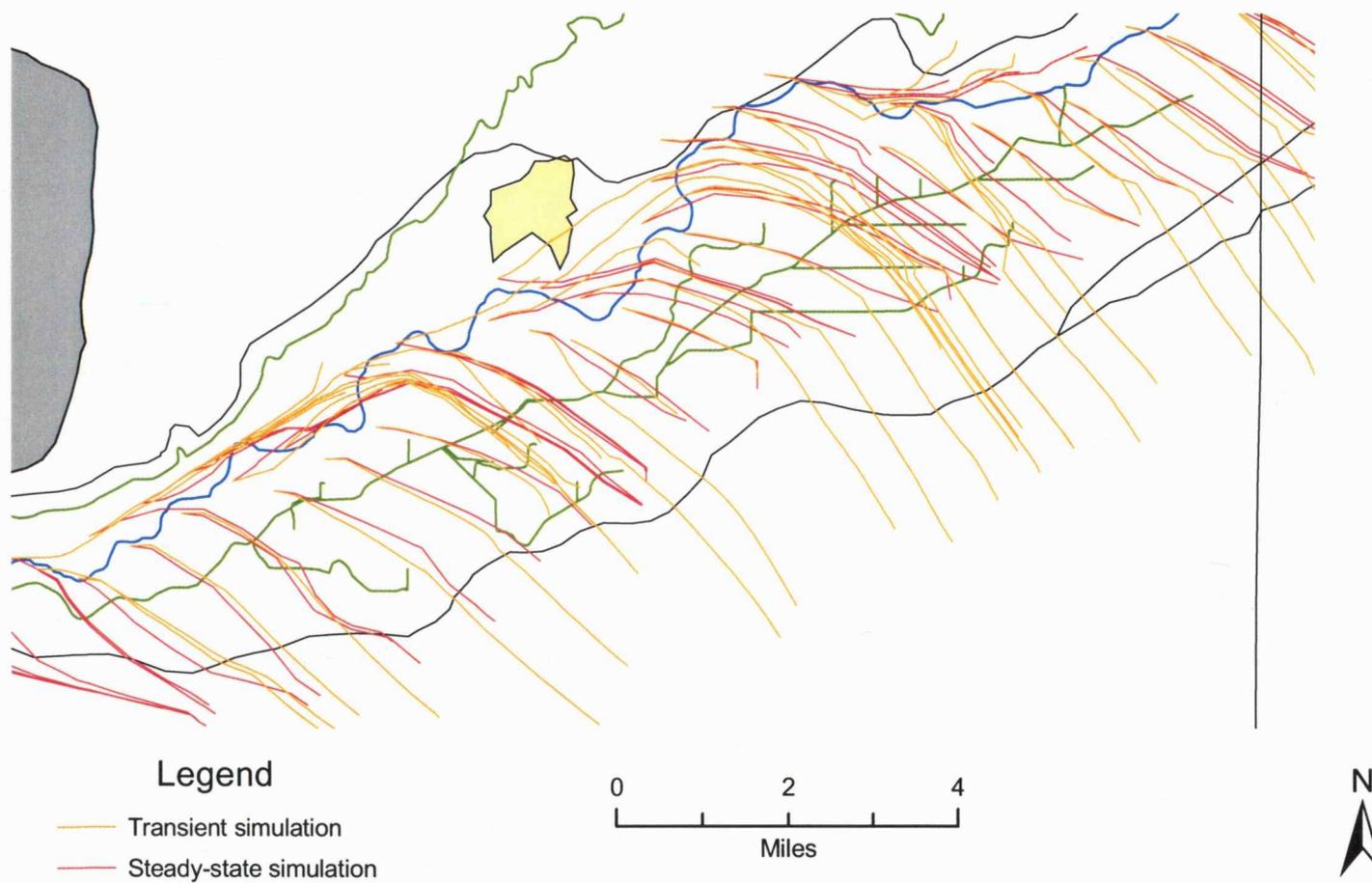


Figure 80. Comparison of particle paths for the transient simulation based on 1990's water use and the steady-state simulation based on constant 1990's water levels for the Lakin region. Particle origins are in the grid cells along the Arkansas River.

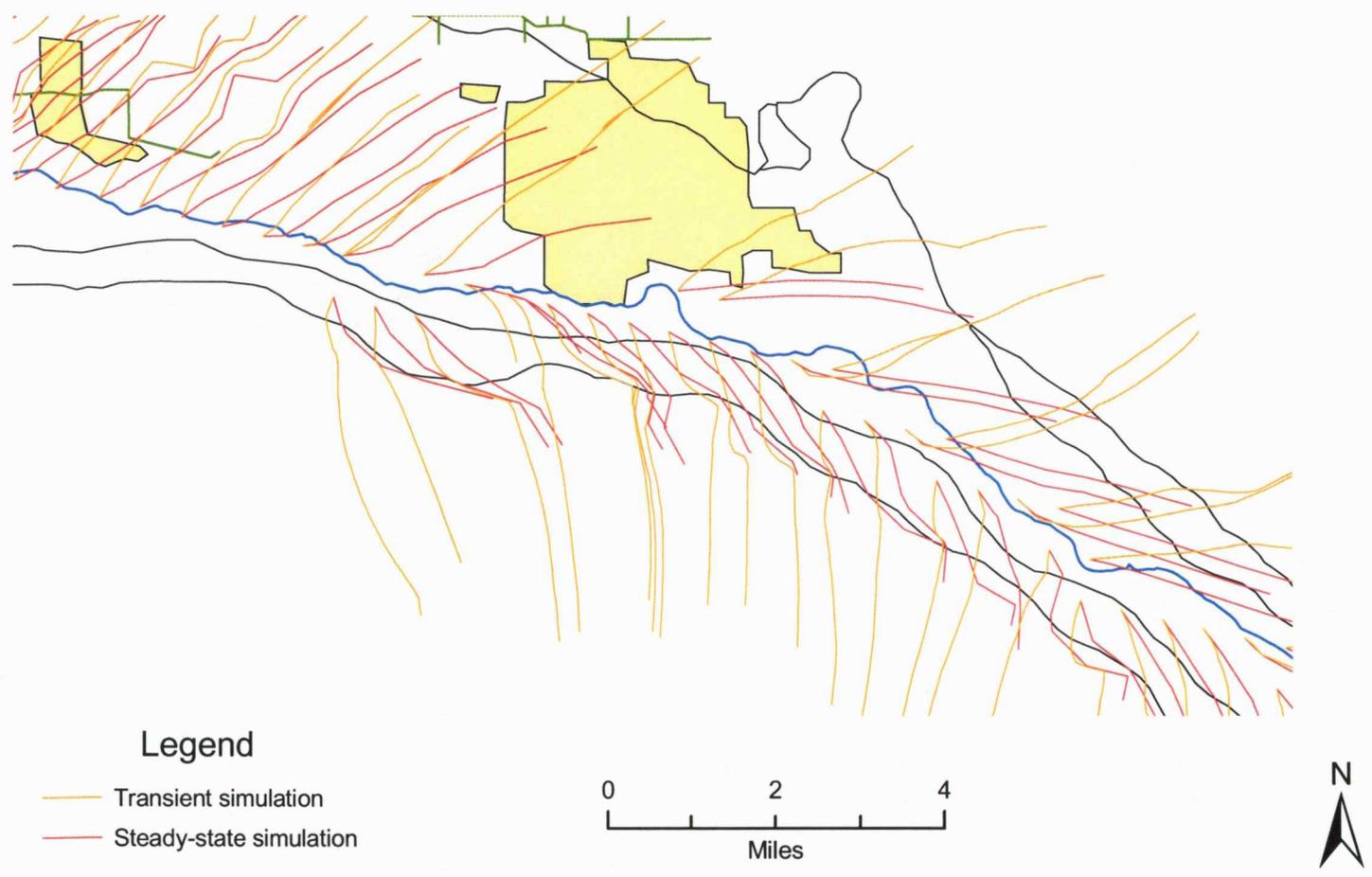


Figure 81. Comparison of particle paths for the transient simulation based on 1990's water use and the steady-state simulation based on constant 1990's water levels for the Garden City region. Particle origins are in the grid cells along the Arkansas River.

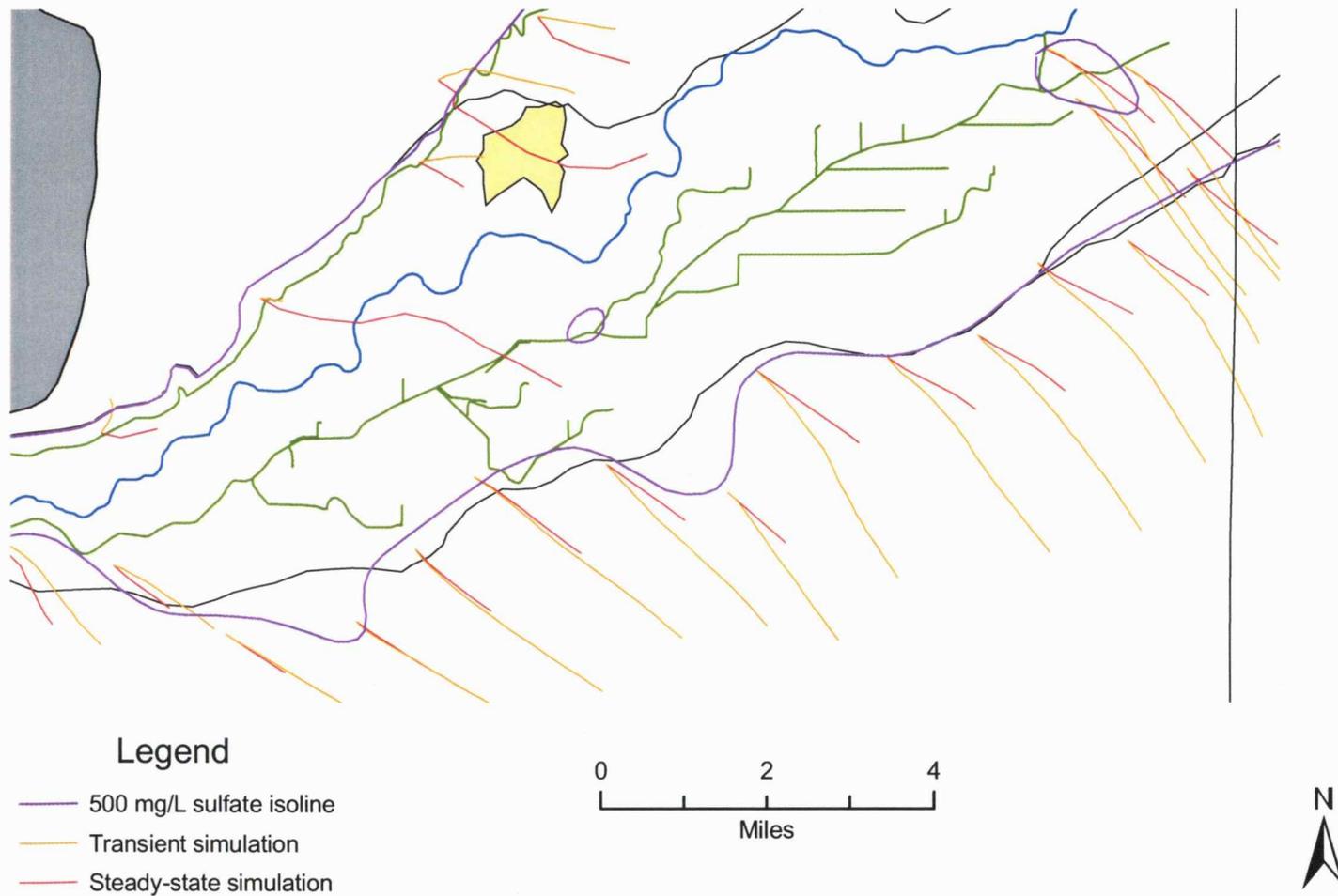


Figure 82. Comparison of particle paths for the transient simulation based on 1990's water use and the steady-state simulation based on constant 1990's water levels for the Lakin region. Particle origins are in the grid cells along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer.

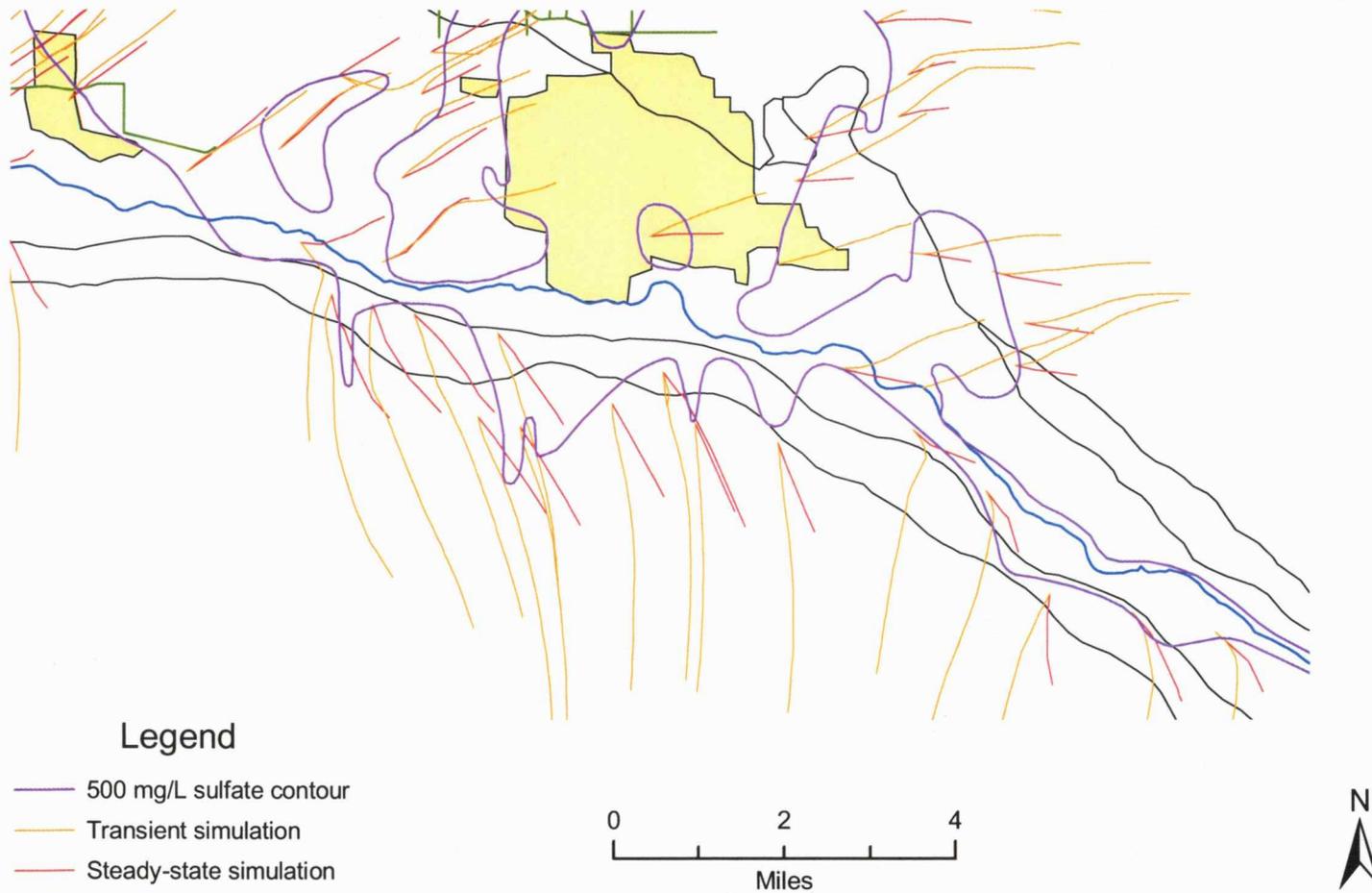


Figure 83. Comparison of particle paths for the transient simulation based on 1990's water use and the steady-state simulation based on constant 1990's water levels for the Garden City region. Particle origins are in the grid cells along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer.

two different simulations. The transient and steady-state simulations represent end-member conditions in which ground-water levels decline in many areas of the model at the maximum and minimum rates, respectively, that are probable for the future.

Figures 80-83 show well where the pathlines for the steady-state case have shorter lengths and somewhat different directions. An important observation is that, in general, the path directions for the transient and steady-state simulations are not appreciably different, indicating that during the next few decades the saline ground water will move into the same general area even if pumping is substantially reduced. The main effect of the reduced pumping is that the time for the saline water to flow the same distance as would result if present pumping were continued would be appreciably greater for many areas. For example, reductions in water use would increase the time for the saline-water–freshwater front south of the Arkansas River from eastern Kearny County to western Gray County to move to wells currently pumping freshwater in the High Plains aquifer. The probable pathlines for the next 40 years would be expected to have lengths and directions between those for the transient and steady-state simulations based on the assumption that appreciable pumping reductions will start to occur within the next couple decades.

#### *Scenario of altered water use*

The following scenario of altered water use was selected to examine the effects on the particle pathlines in the area of the model where there are the greatest differences in the path directions between the 1940 and 1990's simulations and where the saline river water is entering the region of the freshest ground water in the Arkansas River corridor. This area also includes the municipal freshwater supply of Garden City. The scenario should not be interpreted as a recommendation by this study to conduct the scenario as a planning or management action. Planning and management activities are conducted by the appropriate local and state agencies and associations. The results of the scenario are valuable in demonstrating another approach to evaluating the impact that pumping of ground water in the corridor has had and will continue to have on the movement of saline water in the system.

The area with the greatest change in the particle pathlines from the 1940 to the 1990's simulations lies to the south of the Arkansas River from eastern Kearny to western Gray counties. In the 1940 model, the particles originating from the river track primarily in an eastward direction and remain within the alluvial valley. The pathlines remain close to the river in the Garden City area in the 1940 model. In the simulations based on 1990's water use, the particles moving to the south side of the river track to the southeast to south in western Finney County and to the southeast in eastern Finney County. The particle tracks for the simulations for 1990's water use that originate at the river have major parts of the 40-year travel lines in the High Plains aquifer south of the alluvial valley. Most of the pathlines starting at the 500 mg/L sulfate concentration isoline for these 1990's simulations are in the High Plains aquifer to the south of the alluvial valley. The ends of these 40-year particle tracks are past (to the south of) all the 7 sand hills wells in the municipal supply system of Garden City. The present quality of the water in the High Plains aquifer is very fresh starting from near to about 3 miles south of the boundary of the alluvial valley, depending on the

location along the river corridor. Sulfate concentrations are less than 100 mg/L near this transition zone and less than 50 mg/L a short distance farther to the south.

A scenario involving a zone of no pumping was selected to determine its effect on the length and direction of particle paths originating from grid cells both along the river and the 500 mg/L sulfate isoline for the transient and steady-state simulations for 1990's water use and the steady-state case for constant 1990's water levels by substantially reducing pumping. The no-pumping zone was defined as a band underlying the sand dunes that extends from the edge of the Quaternary alluvium or alluvial terrace deposits to approximately 3 miles south of this boundary, and from south-southeast of Lakin to southeast of Garden City in an east-west direction (Figures 84-89). The boundary of the no-pumping band was first drawn in ArcView and then overlain on the model grid for incorporation of the grid cells falling within the band. The pumping in the zone was set at zero and the irrigation return infiltration was removed from the ground-water recharge. The recharge for about a dozen cells with low remaining recharge was increased from the calibrated values in order to obtain simulations that converged. The increased recharge is greater than that used as an initial value for general areal recharge from precipitation before calibration of the 1990's models. The increased recharge in this area fits the sand dune character of the soils in the no-pumping band.

The particle paths in the central corridor region for the 40-year transient simulation based on 1990's water use are displayed in Figure 84 for particles starting at river grid cells and in Figure 85 for particles originating along the 500 mg/L isolines for sulfate concentration. Comparison of Figure 58 without the no-pumping zone to Figure 84 indicates that the particle paths moving south of the river are generally shorter and have a somewhat more easterly component in their direction in the no-pumping simulation. However, the changes in length and direction are not substantial. Many of the particles in eastern Kearny County still move into the High Plains aquifer south of the alluvial valley and the particles south of Garden City track appreciable distances into the High Plains aquifer. The relative differences in the pathline lengths and directions between the simulations with (Figure 85) and without the no-pumping zone (Figure 62) for particles originating at the sulfate concentration isoline are similar to the differences between the corresponding simulations for the particles starting at the river.

Figures 86 and 87 illustrate the particle paths calculated for the solution imported from the steady-state case for constant 1990's water use with the no-pumping zone. The particle paths with origins at the river nodes are in Figure 86 and with origins along the 500 mg/L sulfate isoline are in Figure 87. Comparison of Figure 86 with Figure 66 for the same conditions except without the no-pumping zone and associated recharge adjustment indicates that many of the particle paths in eastern Kearny County and westernmost Finney County that start at the river and move south of the river are substantially shorter for the no-pumping scenario. The pathlines in the same area for the no-pumping simulation also have a more easterly component of direction than for the case without the no-pumping zone. In the Holcomb area, some of the particle tracks move from the river to the northeast in the scenario with the no-pumping zone in contrast with no particle paths tracking to the north of the river in the simulation without the no-pumping band. This indicates that the decrease in the

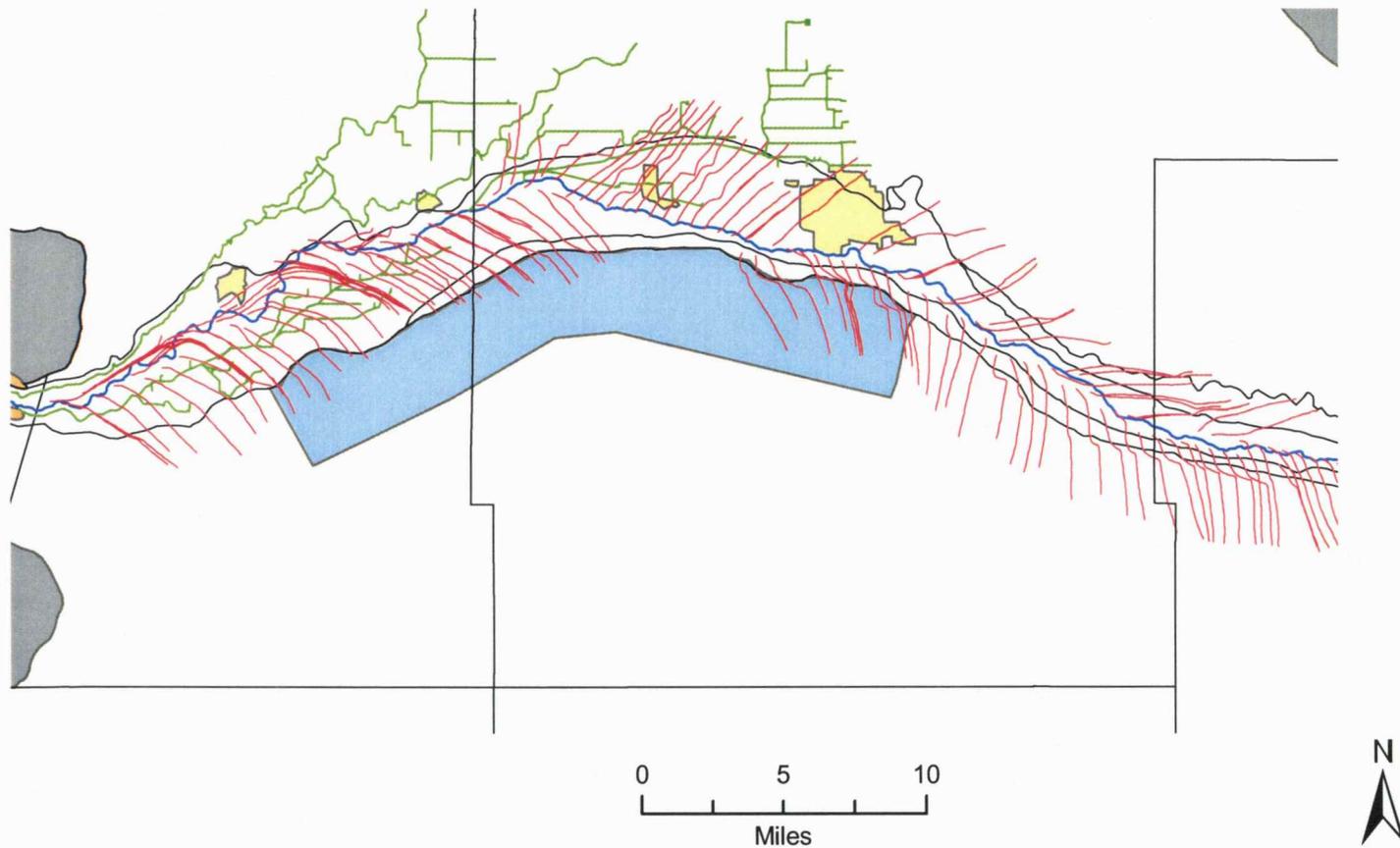


Figure 84. Particle path lines for the 40-year transient simulation with the no-pumping zone based on average 1990's conditions with particle origins in the grid cells along the Arkansas River in southwest Kansas. The area shown includes eastern Kearny County, western Finney County, and part of northwest Gray County.

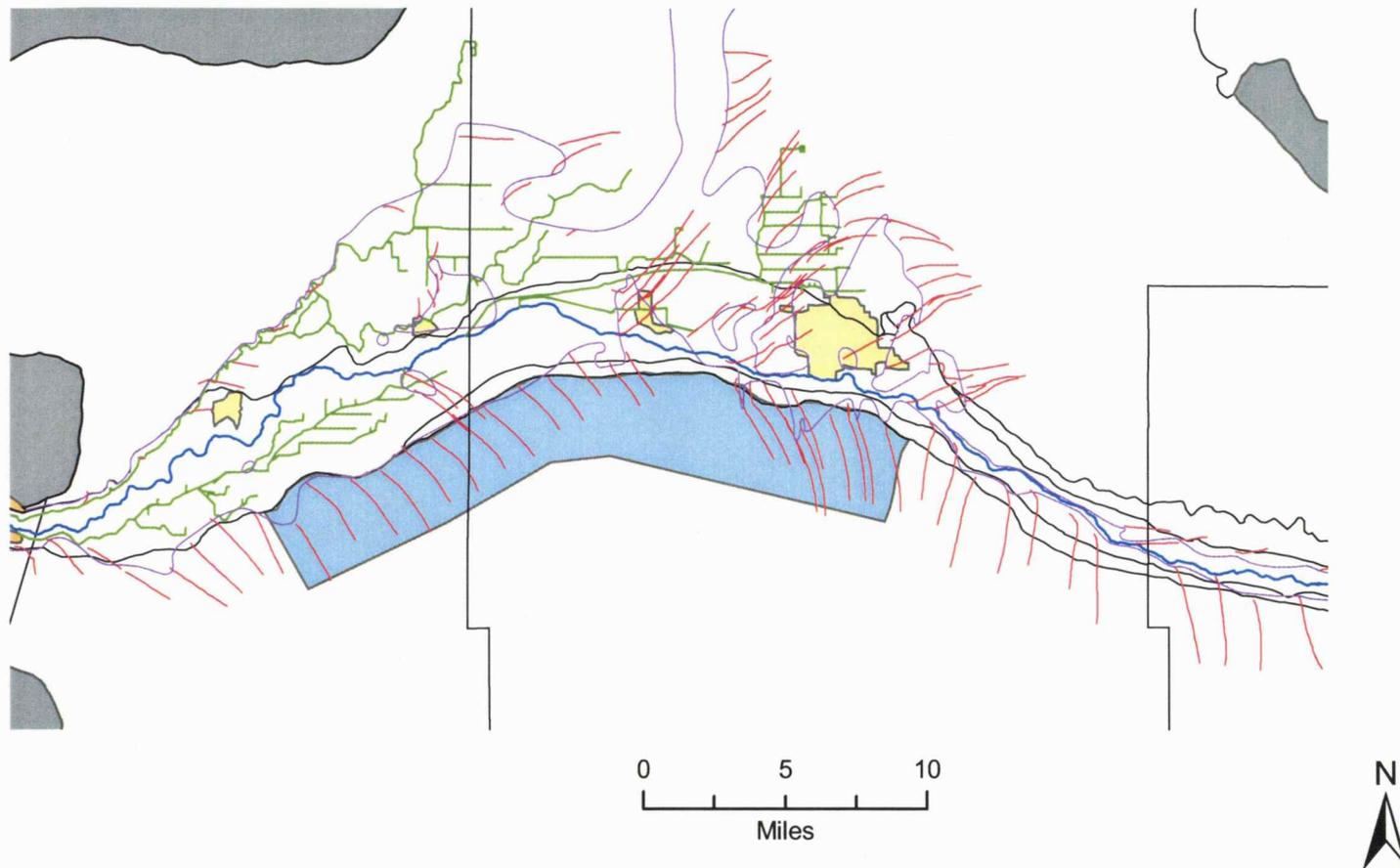


Figure 85. Particle path lines for the 40-year transient simulation with the no-pumping zone based on average 1990's conditions with particle origins in selected grid cells along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer. The area shown includes eastern Kearny County, western Finney County, and part of northwest Gray County.

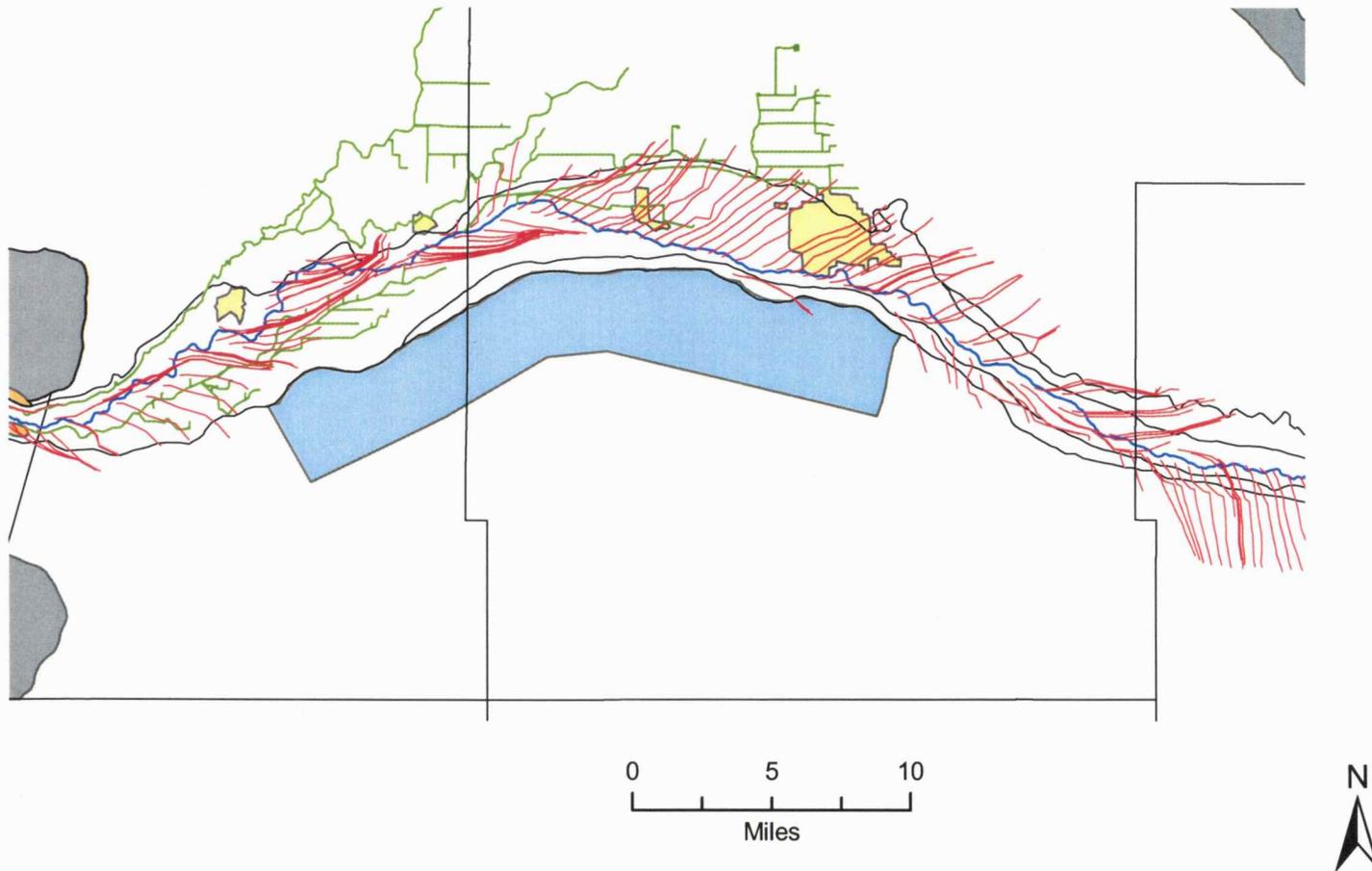


Figure 86. Particle path lines for a 40-year travel time for the steady-state simulation with the no-pumping zone based on average 1990's water use with particle origins in the grid cells along the Arkansas River in southwest Kansas. The area shown includes eastern Kearny County, western Finney County, and part of northwestern Gray County.

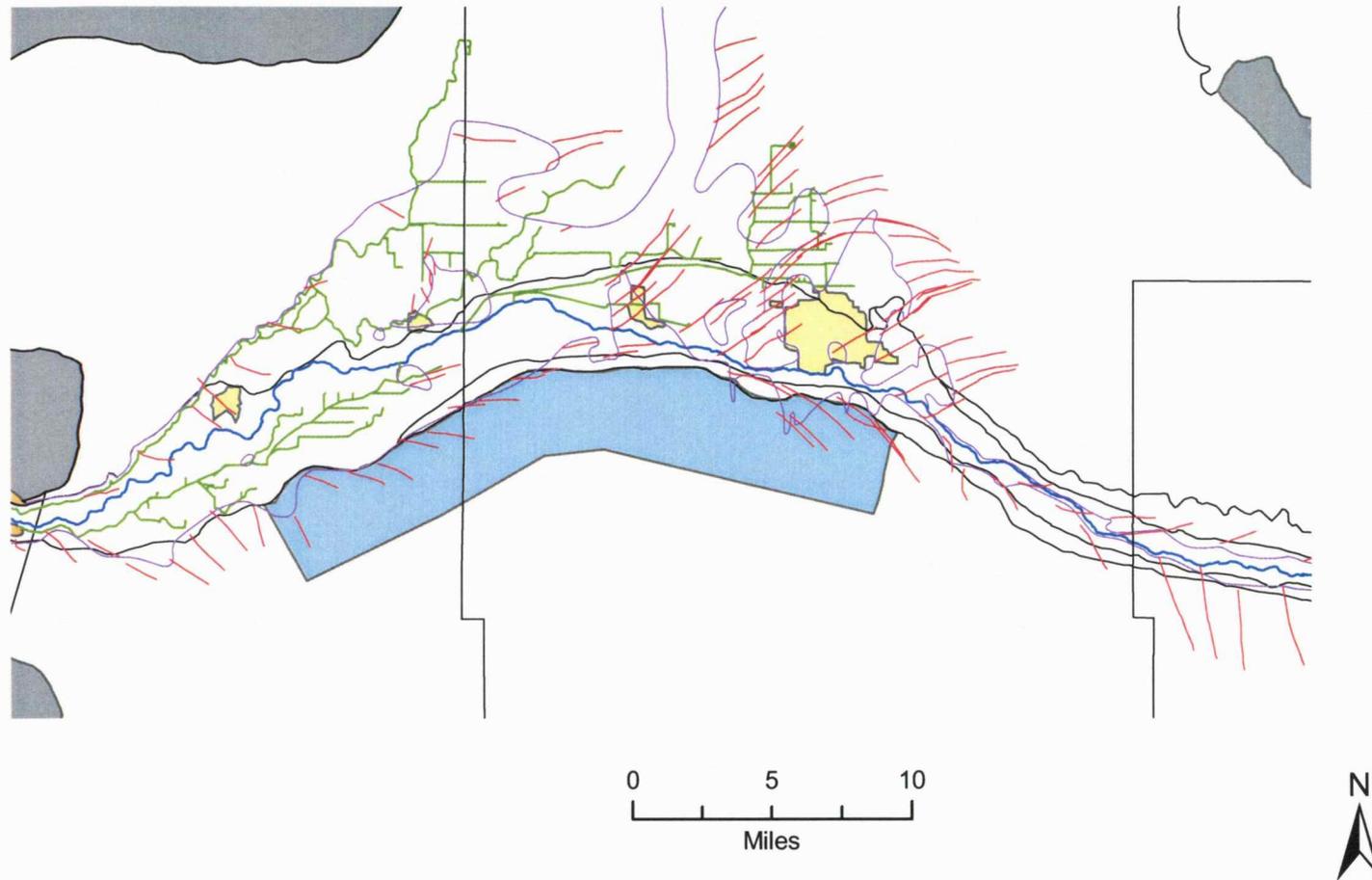


Figure 87. Particle path lines for a 40-year travel time for the steady-state simulation with the no-pumping zone based on average 1990's water use with particle origins in selected grid cells along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer. The area shown includes eastern Kearny County, western Finney County, and part of northwest Gray County.

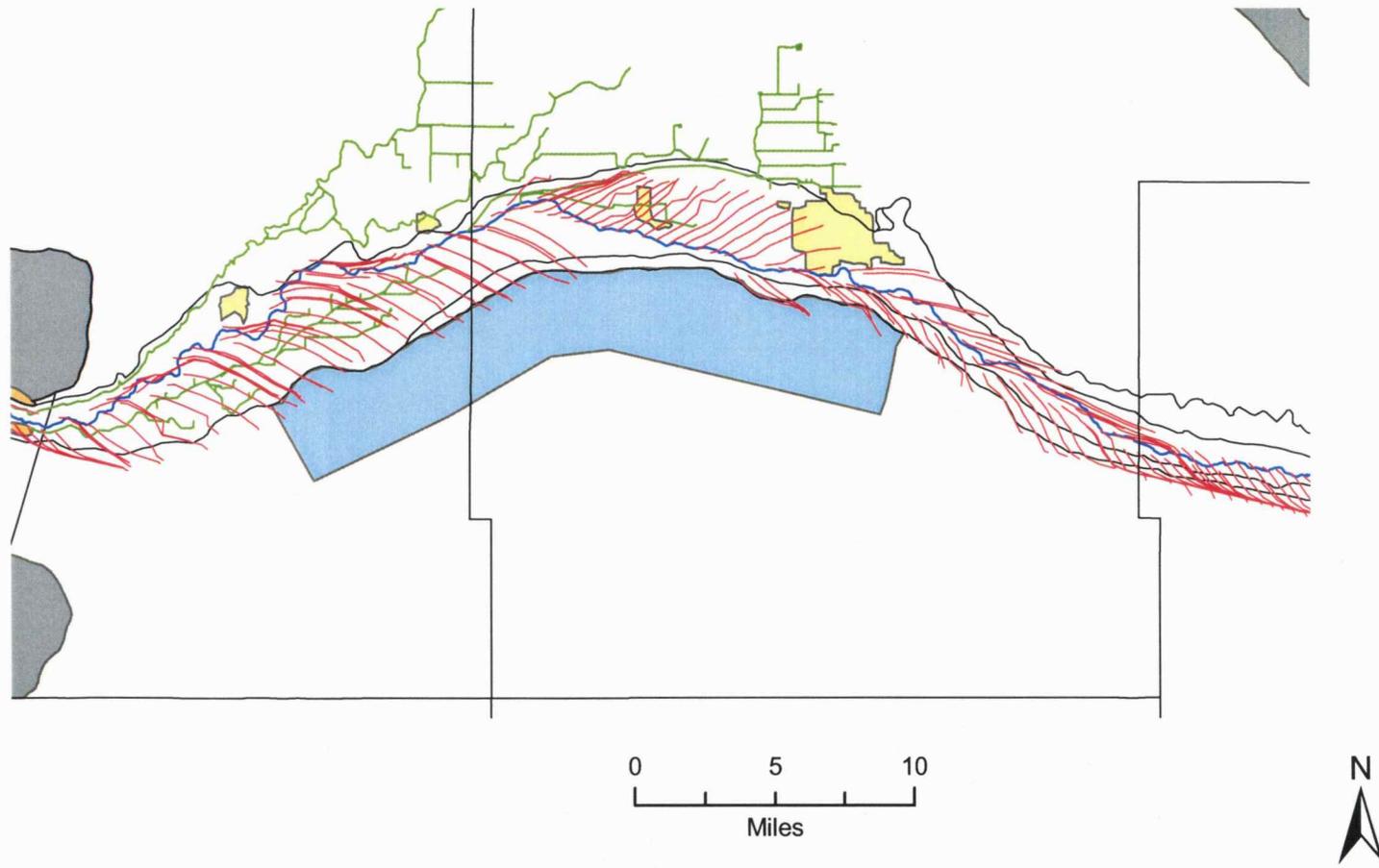


Figure 88. Particle path lines for a 40-year travel time for the steady-state simulation with reduced water use to maintain 1990's ground-water levels and the no-pumping zone. Particles start in the grid cells along the Arkansas River in southwest Kansas. The area shown includes eastern Kearny County, western Finney County, and part of northwest Gray County.

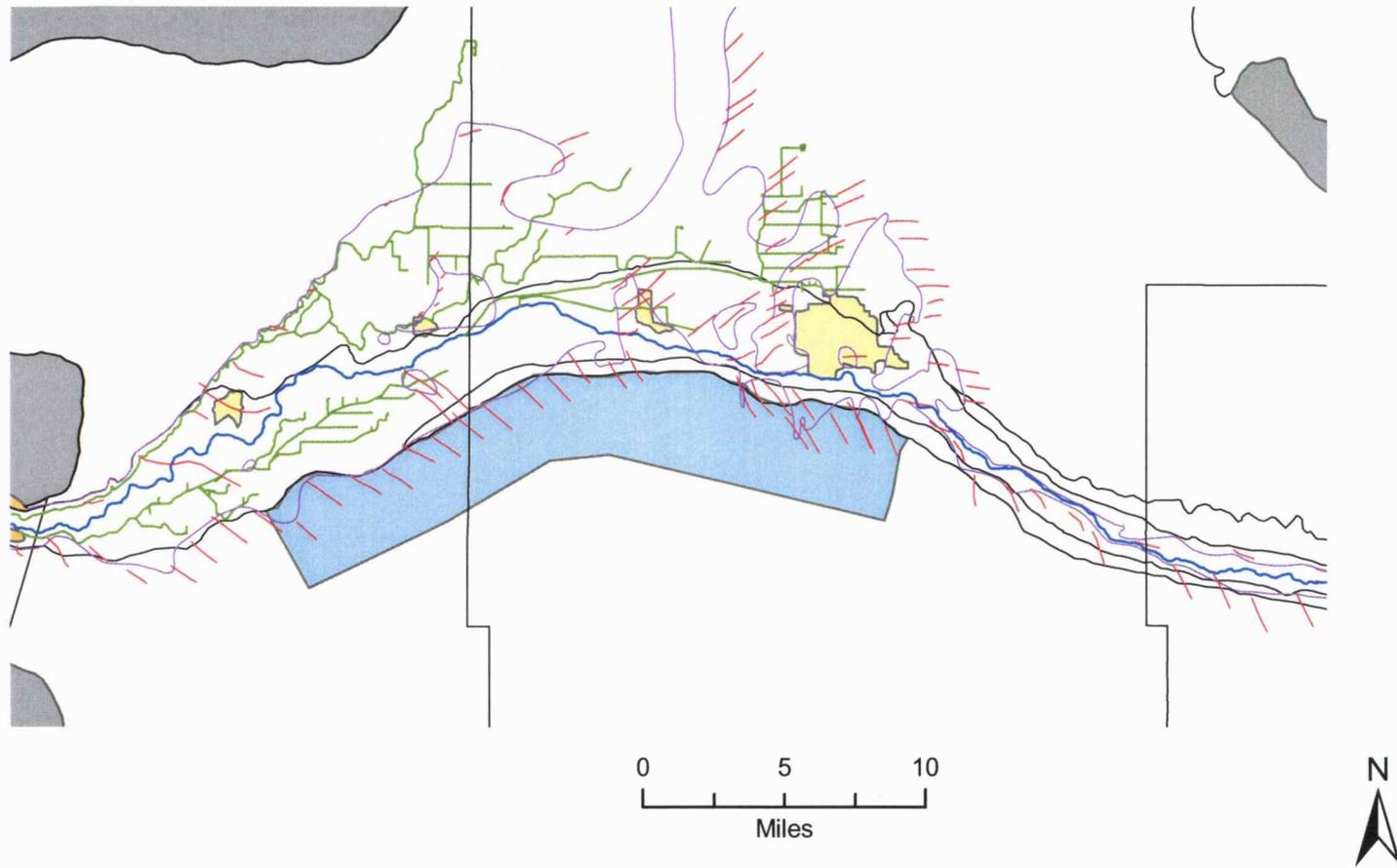


Figure 89. Particle path lines for a 40-year travel time for the steady-state simulation with reduced water use to maintain 1990's ground-water levels and the no-pumping zone. Particles start in selected grid cells along the 500 mg/L isoline for sulfate concentration in the High Plains aquifer. The area shown includes eastern Kearny County, western Finney County, and part of northwest Gray County.

hydraulic head gradient from the river to the south is reduced enough by the no-pumping zone that the gradient to the north of the river becomes relatively greater and shifts the flow direction of some of the ground water that seeps from the river. In the area south of Garden City, the pathlines for the no-pumping scenario are not greatly different from those starting at the river for the simulation without the no-pumping zone. The differences between the simulations with the no-pumping zone (Figure 87) and without the zone (Figure 70) for particles starting along the 500 mg/L sulfate isoline are smaller than those between Figure 86 and 66 for particles originating at the river. Although there are some small differences in the path directions in eastern Kearny County and westernmost Finney County, the lengths of the pathlines in the High Plains aquifer along the area of the no-pumping zone are similar in both cases.

The inclusion of the no-pumping zone into the steady-state simulation based on reduced water use to maintain average 1990's water levels is shown in Figures 88 and 89 for particles origins in grid cells along the river and along the 500 mg/L sulfate isoline, respectively. Comparison of Figure 88 with Figure 74 for the corresponding simulation without the no-pumping zone and, similarly, Figure 89 with Figure 78, indicates that there are no substantial changes in the pathlines in comparison to the changes for the other 1990's simulations. This is expected because the approximately 84 percent reduction in pumping necessary to maintain average 1990's water levels produced a simulation that is much closer to that for the no-pumping zone than for that for the continued 1990's water use.

Although the no-pumping zone has the effect of decreasing the hydraulic head gradient from the river to the High Plains aquifer to the south of the river for the simulations, the current hydraulic head gradient extending from the river valley south in the High Plains aquifer is so great that it apparently will allow substantial ground-water flow through the no-pumping area. The simulations based on continuing 1990's water use show a substantially faster rate of movement through the no-pumping area than for the simulations based on 1990's water use. Thus, the saline water from the river and alluvial aquifer would be expected to continue to track into the area of freshwater in the High Plains aquifer even in the case of the no-pumping zone.

## CONCLUSIONS

The salinity of ground water in the alluvial aquifer of the upper Arkansas River corridor in southwest Kansas has greatly increased since the beginning of irrigation diversions in Colorado and Kansas in the late 1800's. The salinity of the High Plains aquifer along the river corridor has also greatly increased starting at locations of pumping wells after 1900 and then becoming more regional as a result of wide-spread declines in ground-water levels in the aquifer after 1970. The source of the saline water is flow in the Arkansas River that enters Kansas from Colorado. Ground water in the upper Dakota aquifer underlying the river corridor is fresh and is not a source of salinity. The saline river water will continue to enter the High Plains aquifer in substantial amounts in the future and impact an ever increasing area of the aquifer.

Before irrigation diversions in Kansas and the large declines in the ground-water levels of the river corridor, the Arkansas River gained flow along nearly all of its length in southwest Kansas. The ground-water discharge providing baseflow to the river was fresh and decreased the natural levels of dissolved solids in the river water by dilution. The baseflow increased downstream and thus decreased the dissolved solids concentrations progressively downstream. If the numerical simulation of ground-water flow for 1940 conditions represents well the predevelopment environment, some water from the river in eastern Kearny County, where the river flows in an east-northeast direction, could have entered and moved in the regional direction of ground-water flow to the east within the alluvial aquifer. This would have produced elevated concentrations of dissolved solids in water of the alluvial aquifer in that area in comparison to elsewhere in the corridor, but the concentrations would have been much less than observed from the late 1930's to 2000. By the time the ground water from the alluvial aquifer in eastern Kearny County reached the shallow High Plains aquifer to the east, the dissolved solids levels would have been diluted by mixing with fresh ground water such that the mixture would have been fresh but would contain sulfate concentrations greater than the less than 50 mg/L expected in the deep High Plains aquifer to the south of the river.

After irrigation started in Colorado in the 1870's, Arkansas River flow entering Kansas decreased in quantity and became more saline. Although the more saline river water would have affected alluvial ground waters adjacent to the river, the smaller river flow, coupled with the fresh ground-water discharge, would have continued to keep most of the ground water in the alluvial aquifer fresh. However, as indicated above, some of the saline flow might have entered the alluvial aquifer south of the river in eastern Kearny County and increased the salinity of the alluvial aquifer south and east of the river in that area.

After diversions began in the 1880's in Kansas, the salinity of ground water in the alluvial aquifer would have increased in areas underlying the canals and the fields irrigated with the saline river water as a result of seepage and recharge. The increased salinity of water in the alluvial aquifer would have decreased the dilution capacity of discharge from the alluvium to the river. This would have had a small effect on increasing the salinity level of baseflows in the river downstream of the ditch-irrigation areas in Kansas.

The installation and pumping of large-capacity wells in the alluvial aquifer after 1900 would have produced local, shallow cones of depression in the aquifer. This would have induced the 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. The construction and pumping of high-capacity wells in the High Plains aquifer underlying the alluvial aquifer would have generated cones of depression that could have allowed alluvial water to move downwards into the upper parts of well screens in the High Plains aquifer in areas where there are no substantially thick clays underlying the alluvium. If the water in the alluvial aquifer were saline, then some salinity could have started to mix into the upper part of the High Plains aquifer. Even where clays are present, water-quality data indicate that wells in the High Plains aquifer began to draw in some saline water. The primary avenue for the saline-water movement is expected to have been down the gravel packs of wells with annular spaces not sealed through the alluvial aquifer.

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 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 below the shallow zones of the High Plains aquifer. The vertical head gradients that were generated caused a substantial increase in the downward movement of saline water from the alluvial aquifer into the underlying High Plains aquifer, and an increase in the movement of shallow saline water in the High Plains aquifer into the deeper aquifer. The movement occurred both as areal migration where there was no substantial thickness of clay layers to appreciably retard the vertical movement, and as gravel-pack flow in the annular space of large-diameter wells that were not sealed through the alluvial aquifer or the upper part of the High Plains aquifer.

The regional declines in water levels in the High Plains aquifer also changed the direction of ground-water flow in the river corridor. Saline 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.

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 baseflow additions to the river 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. Thus, the salinity of the river water entering Kansas is no longer normally diluted by baseflow except soon after large flow events when bank storage of less saline water returns to the river. The result is that the salinity of river water passing the Colorado-Kansas

state line on a given day does not usually change appreciably as it flows downstream to Dodge City. The current net losses of water from the river channel (in addition to irrigation diversions) are relatively small in the alluvial valley in Hamilton and western Kearny counties. The river seepage becomes substantial downstream, where the High Plains aquifer underlies the alluvial aquifer (east of the Bear Creek Fault zone).

During the 1980's and 1990's, recharge from the ditch service areas, coupled with decreased pumping of ground water when ample supplies of river water were available for irrigation, increased ground-water levels in eastern Kearny and western Finney counties underlying the ditch irrigation areas north of the Arkansas River. However, the large water-level declines in the High Plains aquifer south of the river produced an even greater hydraulic gradient from the river valley to the south than was generated in the 1970's. The simulation of flow based on 1990's water use into the future indicates that saline water from the river will move at substantial rates into the alluvium and thence into the High Plains aquifer south of the river. The migration of saline water from the river could reach as far as 3 miles south of the alluvial valley and the movement from the current isoline for 500 mg/L sulfate concentration could be as far as 4 miles south of the alluvial aquifer south of the Garden City area in 40 years. The results fit with the recent observations that water with a sulfate concentration exceeding 500 mg/L has reached one of the most northerly of the sand hills municipal wells of Garden City south of the city, and a nearby domestic well and two irrigation wells. These 4 wells are approximately two miles south of the river and more than 1.5 miles south of the alluvial valley.

The simulation for pumping reduced sufficiently to maintain the average 1990's water levels indicated that the saline water would continue to migrate from the alluvial valley into the High Plains aquifer south of the valley from eastern Kearny County to western Gray County. However, the rate of movement would be substantially slowed and the flow direction in Finney County and western Gray County would shift somewhat towards the southeast. Thus, saline water would take longer to affect all of the wells in the sand hills well field of Garden City south of the Arkansas River.

The ground-water flow simulations based on 1990's conditions indicate that most of the fresh ground water in the alluvial trough underlying the sand dunes south of the alluvial valley in Hamilton and western Kearny counties should not be significantly affected by saline river or alluvial aquifer water. This conclusion is based on no substantial further development of ground water in the alluvial trough that would lower ground-water levels and induce flow of saline ground water from the alluvial valley into the area of freshwater. The simulations also show that the area of the High Plains aquifer affected by the leakage of saline water from the overlying alluvial aquifer from central Gray County to east of Dodge City should remain under the alluvial valley during the next 40 years. This conclusion also assumes that water levels will not be substantially different from the 1990's in the High Plains aquifer along this section of the river corridor. If future pumping in the High Plains aquifer north and south of the alluvial valley along this valley stretch causes appreciably greater water-level declines than the trend for the 1990's, then some saline water could start to move outward from the edge of the river valley.

The observed salinity distribution in the High Plains aquifer in the river corridor indicates that local pumping effects are enough to cause a substantial increase in the travel rate of saline ground water. Thus, the simulation results in this report should only be used to show the patterns of saline water migration in terms of general direction and distance and not for detailed predictions on a smaller scale.

The simulations averaged conditions for the 1990's and did not consider fluctuations in river flow and salinity. Arkansas River water in southwest Kansas is saline during both low and high flows. This provides a constant source of saline water to the alluvial aquifer when the river is flowing and where the river loses water to the aquifer. The salinity is substantially greater during low flows. The seepage rate from the 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 river bed. The hydraulic conductivity of the alluvium is generally greater than that of the sediments underlying the alluvium. Thus, seepage from the river can 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. Thus, 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. Therefore, a greater percentage of the more saline, 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. The water is less saline during this period. During periods of no flow in the river, recharge from precipitation can dilute some of the saline waters in the alluvial aquifer such as in the Dodge City area.

A predominant result of the evaluation of water-level declines in the High Plains aquifer and the numerical simulations of ground-water flow based on 1990's conditions is the contrast in conditions north and south of the Arkansas River in eastern Kearny and western Finney counties. North of the river, the recharge from the ditch service area produces conditions in which the water levels and the ground-water flow directions often do not change substantially with time. South of the river, the high-rate of ground-water declines has shifted ground-water flow directions to the south and increased flow rates in that direction. Continued declines at the current rate will result in complete depletion of the saturated thickness at distances of more than several miles south of the river. The numerical simulations suggest that recharge from the river and the alluvial aquifer could maintain a west-east band of sustainable saturated thickness that would be several miles wide from the river to the south. The thickness would rapidly decrease in a southward direction.

The recharge from the river channel and the ditch irrigation system to the underlying alluvial and High Plains aquifers exceeded 100,000 acre-ft during the late 1990's when the river flows were greater than average. Although the river water recharging the aquifers is saline, it is a valuable resource if viewed in terms of quantity. The recharge of the High Plains

aquifer by river water seeping from the river channel and infiltrating below the ditch-irrigated areas is on a scale similar to recharge projects in the United States costing many millions of dollars. As water treatment technologies become more cost efficient, desalinization of a local supply might become competitive with distant transport of freshwater if current fresh municipal supplies in the High Plains aquifer become saline. However, management and protection of existing fresh ground waters in the corridor will still be important to minimize salinity impacts for various uses.

The simulation with reduced pumping and the scenario showing the effects of a no-pumping zone in the High Plains aquifer south of the alluvial valley reinforced the importance of the impact that the large water-level declines have on the corridor. Reducing the pumping by approximately 84 percent without irrigation return flow (equivalent to a reduction of about 79 percent with 25 percent return flow) to maintain 1990's water levels substantially decreased the flow rate of ground water south of the river valley in the central part of the model area. Stopping all pumping along a 3-mile band just south of the alluvial valley from eastern Kearny County through western Finney County decreased the southerly component of particle track direction and shortened the pathlines during the 40-year simulation. However, the ground water still migrated at substantial rates towards the freshwater in the aquifer and past the Garden City well field in the sand hills. The implications are that it would take a very large amount of added recharge along the river valley margin to protect the well field. The cost of this approach and the difficulty of obtaining enough fresh ground water to produce the recharge along the corridor suggest that treatment of saline ground water might possibly be more feasible. As indicated in the section on numerical modeling, the reduced pumping and no-pumping scenarios should not be interpreted as recommendations by this study to conduct the action. Planning and management activities should be conducted by the appropriate local and state agencies and associations.

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## **APPENDIX A**

Ming-Shu Tsou and Donald O. Whittemore, A User Interface for Ground-Water Modeling: An ArcView Extension: published in Journal of Hydrologic Engineering, 6 (3), 251-257.

## **A User Interface for Ground-Water Modeling: An ArcView Extension**

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To be published in the Journal of Hydrologic Engineering in 2001

### **Abstract**

Numerical simulation for ground-water modeling often involves handling large input and output data sets. A geographic information system (GIS) provides an integrated platform to manage, analyze, and display disparate data and can greatly facilitate modeling efforts in data compilation, model calibration, and display of model parameters and results. Furthermore, GIS can be used to generate information for decision-making through spatial overlay and processing of model results.

ArcView is the most widely-used, windows-based GIS software that provides a robust user-friendly interface to facilitate data handling and display. An extension is an add-on program to ArcView that provides additional specialized functions. An ArcView interface for the ground-water flow and transport models MODFLOW and MT3D was built as an extension for facilitating modeling. The extension includes pre-processing of spatially distributed (point, line, and polygon) data for model input and post-processing of model output. An Object Data Base is used for linking user dialogs and model input files. The ArcView interface utilizes the capabilities of the 3D Analyst extension. Models can be automatically calibrated through the ArcView interface by external linking to such programs as PEST. The efficient pre- and post-processing capabilities and calibration link were demonstrated for ground-water modeling in southwest Kansas.

### **Introduction**

Numerical models of complex ground-water systems require management and analysis of large amounts of input and output data. A geographic information system (GIS) provides an integrated platform to manage, analyze, and display disparate data and can greatly facilitate data compilation, model calibration, and visualization of model parameters and results. Furthermore, GIS can be used to generate valuable information for decision-making by producing maps with model output spatially overlain on other important GIS data.

Various commercial and public-domain systems involving the integration of GIS and ground-water models were examined for use in sub-regional to regional simulations of salinity transport. These included the Groundwater Modeling System (GMS) developed at Brigham Young University (EMRL). At the start of this examination, the commercial systems could not or did not incorporate powerful GIS software. Although much additional GIS capability has been subsequently built into these systems, the GIS capabilities within the systems are not mature enough to provide the manipulation sometimes needed for complex spatial data. In addition, because publicly shared GIS data are usually in the format of some specific GIS

software such as ArcView, it would be easier to edit these data within the GIS environment. Those modeling interface systems that allow users to create custom-built interfaces distributed as add-ons, such as Argus (Argus Interware, Inc.), do not have as powerful GIS capabilities as the windows-based GIS (ArcView). A decision was made to integrate a widely-used GIS software with commonly applied ground-water flow and transport models. The integration includes a user-friendly interface to allow easier use by water management scientists. The advantages of this development are that the open source code will allow further development for special applications by modelers, and the integration with ArcView can serve modelers, who are also ArcView users, as a useful tool in ground-water modeling.

Various applications of GIS in water resources and the integration of GIS with environmental simulation models have been published (Harlin and Lanfear, 1993, Goodchild et al., 1993). DeVantier and Feldman (1993) reviewed several applications in hydrologic modeling including floodplain hydrology, erosion prediction/control, and water-quality prediction/control. Recently, the integration of GIS with ground-water models has attracted the attention of many researchers. Watkins et al. (1996) described GIS applications in ground-water flow modeling and reviewed some existing programs that interface GIS and ground-water models. The simulation-GIS systems can be broadly classified into two types: (1) integrated GIS - ground-water models, and (2) ground-water models embedded in GIS.

The first approach uses a set of programs or an interface to transfer data between GIS and ground-water models. In other words, the data stored in a GIS data base are transferred into input files of ground-water models, and output data from the models are transferred back into the GIS data base after simulation. The disadvantage of this approach is that one set of data is stored twice, once in the GIS data base and again in ASCII files. This approach requires minimal modification in the GIS and ground-water models and avoids errors in modifying GIS source code and/or ground-water models; hence, it is widely adopted in many applications because of its simplicity. This approach can be enhanced by modifying the ground-water models to directly read model inputs from GIS data files such as "coverages" in ARC/INFO instead of original ASCII files. Thus, only a GIS data base is used and no data-transfer program is required. An example is MODFLOWARC (Orzol and McGrath 1992).

The work by Rifai et al.(1993) and El-Kadi et al.(1994) integrated GIS with some existing ground-water models through data transfer and a user interface. Rifai et al. (1993) integrated the GIS software SYSTEM 9 with the ground-water model WHPA for delineating wellhead-protection areas around public water-supply wells. El-Kadi et al. (1994) integrated the GIS software MAPINFO with a two-dimensional flow and transport model and provided a customized graphical user interface by using MAPBASIC language included in MAPINFO.

The second approach is to embed the equations governing the ground-water flow and solute transport into the GIS as intrinsic functions through modifying the GIS source code or writing macro programs to perform numerical calculations (Watkins et al., 1996). No data conversion occurs in this approach. However, this method requires a great deal of modification, and incorporating complicated numerical procedures into GIS as intrinsic functions is difficult. As an example, McKinney and Tsai (1993) wrote macro programs to

solve sets of finite-difference equations in a raster system. They applied different levels of discretization to minimize numerical errors and to accelerate convergence. Tim et al. (1996) embedded three simplified formulas into the ARC/INFO software to calculate three kinds of indices that indicate the susceptibility of ground water to contamination by pesticides, without involving any ground-water model simulation.

In this study, the first approach (integrated GIS – ground-water model) was adopted because of the flexibility and simplicity. The GIS software ArcView (ESRI, 1994) was customized to serve as an interface for the ground-water models MODFLOW (McDonald and Harbaugh, 1988) and MT3D (Zheng, 1992). ArcView is the most-widely used, robust windows-based GIS software and is compatible with Arc/Info that provides powerful capabilities for developing and analyzing GIS coverages. For convenience, the customized interface was built as an extension, which is an add-on program to ArcView that provides additional specialized functions. For simplicity, only the extension to MODFLOW is discussed in this paper. An example application is presented to demonstrate the utility of the MODFLOW extension.

### **ArcView and 3D Analyst Extension**

ArcView provides a user-friendly interface on a windows-based platform that facilitates the organization, display, querying, analysis, and publication of data. The 3D Analyst extension (ESRI, 1997) to ArcView provides point interpolation, contouring, and 3D-visualization capabilities that greatly facilitate modeling efforts in data compilation, model calibration, and display of model parameters and results. The 3D Analyst extension is required in order to use the ArcView–MODFLOW/MT3D interface.

### **MODFLOW/MT3D Extension**

An interface between ArcView and the ground-water flow and transport models MODFLOW and MT3D was developed for the PC platform. The ArcView interface was built as an extension and was written in AVENUE, a programming language for ArcView. The generalized flow chart for the interface system is shown in Fig. 1. ArcView was customized to provide a modeling system that includes model mesh generation and the capability to pre-process spatial data into model input. Both MODFLOW and MT3D have a modular structure for simulating major components of the hydrologic system by sets of computer programs called packages. The ArcView interface was customized to provide for the major MODFLOW and MT3D packages. In addition, the ArcView interface provides post-processing capability and a link to model calibration.

The ArcView interface contains two customized menus “Modflow/Mt3d” and “Utilities” that appear when the MODFLOW/MT3D extension is imported by ArcView. At this time, the MODFLOW packages supported in the extension are Basic, Block-Center Flow, Well, Drain, River, Evapotranspiration, General-Head Boundary, Recharge, Stream, Strong Implicit Procedure, and Slice-Successive Overrelaxation packages. The approach for linking

dialogs and model input files, the features of the MODFLOW/MT3D extension, and the operational steps are briefly described below.

### Object Data Base (ODB)

The ArcView interface transfers model-input data from shapefiles or coverages to model input files (ASCII or text files). Most modeling methods involve revising or re-entering model-input data stored as ASCII files that were generated from the last modeling session. The common method is to generate many extra files tied to a user interface so that users can enter or edit the input data in these files, which are later transferred into the model-input files when the user finishes entering information.

In this ArcView interface, only one ODB file, which is an ASCII file-based storage and retrieval system of ArcView, is needed and generated. All model-input data for the ArcView interface are stored as objects in the ODB file. The ODB file stores data retrieved from shapefiles or coverages or entered by the user; these data are translated into the model-input files through the ArcView interface. The data in the ODB file are stored as either a List (an ordered collection of heterogeneous objects) or as a Dictionary (an unordered collection of associations between keys and values) based on the classification of MODFLOW packages. These data can also be checked or edited by using any text editor. For each ground-water simulation, all the model-input data are stored in one ODB file (\*.odb). Users can interact with an ODB file by selecting the "Existing simulation" option and the specific ODB file in the starting dialog.

### Generate Mesh

A mesh is a finite-difference grid for the ground-water modeling. The node points are at the center of the mesh cells. The mesh is generated as a polygon shapefile through the function "Generate a mesh" under the menu "Utilities." There are two methods to generate the mesh: one by specifying the coordinates of the lower left point and widths for cells along a row and a column, and the other by specifying the column and row numbers within a selected rectangular region. The advantage of a vector-based model for generating grids is that the grid cell sizes can be made non-uniform by specifying variant sizes of polygons. For example, as shown in Fig. 2, the numbers "5\*10.5 4\*3.6" can be entered into the dialog in the space titled "Widths along a row" for creating a non-uniform mesh with five columns spaced "10.5" and four columns spaced "3.6" along a row. A rotation angle and position shift for the mesh can also be set through the dialog.

To display 3D data in model layers, the spatial data for each layer are stored in a mesh related to that layer so that the data in multiple layers can be displayed simultaneously through the overlay of meshes in the 3D display plane. The node mesh for each model layer can be generated based on the original model mesh by using the item "Generate the mesh for layers" under the menu "Utilities." These meshes are master shapefiles storing spatial data needed as input for each model layer of the 2D and 3D data arrays of MODFLOW.

## Pre-Processing

The ArcView interface can be used to pre-process GIS spatial data into model input arrays. The spatial data are stored in three different types (point, line, and polygon) of shapefiles or coverages. Observation data such as well logs, pumpage, and ground-water levels are stored in the point shapefiles. Model data related to rivers and irrigation canals are stored in line shapefiles. Model data such as areal distribution of soil types, hydraulic conductivity, and recharge are stored in polygon shapefiles.

The data of a node mesh for each model layer can be generated through interpolation, data transfer, and direct entry. The interpolation and data transfer methods are handled by the two functions "Mesh interpolation" and "Intersect and Grouping," respectively, under the menu "Utilities." Both functions require use of the surface models TIN or GRID in 3D Analyst.

In the interpolation procedure, TIN or GRID is used to generate a surface model file based on a shapefile of point observations such as ground-water levels. The "Mesh interpolation" function then selects values on the surface model that correspond to the locations of the center points in all mesh cells, and stores the values in the cells. Spatial data from point, line, or polygon shapefiles are transferred into the model meshes through the dialog "Intersect and Grouping" (Fig. 3). The functions "Intersect" and "Clip" are not supported in ArcView but were programmed for the extension using AVENUE code. Both "Intersect" and "Clip" create a new coverage by overlaying two sets of features. The output coverage of "Intersect" contains only the portions of features that are both in the input and intersect coverages, whereas "Clip" operates as a cookie cutter to clip coverages; only those input coverage features that are within the clipping region are stored in the output coverage.

To transfer the spatial data stored in a point, line or polygon shape format into a node mesh for a model layer, the functions "Intersect" and "Group and Transfer" (Fig. 3) are used. For instance, the point shapefile for pumping wells can be intersected by an overlay mesh so that well pumpage within the same cell can be summed and then transferred into the mesh shapefile. For a stream, the line shapefile is intersected with a mesh in order to sum up the length of arcs in the same cell for each stream segment for later transfer into the mesh. Multiple stream segments such as would converge to a junction can be handled separately in a single cell. The length of a stream is a parameter in the stream package of MODFLOW. A polygon distribution of hydraulic conductivity can also be intersected so that the hydraulic conductivity values of polygons can be transferred to a mesh shapefile.

The attributes (parameter values) in the mesh shapefiles can also be directly edited for the area selected by using the map display or spatial overlay. For example, the active or inactive cells for the model simulation can be assigned through this process. The attributes of the mesh shapefiles can then be displayed in various 2D or 3D views for checking with input data.

## Processing and Post-processing

Once the required data are stored in the node mesh shapefiles, the input files for MODFLOW (or MT3D) can be generated through dialogs launched by selecting the appropriate items under the menu "Modflow/Mt3d." For example, the dialog "Basic" (Fig. 4) can be used to interacted with the Basic package for MODFLOW. The major MODFLOW packages available through the dialogs are also listed in the dialog "Basic." After the input files are generated, the simulation can be launched by selecting the item "Run Modflow" under this menu.

After MODFLOW is run, the item "Retrieve model outputs" under the menu "Utilities" is used to bring the simulation results into the mesh shapefiles. The computed water levels can be overlaid on the observed levels as contours or a 3D surface to show deviations. Map displays of the results can be easily created with the assistance of the map tool in ArcView.

### **Example Application**

To demonstrate the ArcView interface, a ground-water flow model of pre-development (steady-state) conditions was built for a study area located in southwest Kansas that includes the cities of Garden City and Holcomb (Fig. 5). The floodplain and terrace deposits of the Arkansas River valley extend from the west-northwest to the east-southeast part of the area (marked alluvium). The Ogallala aquifer surrounds and underlies these deposits. Locations of water-level observations are shown as solid dots in Fig. 5. Most of the water in the Arkansas River (the irregular line south of the cities) infiltrates from the river channel and irrigation diversions into the alluvial and Ogallala aquifers, together referred to as the High Plains aquifer. Ground-water flow is mainly from west to east.

The MODFLOW mesh for the study area has 24 columns and 14 rows and was generated through the function "Generate a mesh." Each cell is a 805-m (0.5-mile) square. Constant-head boundaries around the study area were specified through "Mesh interpolation" based on pre-development (circa 1940) water-level observations. The High Plains aquifer within the Arkansas River valley was simulated by two model layers because the alluvial aquifer is separated from the lower Ogallala aquifer by a zone of discontinuous clays within the valley. Outside the Arkansas River valley this aquifer was simulated by one layer. Assignments of the active, inactive, and constant-head cells for model layer 1 and layer 2 are directly entered into the mesh shapefiles by using the map-display and spatial-overlay functions of ArcView.

Areal recharge from precipitation is estimated as less than 1.3 cm/yr (0.5 in/yr) in this area of the High Plains aquifer (Dunlap et al., 1985). The estimate of recharge from irrigation return flow and seepage of diverted river water is 2.5 cm/yr (1 in/yr) over the irrigated area (Meyer et al., 1970). A recharge distribution map was created, and the attribute of recharge was transferred into the mesh shapefile through "Intersect and Group."

In a previous modeling study, Dunlap et al. (1985) assumed the alluvial and Ogallala aquifers to be homogeneous. They used an areally constant hydraulic conductivity of 46 m/day (113 ft/day) for layer 1 and a value of 28 m/day (69 ft/day) for layer 2. In contrast, a zonation method for specifying spatial variation in hydraulic conductivity was used in this study. Based on lithologic information (Young et al., 1998), four homogeneous zones along the alluvial valley were identified for layer 1 (alluvial aquifer) and five zones were identified for layer 2. The hydraulic conductivity distributions were transferred into the mesh shapefiles.

With the model parameters available in the mesh shapefiles, the model-input files were then created through the menu "Modflow/Mt3d" and MODFLOW was run. The model was then calibrated. Model calibration involves repeating the pre-processing through post-processing steps using adjusted input based on model output until the deviation between the computed result and the measurement data is acceptable. Adjusting the model parameters and boundary conditions in model calibration is greatly facilitated through the interactive procedures and visual display provided in the ArcView interface.

The model calibration was automated with the aid of the parameter estimation package PEST (Doherty et al., 1994). The final computed piezometric heads for layer 2 are displayed in Fig. 6 and the zonation of the optimal hydraulic conductivities is shown in Fig. 7. The area south of the alluvial valley has the smallest hydraulic conductivity (3 m/day or 10 ft/day), whereas higher values (26-33 m/day or 86-107 ft/day) are in the Garden City area where more permeable materials are present. Slug tests for four multi-level observation wells located south of Garden City (Fig. 7) (Butler and Healey, 1999) gave a hydraulic conductivity range of 1.5-23 m/day (5-74 ft/day) and an average of 12 m/day (40 ft/day) for the lower Ogallala aquifer. Butler and Healey (1999) indicated that the hydraulic conductivities should be considered as low-end values. The average value of 12 m/day and the value of 28 m/day used by Dunlap et al. (1985) for the corresponding zone are within a range comparable to the optimal value of 26 m/day.

## Summary

The Modflow/Mt3d extension developed as an ArcView interface was demonstrated as efficient for data handling, processing, and display in the example application. The complexity and assembly of a large amount of input data, the assessment of the hydrogeological parameters and boundary conditions during model calibration, and the visual comparison of simulated results and observed measurements make ground-water modeling a laborious and time-consuming task. The development of the ArcView interface for ground-water modeling facilitates the modeling process by including the advantages of the most widely-used, desktop GIS software and automating many modeling steps.

The ArcView interface provides a useful tool for ground-water modelers who are familiar with ArcView and the 3D Analyst extension. The specific advantages of the system are: (1) it uses an ODB file to store transferred data instead of generating many temporary files; (2) it efficiently generates the mesh for the modeling area; (3) it assigns available information to each cell and automatically transforms them to the data format of the model

input; (4) it provides error checking of the model input through display; (5) it improves model calibration procedures by allowing interactive adjustment of parameter values or by linking an external package for automated parameter estimation; and (6) it displays the final results and generates maps using powerful GIS software.

### **Acknowledgments**

The work was funded by the Kansas Water Plan through the Kansas Water Office and by the Kansas Geological Survey. We gratefully acknowledge the assistance of Jinwu Ma in the development of the GIS interface. The recommendations and editing of two anonymous reviewers led to substantial improvements in the paper. Reviews by Carl E. McElwee and Marios Sophocleous are also acknowledged.

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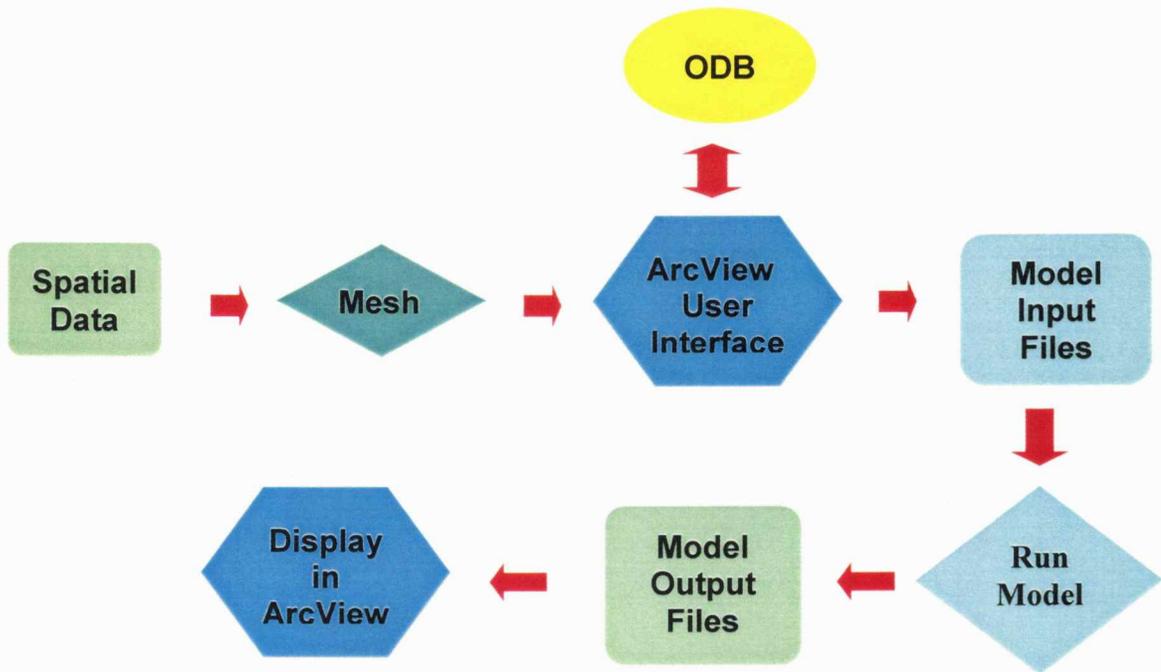


Fig. 1. Schematic diagram for pre-processing and post-processing components of the ArcView interface.

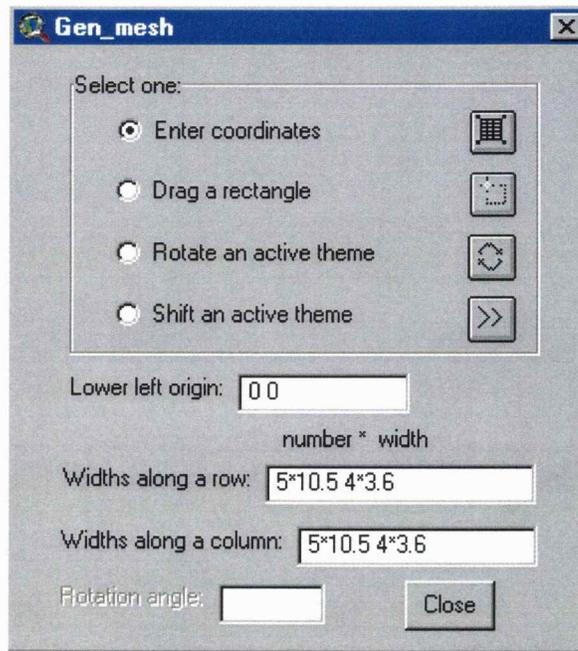


Fig. 2. Dialog for generating, rotating, and shifting the mesh. The rotation angle function is activated when the radio button “Rotate an active theme” is selected.



Fig. 3. The dialog for “Clip”, “Intersect”, and “Group and Transfer.”

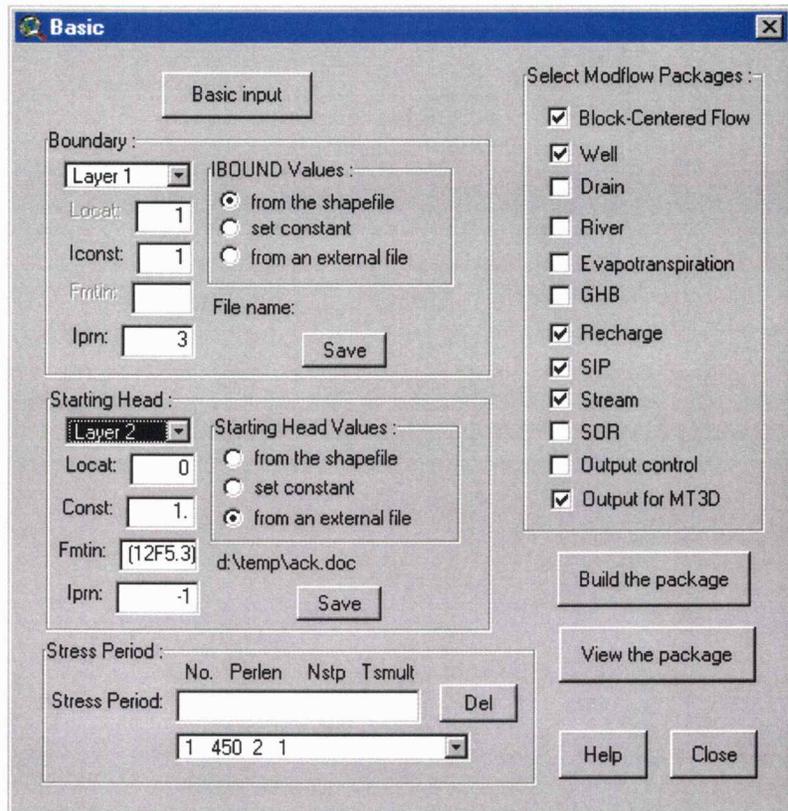


Fig. 4. Dialog for the MODFLOW Basic package that provides for data input. Dialogs for data input to other MODFLOW packages are selected from the main “Modflow/Mt3d” menu.

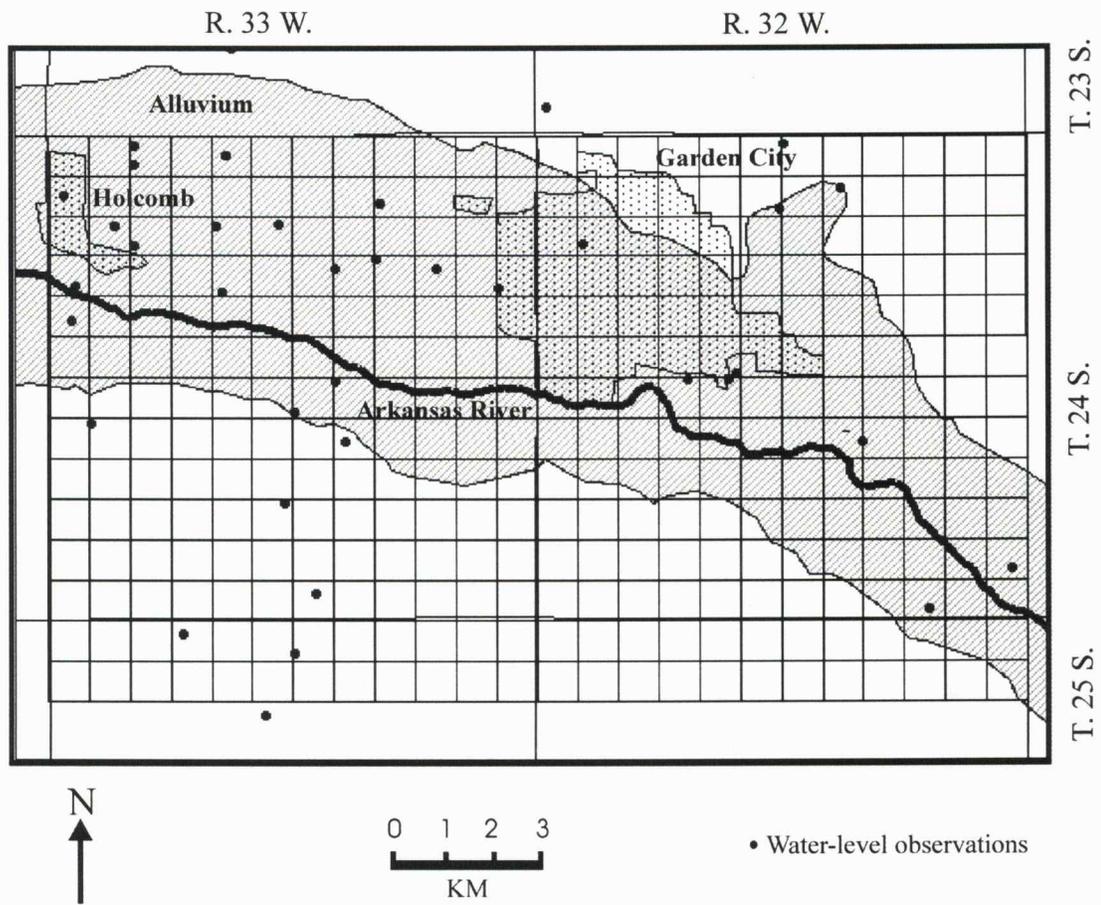


Fig. 5. Study area and locations of water-level observations.

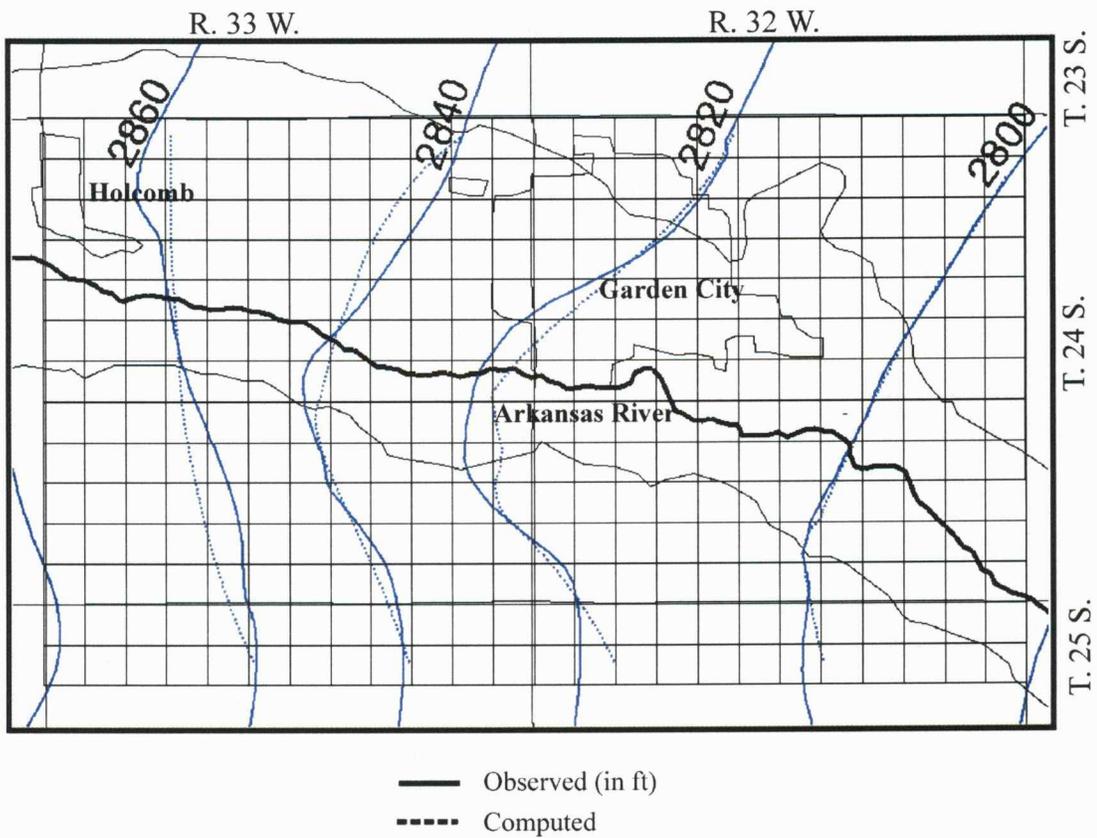


Fig. 6. Computed and observed water levels for layer 2. (To convert ft to m multiply by 0.305.) The map features and dimensions are the same as in Fig. 5.

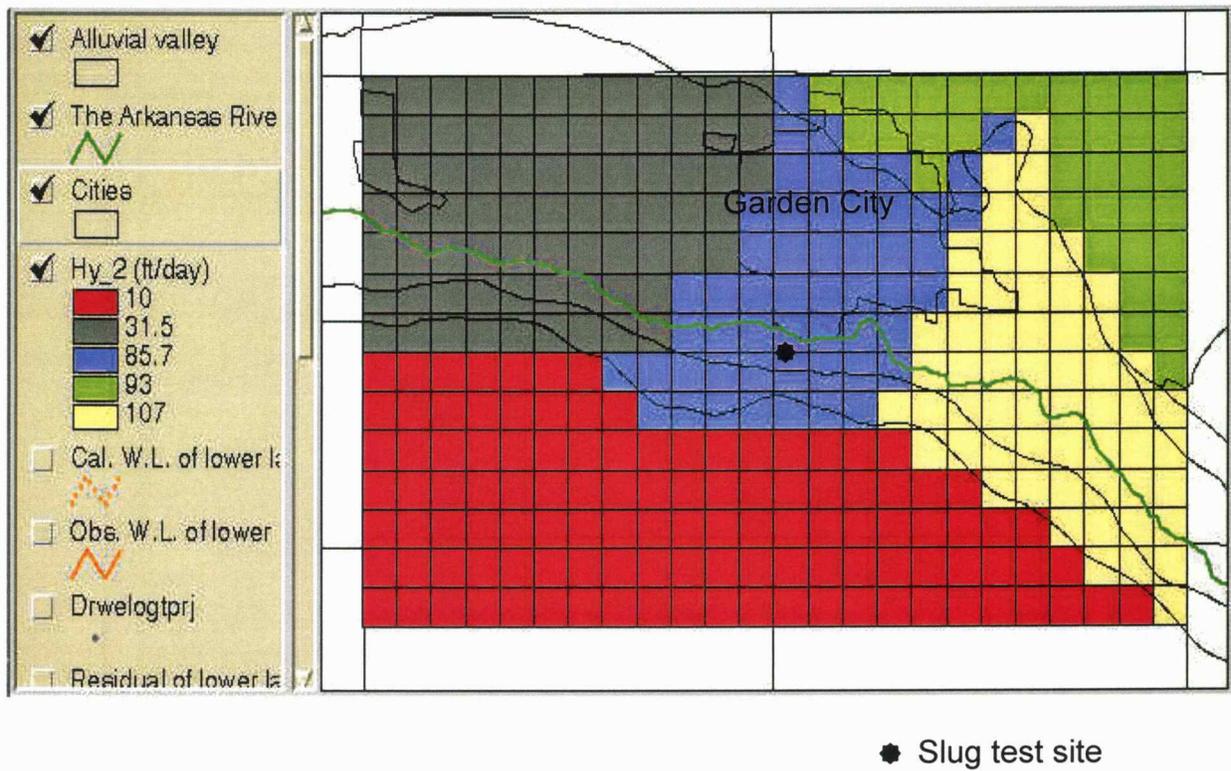


Fig. 7. Optimal values of hydraulic conductivity computed for cells in layer 2. (To convert ft to m multiply by 0.305.) The map features and dimensions are the same as in Fig. 5.

## **APPENDIX B**

Selected Details of the Numerical Simulation Procedures.

## **B1. GIS-Based Methods Applied to the Upper Arkansas River Corridor Model**

The ArcView preprocessor GME, presented in Appendix A, organizes input data for the ground-water model as fields in shapefile attribute tables associated with each model layer. Key attributes correspond to the input data requirements for MODFLOW, and are analogous to columns in a spreadsheet, but have the important advantage of being georeferenced so that both input and output may be easily visualized in their proper geographic setting. Once the model grid attributes have been specified, the ArcView preprocessor's functions are used to automatically write the input data files for MODFLOW in their required formats.

### **Aquifer Model Elevations and Hydraulic Conductivity**

The key data for the model grid include elevations of the layers, hydraulic conductivity, water-level observations, recharge, water use, and characteristics of the Arkansas River related to its interaction with ground water. The first two of these, elevations and hydraulic conductivity for the alluvial and High Plains layers of the model grid, were based in large part on approximately 460 lithologic data profiles that were interpreted and compiled in a parallel study (Young et al., 2000). Methods for using these data in the ground-water model are summarized below.

For the purpose of characterizing elevation ranges and hydraulic conductivity of the alluvial and High Plains aquifers in the model area, drillers' well logs (WWC-5 forms), published USGS and KGS lithologic logs of wells and test holes, and logs of wells drilled for this study were selected along transects crossing the alluvial valley, shown in Figure B1, for lithologic interpretation in a parallel study (Young et al., 2000). The profiles were used to develop spatial distributions of the top and bottom elevations and hydraulic conductivity for the alluvial and High Plains aquifers in the model area (Appendix B, Figure B2). For each transect, an Excel workbook was used to plot the vertical profiles of each well log, where the classification of geologic material within ranges of each profile was color-coded and associated with an estimated hydraulic conductivity. Visual Basic for Applications (VBA) programs were written to convert between visual graphs and numeric tables to represent the profiles, and to evaluate vertical and horizontal components of hydraulic conductivity over specified ranges of depth. Using visual inspection and geologic interpretation, top and bottom elevations of the alluvial and High Plains aquifer units corresponding to each well log were identified. For profiles lying within the alluvial valley, the base of the alluvial aquifer and the top and bottom of the High Plains aquifer were specified, and the top of the alluvial aquifer was represented by the land surface. Outside the alluvial valley, the bottom elevation of the High Plains aquifer was specified, and the top of the aquifer was represented by the land surface.

For each profile, vertical and horizontal components of hydraulic conductivity were calculated over the range of geologic layers between the top and bottom elevations of each aquifer. Each geologic layer,  $i$ , was associated with a depth,  $d_i$ , and a value of hydraulic conductivity,  $K_i$ , that was taken to be homogeneous and isotropic. Vertical and horizontal

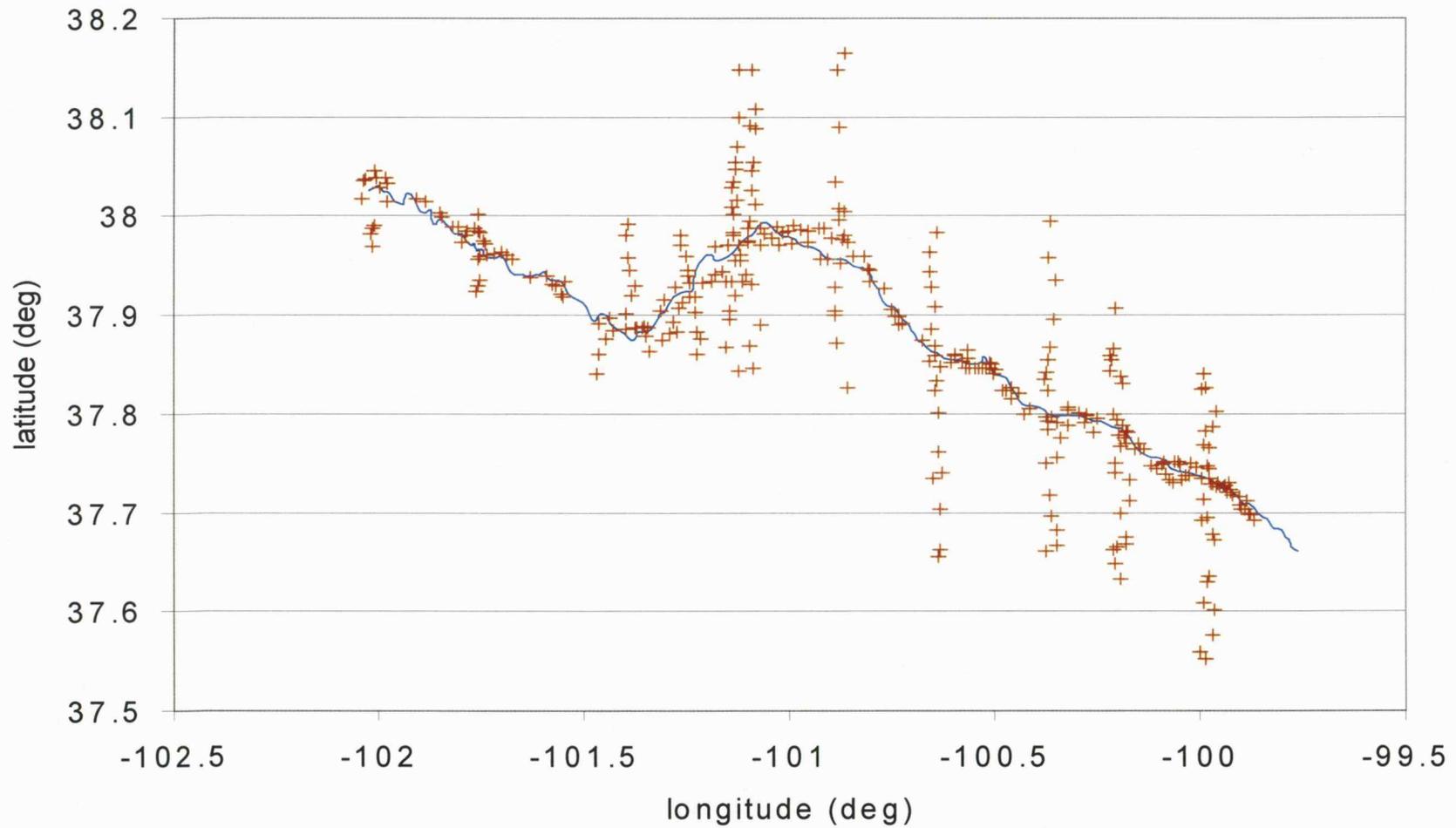


Figure B1. Locations along transects crossing the upper Arkansas River valley in plan view for wells where logs of wells and test holes provided a basis for developing spatial distributions of elevation ranges and hydraulic conductivity for alluvial and High Plains aquifer layers in the model area. (See Young et al., 2000 for further information on logs and their interpretation).

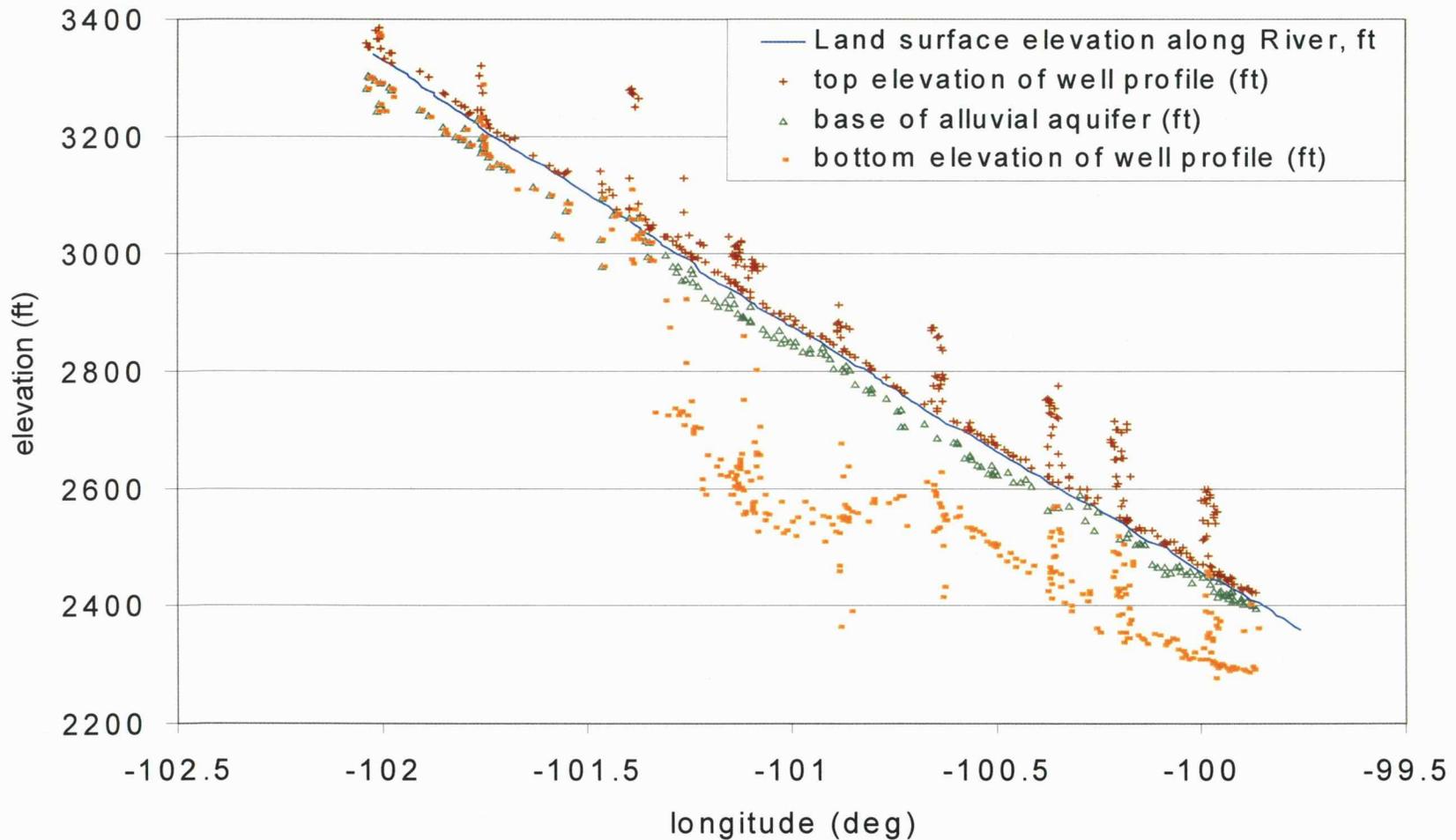


Figure B2. Elevations for the alluvial and High Plains aquifer layers, based on interpretation of well and test hole logs along transects shown in Figure B1, are shown as a projection onto a vertical plane viewed from the south of the model area. (See Young et al., 2000 for further information on the logs.) Also shown are elevations taken from USGS 1:24000 topographic maps at intersections of elevation contours with the Arkansas River.

components of hydraulic conductivity over a range of  $n$  layers were calculated separately for elevation ranges over the alluvial and High Plains aquifers within each profile (Freeze and Cherry, 1979). Vertical hydraulic conductivity (that is, in series through the layers in a direction transverse to the layers) is given by

$$K_z = d \left( \sum_{i=1}^n \frac{d_i}{K} \right)^{-1}$$

Horizontal hydraulic conductivity (in parallel through the layers) is given by

$$K_x = \frac{1}{d} \sum_{i=1}^n K_i d$$

From the elevations along these transects, surfaces were generated with triangulated irregular networks (TINs) to represent top and bottom elevations for the alluvial and High Plains aquifer layers over the model area. The TINs were interpolated at the model grid cell centers to provide the required geometrical description of the aquifer layers for input to MODFLOW. From calculated values of hydraulic conductivity for the two aquifer layers along the transects, TINs were used to represent spatial distributions of hydraulic conductivity as surfaces for each layer, which were also interpolated at each grid cell center. The Groundwater Modeling Extension (GME, Tsou and Whittemore, 2001) was used to convert these data from shapefile attribute fields to input data files for MODFLOW.

The aquifer geometry and hydraulic conductivity were initially specified for the ground-water model as summarized above, but then modified to better represent the ground-water model as follows.

First, ground-water-level measurements were used to generate TINs in order to represent ground-water elevations as a continuous surface, which were also interpolated at model grid cell centers. The ground-water elevation surface based on measurements was compared with aquifer elevations, which were adjusted in a few areas where ground-water measurements provided evidence that the aquifer base was deeper than the values given by the interpolated lithology.

Second, the complexity of the ground-water model and initial difficulty experienced in obtaining convergent solutions led to a simplification of the spatial distribution of hydraulic conductivity by replacement with a mean value for each layer. Once a converging steady-state solution was obtained for 1940 conditions, the solution was refined by adjusting model parameters, consisting of spatial distributions of hydraulic conductivity and recharge, to meet the model target, consisting of interpolated ground-water surface measurements (see “Model Calibration”). The spatial distribution of hydraulic conductivity developed for the steady-state groundwater model under 1940 conditions was used for subsequent simulations.

### Initial Ground-Water Levels

For the steady-state, predevelopment model, alluvial and High Plains ground-water levels were assumed to be in equilibrium. Additionally, alluvial ground-water levels were assumed to be in equilibrium with stream stage along the Arkansas River. Consequently, locations where elevation contours were shown crossing the Arkansas River on USGS 1:24000 topographic maps were used as an additional set of initial ground-water levels for the steady-state model. The same set of elevations was also used as the basis for generating input data files for the Stream package of MODFLOW.

### Groundwater Recharge

The recharge function provides a spatially distributed model of recharge that is based on estimates over the model grid area of precipitation, specified-flow boundary conditions along the western border of the High Plains aquifer, irrigation return flow, and streambed leakage. Based on conditions specified through a menu for the recharge function, recharge components are distributed over the grid cells of the model by first calculating these components for the corresponding records of an attribute table associated with a shapefile for the grid in ArcView. Key components of the recharge distribution are evaluated as follows.

An estimate was made for specified inflows to the model grid cells along the western border of the High Plains aquifer within the model area based on Darcy's law,

$$Q = KA dh/dl. \quad (B1)$$

Values for the factors on the right-hand side are given by shapefile attributes corresponding to specified grid cells along this boundary. These include hydraulic conductivity,  $K$ ; projected vertical area,  $A$ , of the High Plains aquifer face through which the specified flow,  $Q$ , crosses; and the hydraulic gradient,  $dh/dl$ . The projected vertical area,  $A$ , for a given grid cell is given by  $A = Wy$ , where  $W$  = row width, assuming flow parallel to the rows, and  $y$  = saturated thickness of the High Plains aquifer along its western edge within the model area. Saturated thickness is given by the difference between initial, predevelopment heads and bedrock elevation. An approximation for the hydraulic gradient was based on the predevelopment heads.

Irrigation return flow from surface-water diversions is specified as a fraction of the diversions allocated for surface-water irrigation to each of the five irrigation districts in the model area. Within each irrigation district, the irrigation return flow is distributed over the existing water rights in proportion to the irrigated area associated with each right. A normalized distribution function for each district was computed as the irrigated area associated with each water right divided by the total irrigated area within the district. The total estimated irrigation return flow for each district was then multiplied by the irrigated areal fraction of each water right to specify irrigation return flow for the attribute table record corresponding to the grid cell associated with each water right. The spatial distribution of water rights and the model grid were associated by intersecting a point attribute shapefile

representing the water rights with a polygon attribute shapefile representing the model grid. Key attributes contributed to the resulting shapefile from the two component shapefiles included water right location (latitude, longitude), the irrigation district with which the water right is associated, irrigated areal fraction of the district, row and column of the model grid, and record identifiers.

The streambed leakage component is based on differences in mean streamflow between gaging stations along the Arkansas River within the model domain. This component is distributed along the grid cells corresponding to stream reaches between the gaging stations.

### **Arkansas River Model**

The Stream package OF MODFLOW was also invoked to provide an alternative, physically-based method for evaluating this recharge component, in which case the specified streambed leakage component of the ArcView-based recharge function is set to zero. Development of the input data for the Stream package is summarized as follows.

1. The dataset of land-surface elevations taken from USGS 1:24,000 topographic maps were given by contour intersections with the Arkansas River. This set of elevations was used as part of the initial, predevelopment ground-water levels, which are incorporated into ArcView as a point attribute shapefile.
2. The record subset of this shapefile corresponding to the stream elevations taken from the 1:24,000 topographic maps were selected and used to create a TIN surface, which was then interpolated onto the model grid using functions provided by the ArcView extension, GME.
3. A line attribute shapefile for the stream hydrography in Kansas based on the EPA River Reach data set, RF1, was selected for the main step along the Arkansas River. This selected subset was combined with a polygon attribute shapefile for the model grid using an intersect operation provided by the Xtools extension (ref.). The intersection of these shapefiles produced a "polyline" shapefile that provided the length of stream reach along the Arkansas River within each grid cell, the streambed elevation based on the interpolated elevation tin (above), and identifiers for both the stream and grid shapefiles.
4. Using another function of the Xtools extension, the polyline shapefile's attribute table was exported to an Excel spreadsheet, where the elevation and stream length attributes for each grid cell were used to develop a sequence of stream segments for routing, and stream channel slope, which was used in turn to approximate missing streambed elevations. The results of this analysis were exported to a comma-delimited file, which could be imported into ArcView as an event table and compared to the original land surface elevations and stream hydrography.
5. The results of the above analysis (4) were also used to construct an input data file for the Stream package of MODFLOW.

## Water Use: Procedure to Represent 1990's Conditions

### *Summary of data processing procedure*

The database of reported water use consists of two ArcView shapefiles and their associated attribute database. One shapefile, obtained from Brownie Wilson at DWR, represents all of the model area except for a triangular area in north Haskell County, and contains about eight annual water use reports for each point of diversion for the years 1991-1998. The other shapefile contains water use reports for Haskell County. These two sources were used to represent ground-water use in the model area during the 1990s.

Water rights are distinguished by source, either ground water ("G") or surface water ("S"). We added an attribute to classify wells according to the ground-water unit in which they are screened. The wells are classified by the designations Quaternary Alluvium ("QA"), High Plains ("HP"), and Dakota ("KD") geologic units. Alluvial wells are associated with model layer 1, and High Plains wells with model layer 2. Dakota wells and the Dakota aquifer are excluded from the model, in which the Dakota aquifer is treated as part of the bedrock.

Four identifying keys in the water-use report database were combined to produce a primary key that uniquely identifies points of diversions (details are given below). Alluvial and High Plains wells were summarized separately, each in two steps. First, wells were summarized on the basis of the composite primary key to produce an average reported use for each well during the 1990's. Note that this average was taken over all water use reports for a given well, including reports of zero water use, so that actual conditions of zero water use are represented as part of the average. Second, the average reported use for each well during the 1990's was summarized on the basis of the index to the model grid, Uagrid\_id, to produce a total over the reported use of the wells within each grid cell, averaged over the 1990's.

The index to the model grid was associated with the wells in the water-use report database by intersecting each of the corresponding point shapefiles with a polygon shapefile representing the model grid cells. This operation was performed as a preliminary step that was followed by the procedure described below. Several hours of time were required for this operation. This time might be reduced by about an order of magnitude by applying the following operation between steps 5 and 6 (below). Instead of intersecting the original water use report shapefiles with the grid polygon shapefile, intersect the summary table produced in step 5 with the grid shapefile, since the Uagrid\_id is not needed until step 6.

#### Details of procedure to summarize water use for grid layers 1 and 2

1. Start with the following two shapefiles containing water-use data

Model area except for Haskell County: d:\tsou\uarc\shp\90s\ark\_wu90s.shp

Model area within Haskell County: d:\tsou\uarc\shp\90s\hask\_wu.shp

2. Add a new field for the geologic unit code 'geo\_code' in ark\_wu90s.shp and hask\_wu.shp.

- QA: alluvium, use the intersect selection for the wells within the alluvial valley and then select [source= "G"] and [Depth\_well < 60 ft] and [Depth\_well > 0 ft] from the previous selection.
- KD: Dakota, select [Depth\_well > 600 ft]; in some areas, well depths over 500 ft were interpreted as Dakota wells.
- HP: high plains, select [source= "G"] and [geo\_code <> "QA"] and [geo\_code <> "TO"]
3. Intersect ark\_wu90s.shp with uagrid.shp to have each well with uagrid\_id. Do the same thing to hask\_wu.shp.
  4. Create a primary key for the two shapefiles.  
[pri\_key]= [wr\_id] + [pdv\_id] + [wuapers\_id] + [umw\_code].
  5. Summarize the tables of the two shapefiles by using the function of "Summarize" under "Field" within "Tables." Let [pri\_key] be active and select "uagrid\_id" with "First", "geo\_code" with "First", and "Af\_used" with "average" (to exclude the duplicated records) to generate a summarized table "sum1.dbf."
  6. Summarize the "sum1.dbf" to get the total pumpage within a grid cell. Query [geo\_code]= "QA" for layer 1 and "QU" for layer 2. Based on the selection, let [uagrid\_id] be active and select "Af\_used" with "summation" to generate a summarized table for layer1 (sum2.dbf) and layer 2 (sum3.dbf).
  7. Join "sum2.dbf" with "uagrid.shp" and copy the records of total pumpage into "uagrid.shp" to give a new field "w190s\_1." Apply the same procedure to "sum3.dbf" to add the field "w190s\_q."
  8. The summarized table "sum4.dbf" is obtained by summarizing "hask\_wu.shp." The "sum4.dbf" is too joined to "uagrid.shp" to generate a new field "w190s\_h." Sum up [w190s\_q] and [w190s\_h] together to generate a new field [w190s\_2].
  9. [w190s\_1] and [w190s\_2] are the pumping records for layer 1 and layer 2, respectively. Reported use units are [acre-ft/year]; multiply by 3.377 to convert to [cubic meters/day].

Number of water use reports by source and geologic unit

<i>Number</i>	<i>Source</i>
267	Surface water rights
46,041	Groundwater rights
<i>Number</i>	<i>Geologic Unit</i>
903	Alluvial aquifer water-use reports
44,981	High Plains aquifer water-use reports
157	Dakota aquifer water-use reports
46,041	Sum of QA, HP, and DK wells

## B2. Stream-Aquifer Interaction and Model Parameters

### River Channel and Depth-Flow Characteristics

The term “normal flow” has an operational definition, and refers to streamflow conditions under which the water-surface slope and the bed slope are equal. Under such normal conditions, a relationship between flow rate  $Q$  and stream depth  $d$  can be expressed by

$$Q = KS^{1/2}, \quad (\text{B2})$$

where  $K$  is a conveyance factor that has various forms corresponding to Chezy, Manning, and Darcy-Weisbach equations (USBR, 1997). For Manning’s equation (Henderson, 1966), which is commonly used in the United States and is incorporated into the Stream package of MODFLOW (Prudic, 1989), the conveyance factor is given by

$$K = (c_m / n)AR^{2/3}, \quad (\text{B3})$$

where  $c_m$  = unit conversion factor,  $n$  = Manning roughness,  $A$  = transverse flow sectional area,  $R$  = hydraulic radius, and  $S$  = bed slope. For SI units (mks),  $c_m = 1$ ; for English units (fps),  $c_m = 1.486$ . The hydraulic radius is given by  $R = A / P_w$ , the ratio of flow section,  $A$ , to wetted perimeter,  $P_w$ . For a stream channel that is approximated by a rectangular section of width,  $w$ , wetted perimeter is given by  $P_w = w + 2d$ . For a relatively wide channel such that  $w \gg d$ , wetted perimeter and hydraulic radius are approximated by  $P_w \approx w$  and  $R \approx d$ . Under steady flow conditions for a relatively wide rectangular channel, Manning’s equation expresses stream depth in terms of flow rate by

$$d = \left( \frac{nQ}{c_m w S^{1/2}} \right)^{3/5}, \quad (\text{B4})$$

Conditions assumed for the Arkansas River through the model area in the 1990’s were approximated as shown in Table B.1.

Table B.1. Streamflow conditions for 1990s and parameters used to estimate stream depth.

Manning’s equation factors	Value	SI units
Streamflow, $Q$	5.66	m <sup>3</sup> /s (200 cfs)
Manning roughness, $n$	0.03	
Constant, $c_m$	1	
Stream width, $w$	50	
Bed slope, $S$	0.0012	m/m
Stream depth, $d(Q)$	0.247	m

Stream stage,  $h_s$ , the elevation of the stream water surface, is given by the sum of stream depth,  $d$ , and the streambed top elevation,  $h_i$ ; that is,

$$h_s = h_t + d . \quad (B5)$$

Top and bottom elevations of the streambed are related by an assumed thickness,  $\Delta l$ :

$$\Delta l = h_t - h_b . \quad (B6)$$

Streambed (top) elevations,  $h_t$ , were interpolated to each grid cell along the Arkansas River path based on points of intersection of the Arkansas River and 5-ft or 10-ft contour lines of USGS 1:24000 topographic maps. These elevations were used to define both streambed top elevations and the ground-water surface for 1940 under the assumption that ground-water elevations and stream stage coincided along the river for this quasi-predevelopment period.

Evidence based on stream gaging records indicates channelization along the Arkansas River that produced a decline in streambed elevation of approximately 1 m west of Bear Creek fault and approximately 2 m east of the fault. Streambed elevations were adjusted by these values to represent average conditions for the 1990's decade.

### **Stream-Aquifer Interaction Based on Darcy's Law**

Flow across the channel bed between the river and ground water is bidirectional and varies in both space and time. This is referred to both as baseflow and streambed leakage, which are understood to differ only by the direction of the flow. Darcy's Law approximates streambed leakage by

$$Q_L = K_s A_s \frac{\Delta h}{\Delta l} , \quad (B7)$$

where  $K_s$  = streambed hydraulic conductivity,  $A_s$  = cross sectional area of flow for streambed leakage,  $\Delta h$  = hydraulic head across streambed, and  $\Delta l$  = streambed thickness. The transverse area of flow for streambed leakage is given by  $A_s = LP_w$ , where  $L$  = reach length, and  $P_w \approx w$  for a relatively wide channel. Reach length was derived for each grid cell by intersection of the line coverage for the river and the polygons defining the grid. Parameters other than the hydraulic head,  $\Delta h$ , are lumped together as streambed conductance,  $C$ , which is defined to be

$$C = K_s A_s / \Delta l . \quad (B8)$$

Streambed conductance was calculated for each reach based on the GIS-derived reach length and assumed values for hydraulic conductivity, stream width, and streambed thickness shown in Table B.2.

Table B.2. Parameters used to estimate streambed leakage according to Darcy's Law.

Conductance factors	Value	SI units
Hydraulic conductivity, $K_s$	5.787e-5	m/s (5 m/d)
Stream width, $w$	50	m
Streambed thickness, $\Delta l$	2	m

The hydraulic head,  $\Delta h$ , that drives streambed leakage is defined for two cases, depending on whether the aquifer head,  $h$ , is higher than the bottom of the streambed,  $h_b$ :

$$\Delta h = \begin{cases} h_s - h, & h > h_b \\ h_s - h_b, & h \leq h_b \end{cases}. \quad (\text{B9})$$

For the case that aquifer head,  $h$ , is higher than the bottom of the streambed,  $h_b$ , the stream and aquifer are considered to be hydraulically coupled; otherwise, the hydraulic head is limited to the difference of the stream stage and bottom elevation of the streambed,  $h_s - h_b$ , which is equivalent to the sum of the stream depth and streambed thickness,  $d + \Delta l$ . Consequently, the RIVER and STREAM packages in MODFLOW (McDonald and Harbaugh, 1988) both represent streambed leakage separately for these two cases as follows:

$$Q_L = \begin{cases} C(h_s - h), & h > h_b \\ C(h_s - h_b), & h \leq h_b \end{cases}. \quad (\text{B10})$$

### References

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### B3. Calibration Procedure

Calibration targets included observed heads and streambed leakage, although most of the calibration effort was directed at matching observed heads. Calibration parameters for these targets are summarized as follows.

#### GIS-Based Calibration of Ground-Water Recharge and Hydraulic Conductivity

Error in the model calibration target, computed head, was reduced by adjusting hydraulic conductivity and recharge. The approach to calculating initial estimates of hydraulic conductivity,  $K$ , and recharge,  $R$ , as spatially distributed properties for the groundwater model was reviewed in the report. Spatially distributed adjustments were then made to both  $K$  and  $R$  to minimize the error between computed and observed, interpolated heads. Methods for doing this are based on calculations that were performed in the ArcView environment, and are summarized below.

Measured water levels were used to generate a ground-water surface using a triangulated irregular network (TIN), which was evaluated at the center of each active grid cell,  $i$ . These values are used in the ground-water model as starting heads for simulations. For steady-state simulations, they also represent the calibration target, for which model parameters are adjusted so that computed heads and starting heads agree. Model error,  $e_i$ , is defined as the difference between computed heads,  $h_i$ , and these interpolated values,  $s_i$ , at each active grid cell:

$$e_i = h_i - s_i$$

For the 1940 steady-state simulation, model error was found to be sensitive to both recharge,  $R$ , and hydraulic conductivity,  $K$ . Sensitivity analysis was applied to both parameters on a cell-by-cell basis and used to determine a spatially variable direction for adjusting  $R$  and  $K$  to reduce the model error. The distributions  $R$  and  $K$  were varied one at a time on an alternating basis to reduce error. This approach succeeded in reducing simulated head error to a mean of less than 0.3 m with a standard deviation of less than 1 m.

#### *Initial recharge and aquifer layer adjustments*

$R$  was first adjusted to eliminate dry nodes and reduce computed head error. For four recharge estimates  $R_i = R1..R4$  and corresponding solution errors,  $ei$ :

At each dry node, double recharge: set  $R_i = 2 * R_{i-1}$ ;

At each active node, adjust recharge by 10 percent to reduce error,  $ei = h_i - h_{obs}$ :

If  $ei > 0.3$  m, set  $R_i = 0.9 * R_{i-1}$ ;

If  $ei < -0.3$  m, set  $R_i = 1.1 * R_{i-1}$ ;

With the third revision of recharge,  $R3$ , most dry nodes were eliminated.  $R3$  was also based on a revised approximation of aquifer layer elevations. In some areas, bottom elevations of the alluvial aquifer were decreased 5 m so that they would lie below the

interpolated water-level measurements, which provided evidence that the alluvial aquifer was deeper than the initial approximation. In these areas, the top of the lower (High Plains aquifer) layer derived from a TIN was decreased so that its elevations lay at or below the base of the alluvial aquifer.

The elevation model for the top of the aquifers would have been more easily and accurately specified by using 24K digital elevation models (DEMs)

#### ***Hydraulic conductivity adjustments***

Adjust High Plains hydraulic conductivity,  $K$ , to reduce error,  $ei = h_i - h_{obs}$ , as follows.

At each active node, adjust  $K$  by 5 percent to reduce error,  $ei$ :

If  $ei > 0$  m, set  $K_i = 1.05 * K_{i-1}$ ;

If  $ei < 0$  m, set  $K_i = 0.95 * K_{i-1}$ ;

#### **Calibration of 1990's Transient Simulation**

A different approach was taken for calibrating the model for 1990's conditions, when water use was far greater than in 1940. Instead of a steady-state case, a transient case was initially used in which parameters were adjusted to approximately match temporal changes in ground-water heads over a ten-year period in the 1990's. As part of this approach, the southern grid boundary condition was changed from specified heads to specified recharge. A spatially variable adjustment was applied to specified recharge in order to roughly match the change in heads along this boundary.

The calibrated results for the transient case were also used for a steady-state solution run to equilibrium for 1990's water use. This steady-state solution (R3s) was run with the same conditions as the transient case, including estimated water use. A small adjustment was made to the recharge specified along the southern grid boundary to improve solution convergence. Error reduction was not attempted for this case, since the imbalance between recharge and water use in the 1990's naturally drives ground water to depletion in the south-central part of the model as shown in the report. A steady-state simulation (Wc16n) was run in which irrigation water use was reduced sufficiently to approximately maintain ground-water heads at average 1990's levels. For this case, irrigation water use was reduced to approximately 16 percent of the average 1990's use (without irrigation return flow), with some minor spatial variation in the reduction.

#### **B4. Automatic Calibration**

In contrast to GIS-aided manual calibration through trial-and-error, the automatic calibration approach applied mathematical optimization techniques to minimize the weighted sum of squared errors between calculated and observed piezometric head.

Let  $\mathbf{u}_{\text{obs}}$  be a vector of the observed piezometric heads and  $\mathbf{u}(\mathbf{P})$  a vector of computed piezometric heads as a function of parameter vector  $\mathbf{P}$ . The vector  $\mathbf{e}$  is the difference between the observed and computed piezometric heads and is a function of  $\mathbf{P}$ .

$$\mathbf{e} = \mathbf{u}_{\text{obs}} - \mathbf{u}(\mathbf{P}) \quad (1)$$

The optimal estimates of model parameters minimize the following constrained weighted squares of errors:

$$Z = \mathbf{e}^T \mathbf{w} \mathbf{e} = (\mathbf{u}_{\text{obs}} - \mathbf{u}(\mathbf{P}))^T \mathbf{w} (\mathbf{u}_{\text{obs}} - \mathbf{u}(\mathbf{P})) \quad \mathbf{P}_L \leq \mathbf{P} \leq \mathbf{P}_U \quad (2)$$

where

$\mathbf{T}$  = transpose,

$\mathbf{w}$  = a diagonal weighting matrix indicating the reliability of  $\mathbf{u}_{\text{obs}}$ ,

$\mathbf{P}_L$  = the estimated lower bounds of the vector  $\mathbf{P}$ ,

$\mathbf{P}_U$  = the estimated upper bounds of the vector  $\mathbf{P}$ .

The upper and lower bounds of the parameters can be defined based on field data and literature. The objective function, Equation (2) subject to constraints, forms a nonlinear optimization problem. The optimal estimate of  $\mathbf{P}$  can be obtained by solving the nonlinear optimization problem through an iterative procedure as follows. The gradient vector  $\mathbf{g}$  of the objective function can be written as

$$\mathbf{g}(\mathbf{P}) = \nabla Z = 2 \mathbf{J}(\mathbf{P})^T \mathbf{w} \mathbf{e}(\mathbf{P}) \quad (3)$$

where  $\mathbf{J}(\mathbf{P})$  is the Jacobian matrix

$$\mathbf{J}(\mathbf{P}) = \begin{bmatrix} \frac{\partial e_1}{\partial p_1} & \frac{\partial e_1}{\partial p_2} & \dots & \frac{\partial e_1}{\partial p_s} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \frac{\partial e_r}{\partial p_1} & \frac{\partial e_r}{\partial p_2} & \dots & \frac{\partial e_r}{\partial p_s} \end{bmatrix} \quad (4)$$

where  $r$  indicates the number of observations and  $s$  is the number of model parameters. Each element of the Jacobian matrix represents the derivative of each residual with respect to each parameter. Since the residual is computed based on the model output and the observation, the derivative in the matrix cannot be directly calculated from some equations describing the residual. Hence, the derivative is approximated by the increment of the residual due to parameter change divided by the increment of the parameter.

Let  $\mathbf{P}^{(k+1)}$  be the  $(k+1)$ st iteration value of  $\mathbf{P}$ . The gradient at  $\mathbf{P}^{(k+1)}$  is approximated by

$$\mathbf{g}[\mathbf{P}^{(k+1)}] \approx \mathbf{g}[\mathbf{P}^{(k)}] + \mathbf{H}[\mathbf{P}^{(k)}] \Delta \mathbf{P} \quad (5)$$

where  $\mathbf{H}$  is the Hessian matrix and  $\Delta \mathbf{P} = \mathbf{P}^{(k+1)} - \mathbf{P}^{(k)}$ , referred as parameter upgrade vector. The necessary condition for a minimum to exist at  $\mathbf{P}^{(k+1)}$  is  $\mathbf{g}[\mathbf{P}^{(k+1)}] \approx 0$ . Thus, from equation (5) the following is obtained

$$\Delta \mathbf{P} = \mathbf{H}[\mathbf{P}^{(k)}]^{-1} \mathbf{g}[\mathbf{P}^{(k)}] \quad (6)$$

Based on the Gauss-Newton method, the Hessian matrix can be approximated by

$$\mathbf{H} \approx 2 \mathbf{J}^T \mathbf{w} \mathbf{J} \quad (7)$$

Equations (3), (6) and (7) lead to the approximation of the parameter upgrade vector

$$\Delta \mathbf{P} = (\mathbf{J}^T \mathbf{w} \mathbf{J})^{-1} \mathbf{J}^T \mathbf{w} \mathbf{e} \quad (8)$$

Equation (8) can be replaced by using the Marquardt correction

$$\Delta \mathbf{P} = (\mathbf{J}^T \mathbf{w} \mathbf{J} + \lambda \mathbf{I})^{-1} \mathbf{J}^T \mathbf{w} \mathbf{e} \quad (9)$$

where  $\lambda$  is a positive coefficient and  $\mathbf{I}$  is the unit matrix. When  $\lambda$  tends to infinity, the minimization approaches a steepest descent search. In contrast, when  $\lambda$  tends to zero, it reduces to the Gauss-Newton method. The algorithm has been applied in several parameter estimation packages. PEST (Doherty, 1994), a model-independent parameter estimation package, was used to solve the inverse problem for parameter estimation in this study. The advantage of PEST is that it can link to any numerical model to estimate model parameters by supplying the starting parameter values and model input files. In order to obtain reasonable estimates of parameters, the number of parameters must be less than the number of observations.

### Reference

Doherty, J., 1994. PEST. Watermark Computing, Corinda, Australia.

## **B5. Summary of Simulation Cases**

The ground-water model cases that were developed in the ArcView environment and simulated using MODFLOW and MODPATH include the following:

“Predevelopment”: one steady state case under 1940s conditions;

“Postdevelopment”: simulations under 1990s conditions:

Transient case: 40-year simulations begin with average 1990s groundwater levels.

1t. Base case: water use based on 1999 reports

2t. “Moratorium area” case: water use curtailed in a specified area south of Garden City.

Steady-state cases:

1s. “Base case” conditions of 1990’s water use, driving aquifer to depletion south of the Arkansas River. (The MODFLOW simulation was run to steady-state equilibrium, the solution for which was imported into MODPATH and run as a steady-state case.)

2s. Water use curtailed sufficiently to maintain average 1990’s groundwater levels.

Simulations were run for two general sets of conditions corresponding to 1940 and the 1990’s. These simulations were run from different directories to keep the corresponding data files and associated ArcView shapefiles and data base separate. The simulated cases are

summarized here. The ground-water model can be run using the following executables for MODFLOW and MODPATH.

Directory: d:\bin\  
MODFLOW: modflw96.exe  
MODPATH: mpath3L.exe

### **1940 Conditions (Steady-State Case)**

Spatial distributions for ground-water use, ditch irrigation, hydraulic conductivity, confining layer thickness, recharge, and Arkansas River characteristics were developed based on available data. The model was then calibrated. Spatial distributions of hydraulic conductivity and recharge were adjusted to minimize computed head errors. Simulation cases run with MODFLOW and MODPATH are summarized as follows.

#### ***Name files corresponding to MODFLOW simulations***

K2opt2.nam: run calibrated steady-state case for 1940 conditions; write computed heads as a text file for import into ArcView.

K2opt2b.nam: run the same case as above, but write computed heads and budgets as binary files for input to MODPATH.

#### ***MODPATH cases corresponding to MODFLOW simulation***

Arkpath: Particle starting locations are in the alluvial aquifer grid cells along the Arkansas River.

Dtchpath: Particle starting locations are in the High Plains aquifer grid cells along the irrigation ditches.

SO4path: Particle starting locations are in the High Plains aquifer grid cells along the 500 mg/L sulfate contours based on measurements in the 1990's. These starting locations were used for the particle path simulations under 1940 conditions as a reference for comparison with particle path simulations under 1990's conditions (see Figs. 88 and 89 in the chapter, "Regional Model Results").

These cases are based on the MODFLOW steady-state solution given by case k2opt2 (Name file k2opt2b.nam). For each case, the response file specifies for MODPATH the MODPATH Name file (extension .mpn) and the particle starting location file (extension .loc). As in the case of MODFLOW, the MODPATH Name file specifies input and output files for the case to be run by MODPATH.

The following two directories may be used to run the steady state case calibrated for the 1940 conditions:

d:\uarkr\gwmod\1940s\mflow40s\ run MODFLOW  
d:\uarkr\gwmod\1940s\mpath40s\ run MODPATH

The procedure for running the calibrated steady-state case under 1940 conditions is as follows.

Run MODFLOW to obtain computed heads as text file k2opt2.hds:

```
d:\UarkR\gwmod\mflow40s\>      \bin\modflw96
Enter Name file:                k2opt2.nam
```

Run MODFLOW to obtain computed heads as binary file k2opt2.hed and budget flow rates as binary file k2opt2.bud:

```
d:\UarkR\gwmod\mflow40s\>      \bin\modflw96
Enter Name file:                k2opt2b.nam
```

The Name files specify input files and their paths. These files define the cases to be run. Most input files specified by the Name files are located in the parent directory d:\uarkr\gwmod\; most output files are written in the local directory (from which the cases are run).

The computed heads given by text file k2opt2.hds may be imported into ArcView using the Groundwater Modeling Extension GME. The binary files with computed heads and budget flow rates are required as input to MODPATH.

Run MODPATH to obtain paths of particles beginning in the alluvial aquifer grid cells along the Arkansas River:

```
D:\uarkr\gwmod\mpath40s\>      \bin\mpath3L arkpath.rsp
```

Run MODPATH to obtain paths of particles beginning in the High Plains aquifer grid cells along the irrigation ditches:

```
D:\uarkr\gwmod\mpath40s\>      \bin\mpath3L dtchpath.rsp
```

Run MODPATH to obtain paths of particles beginning in the High Plains aquifer grid cells along the 500 mg/L sulfate contours for 1990's measurements:

```
D:\uarkr\gwmod\mpath40s\>      \bin\mpath3L SO4Cpath.rsp
```

The response files arkpath.rsp, dtchpath.rsp, and SO4Cpath.rsp provide instructions to MODPATH for the cases to be run, including the names of the MODPATH Name file (\*.mpn) and particle starting locations (\*.loc) files. The MODPATH Name file specifies the names of input files, many of which are the same as MODFLOW input or output files, and particle path and endpoint output files.

### **Summary of Base Case Simulation for 1940 Conditions**

Run MODFLOW for 1940s simulations from these directories:

```
d:\uarkr\gwmod\1940s\mflow40s\      (steady-state cases)
```

Run MODPATH and postprocess MODPATH results for 1990s simulations from:

d:\uarkr\gwmod\1940s\mpath40s\ (steady state cases)

Input files for both MODFLOW and MODPATH cases of 1940s simulations are in the parent directory, d:\uarkr\gwmod\1940s\.

MODFLOW 1940s simulation cases with key input data and output solution files

MODFLOW name file (*.nam)	Directory	Well file (*.wel)	Recharge (*.rch)	River (*.riv)	Solution (*.hds, *.hed, *.bud)
K2opt2	\mflow40s\	..\Arkss1	..\arkss1	..\ArkLowcb	K2opt2.hds
K2opt2b	\mflow40s\	..\Arkss1	..\arkss1	..\ArkLowcb	K2opt2.hed,bud

MODPATH 1940s simulation cases and particle path files

MODFLOW solution (*.hed, *.bud)	MODPATH files: Response (*.rsp), Name (*.mpn)	Particle starting locs (*.loc)	Particle path solution (*.s)	Particle endpoint solution (*.s)	Particle path postprocessing Excel workbook (*.xls)
K2opt2	Arkpath	ArkRiv	Arkpath	ArkEndpt	R3s
	DtchPath	DtchStrt	DtchPath	DtchEndp	R3s
	SO4CPath	SO4C_90s	SO4CPath	SO4CEnd	R3s

Files associated with MODPATH particle path postprocessing for import to ArcView

MODPATH files: Response (*.rsp), Name (*.mpn)	Particle path solution (*.s)	Particle path postprocessing Excel workbook (*.xls)	File imported by ArcView as event table (*.txt)	ArcView Line shapefile (*.shp) produced from event table
Arkpath	Arkpath	R3s	ArkR40s	ArkR40sL
DtchPath	DtchPath	R3s	Dtch40s	Dtch40sL
SO4CPath	SO4CPath	R3s	SO4C40s	SO4C40sL

Excel workbooks used to produce input files for MODFLOW Well and Stream packages and for MODPATH:

d:\UarkR\gwmod\1940s\ArkR\_wel.xls  
add Face column for MODPATH.

d:\UarkR\gwmod\1940s\ArkR\_str.xls  
add face column for MODPATH;  
plot Fig. 35, profile of simulated baseflow from groundwater into Ark R., based on results given for MODFLOW case K2opt2b in std. Output (K2opt2b.Lst).

Plot and preprocess elevations taken from USGS 24k topographic maps along Ark R. at contours.

Excel workbook used as postprocessor to transform particle paths from MODFLOW grid coordinates to projected coordinates:

D:\UarkR\gwmod\1990s\mpath90s\R3s.xls—Used to transform results for both 1940s and 1990s steady-state cases; also used to transform the 1990s case R3s.

### **Simulations under 1990's Conditions (Transient and Steady-State Cases)**

MODFLOW was run for both transient and steady-state cases. Two 50-year transient cases were run. The first transient case (R3trn50) represented ground-water use as estimated, based on DWR water use reports. The second case (R3tm50) represented the same ground-water use except for a hypothetical moratorium area within which irrigation pumping was eliminated. An initial calibration was applied as follows for the base case: recharge was adjusted so that the decline of computed hydraulic heads from 1990-2000 approximately matched observed declines, represented as interpolated surfaces. The 50-year simulation results were used to provide input for 50-year particle path simulations under MODPATH.

A simulation allowed to proceed to a steady-state equilibrium (R3s) was run under almost identical conditions as the base transient case; the only difference was in recharge specified along the southern grid boundary, which was adjusted to obtain a solution for MODFLOW. For the steady-state case Wc16n, the estimated water use was reduced sufficiently to obtain an approximate match between computed and observed heads for the 1990s. This required reducing irrigation pumping to approximately 16 percent of the estimated use, but with zero return flow. These conditions correspond roughly to reducing irrigation pumping to 21 percent of estimated use with a 25 percent return flow.

Both steady-state cases were also run under the moratorium scenario for which the transient case was run. These cases were denoted by the identifiers R3s\_mor and Wc16nmor, respectively.

Two MODPATH particle simulations were run for each MODFLOW case. MODPATH was run first with starting particles located in alluvial aquifer grid cells along the Arkansas River in layer 1, and then with starting particles situated in High Plains aquifer grid cells along sulfate concentration contours of 500 mg/L in layer 2.

A preliminary set of simulations was run from the following directories for 1990's conditions.

d:\uarc\sp\gw90s\inv\_rch\ run MODFLOW (both steady state and transient cases)  
d:\uarc\sp\gw90s\mp\_50yr\ run MODPATH (50-year transient cases r3trn50, r3tm50)  
d:\uarc\sp\gw90s\mp\_ss90s\ run MODPATH (steady state cases r3s, wc4r1s4)

Water-use estimates were revised to correct some minor errors in the assumptions made for these cases, which were then run again from a separate set of directories as follows.

Run MODFLOW for 1990s simulations from:

- d:\uarc\gwmod\1990s\mflow90t\ (transient cases)
- d:\uarc\gwmod\1990s\mflow90s\ (steady state cases)

Run MODPATH and postprocess MODPATH results for 1990s simulations from:

- d:\uarc\gwmod\1990s\mpath90t\ (transient cases)
- d:\uarc\gwmod\1990s\mpath90s\ (steady state cases)

MODFLOW 1990s simulation cases with key input data and output solution files

MODFLOW name file (*.nam)	Directory(*)	Well file (*.wel)	Recharge (*.rch)	River (*.riv)	Solution (*.hds, *.hed, *.bud)
R3trn50b	\mflow90t\	..\Ark90sn	..\r3trn	..\Ark_LC4	..\R3trn50
R3tm50b	\mflow90t\	..\Mor90sn	..\r3tmor	..\Ark_LC4	..\R3tm50
R3sb	\mflow90s\	..\Ark90sn	..\r2sobc	..\Ark_LC2	..\R3s
R3s_mor	\mflow90s\	..\Mor90sn	..\r2sobc	..\Ark_LC2	..\R3s_mor
Wc16nb	\mflow90s\	..\Ar16n	..\w1s	..\Ark_LC4	..\wc16n
Wc16nmorb	\mflow90s\	..\Ar16nmor	..\w1s	..\Ark_LC4	..\wc16nmor

\* Input files for both MODFLOW and MODPATH cases of 1990s simulations are in the parent directory, d:\uarc\sp\gw90s\.

MODPATH 1990s simulation cases and particle path files

MODFLOW solution (*.hed, *.bud)	MODPATH files: Response (*.rsp), Name (*.mpn)	Particle starting locs (*.loc)	Particle path solution (*.pat)	Particle endpoint solution (*.end)	Particle path postprocessing Excel workbook (*.xls)
R3trn50	Arkr_90t	ArkRiv2	Arkbass50	Arkbass50	R3trn50
	SO4C_90t	SO4C_90s	SO4bas50	SO4bas50	R3trn50
R3tm50	Arkr_mor	ArkRiv2	Arkmor50	Arkmor50	R3tmor50
	SO4C_mor	SO4C_90s	SO4mor50	SO4mor50	R3tmor50
R3s	Arkr_90s	ArkRiv	ArkR_90s	ArkR_90s	R3s
	SO4C_90s	SO4C_90s	SO4C_90s	SO4C_90s	R3s
R3s_mor	ArkRmors	ArkRiv	ArkRmors	ArkRmors	R3s
	SO4Cmors	SO4C_90s	SO4Cmors		R3s
Wc16n	W16_ArkR	ArkRiv	W16_ArkR	W16_ArkR	Wc16n
	W16_SO4C	SO4C_90s	W16_SO4C	W16_SO4C	Wc16n
Wc16nmor	W16morAr	ArkRiv	W16morAr	W16morAr	Wc16n
	W16morSO	SO4C_90s	W16morSO	W16morSO	Wc16n

Files associated with MODPATH particle path postprocessing for import to ArcView

MODPATH files: Response (*.rsp), Name (*.mpn)	Particle path solution (*.pat)	Particle path postprocessing Excel workbook (*.xls)	File imported by ArcView as event table (*.txt)	ArcView Line shapefile (*.shp) produced from event table
Arkr_90t	Arkb50	R3trn50	Arkb50	Arkb50L
SO4C_90t	SO4bas50	R3trn50	SO4bas50	SO4bas50L
Arkr_mor	Arkmor50	R3tmor50	Arkmor50	Arkmor50L
SO4C_mor	SO4mor50	R3tmor50	SO4mor50	SO4mor50L
Arkr_90s	ArkR_90s	R3s	ArkR_90s	ArkR_90sL
SO4C_90s	SO4C_90s	R3s	SO4C_90s	SO4C_90sL
ArkRmors	ArkRmors	R3s_mor	ArkRmors	ArkRmorsL
SO4Cmors	SO4C_90s	R3s_mor	SO4Cmors	SO4CmorsL
W16_ArkR	W16_ArkR	Wc16n	W16_ArkR	W16ArkRL
W16_SO4C	W16_SO4C	Wc16n	W16_SO4C	W16SO4CL
W16morAr	W16morAr	Wc16nmor	W16morAr	W16morAL
W16morSO	W16morSO	Wc16nmor	W16morSO	W16morSL

Excel workbooks used to produce input files for MODFLOW Well and Stream packages:

d:\UarkR\gwmod\1990s\Ar90swel.xls  
d:\UarkR\gwmod\1990s\mflow90s\R2\_Lkg.xls

The following Excel workbooks served as preprocessors to produce Well input files for the 1990's steady-state cases with sustained ground-water levels, including cases Wc16n (base) and Wc16nmor (with moratorium area).

Preprocessors used to produce Well input files for sustained steady state 1990's conditions

Case	Excel workbook path and filename	Well input file produced
W16n	d:\UarkR\gwmod\1990s\Ar90swel.xls	Ar16n.wel
W16nmor	d:\UarkR\gwmod\1990s\wel90mor.xls	Ar16nmor.wel

A vba routine was used to apply the following conversion to well pumping input data from the format of grid-based fields in the ArcView shapefiles for each layer (uagrid\_1.shp and uagrid\_2.shp) to the format

Postprocessor applied to MODFLOW results:  
D:\UarkR\gwmod\1990s\Ar90sriv.xls, Chart "Ch\_Basef190s(wc16n)"

Postprocessor applied to MODPATH results:  
d:\UarkR\gwmod\1990s\mpath90s\wc16n.xls

This workbook was used to produce particle path files in projected coordinates that were exported from Excel in comma-delimited format for input to ArcView. Once imported into ArcView, these files were added to views as event themes and then converted to line shapefiles using an extension available on the ESRI website, Pt2ln2pl.avx (“points to lines or polylines”).

### Summary of Particle Pathline Shapefiles by Subdirectory

d:\UarkR\shapefiles\ua40s\ shapefiles for 1940s cases

\mpath40s\	1940s, steady state case
\K2opt2\	calibrated steady-state case
Particle travel times limited to 40 years:	
ArkR40sL.shp	paths starting along river in alluvium
Dtch40sL.shp	paths starting along irrigation ditches

d:\UarkR\shapefiles\ua90s\ shapefiles for 1990s cases

\mpath90s\	1990s, steady state cases
\R3s\	1990s pumping
ArkR_90sL.shp	pathlines starting along river in Qa
SO4C_90sL.shp	pathlines starting along [SO4] in HP
\R3s_mor\	1990s pumping with moratorium area
ArkRmorsL.shp	pathlines starting along river in Qa
SO4CmorsL.shp	pathlines starting along [SO4] in HP
\Wc16n\	pumping at 16 pct of 1990s reported use
W16ArkRL.shp	pathlines starting along river in Qa
W16SO4CL.shp	pathlines starting along [SO4] in HP
\Wc16nmor\	pump at 16 pct of 1990s, with moratorium
W16ArkmL.shp	pathlines starting along river in Qa
W16SO4mL.shp	pathlines starting along [SO4] in HP

[*] \mpath90t\	1990s, transient cases
\R3trn50\	1990s pumping
ArkBas50L.shp	pathlines starting along river in Qa
SO4Bas50L.shp	pathlines starting along [SO4] in HP
\R3mor50\	1990s pumping
Arkmor50L.shp	pathlines starting along river in Qa
SO4mor50L.shp	pathlines starting along [SO4] in HP

Notes:

[\*] MODFLOW transient simulations were run for 50 years, but particle travel times for MODPATH simulations were limited to 40 years for all cases (both transient and steady-state).

## **B6. Simulation Procedure**

MODFLOW and MODPATH were used in conjunction with ArcView according to the following procedure to simulate the cases of interest (see Appendix B5 for details).

- 1a. Set up input files for MODFLOW using the interface provided by the Groundwater Modeling Extension (GME; Tsou and Whittemore, 2001).
- 1b. Run MODFLOW to obtain a solution for heads in layers 1 (alluvial) and 2 (High Plains) as a sequential text file.
- 1c. Import the text file into ArcView through the “Import a File” function on the Utilities menu of the Groundwater Modeling Extension (GME).
- 2a. Run MODFLOW again to write heads and flow rates to binary files. This is not done as part of step 1 because the Output Control package of MODFLOW allows heads to be written only one way, either as a sequential, text file or as a direct, binary file.
- 2b. Run MODPATH, and read the binary files from step 2a. This should produce a text file of final particle locations or particle paths, depending on the options chosen. The locations are given in grid coordinates.
- 2c. Postprocess MODPATH simulation results as follows:
  - Import the particle path results file into Excel.
  - Transform the particle paths from grid to projected coordinates, equation (2), using Excel.
  - Write the results out to a comma-delimited file (\*.csv) and change the extension to “txt”.
  - Import the renamed comma-delimited file into ArcView (“Add table”), convert to a shapefile, and convert the point shapefile to a line shapefile.

For these, Excel is used to apply the following additional steps:

- Sort records into the required order (by particle ID, travel time, and simulation time step);
- Delete duplicate records (particle location at the end of each time step is repeated at beginning of following time step);
- Select only particles corresponding to an appropriate density along the path (approx. 200 m between particle locations).

Once these additional steps have been taken, particle locations are transformed from grid to projected coordinates, and a particle sequence ID is calculated for all coordinate pairs of each particle. This attribute is required by a point-to-polyline script that can be applied once the particle paths have been imported into ArcView and converted to a point shapefile.

### **Preprocessing and Postprocessing Procedures for MODPATH Simulations**

The 1990’s particle path shapefiles were imported as comma-delimited text files that had been exported from Excel spreadsheets on file so4path1.xls. Map 8, particles beginning along the river, originated with export from spreadsheet ArkR\_90s(2); Map 9, particles beginning along [SO4] contours, originated with export from spreadsheet SO4C\_SS on this Excel file. Both particle maps were simulated using results from the same MODFLOW

simulation, r2s (same as r2 but with streambed elevations decreased from 1 to 2 m). The corresponding MODPATH simulations were run as follows.

Run MODPATH for both particle maps from d:\uarc\sp\gw90s\mp\_ss\

From the above area, run MODPATH as follows:

1. River particle simulation from layer 1 for Map 8:  
    ..\bin\mpath3L ArkR\_90s.rsp
2. SO4 contour simulation from layer 2 for Map 9:  
    ..\bin\mpath3L SO4C\_90s2.rsp

In each case, the response file (\*.rsp) specifies a master file (\*.mpn), which in turn specifies all the input and output files for the MODPATH simulation except for the starting locations (\*.loc) file, which is also specified by the response file. The \*.mpn file specifies the names of the particle path and ending location files for each run. The particle path files were imported into the Excel spreadsheet So4path1.xls (noted above). In the Excel environment, the grid coordinates of the particle paths were transformed to the projected coordinate system of the ArcView model. For other Excel-based conversions: For each particle location, time of travel was converted from days to years; travel distance and Darcy velocity were computed. A field was added to identify location sequence along each particle's path to make the "Point-to-Polyline" script easier to apply within ArcView. The resulting spreadsheets were exported as comma-delimited text files with the extension ".csv", which was renamed to ".txt" for import into ArcView.

## **B7. Postprocessing of Particle Paths simulated by MODPATH**

MODPATH results are given in grid coordinates. These are imported into an Excel workbook, transformed to projected coordinates, and then written as comma-delimited files for input to ArcView using the "Add a Table" function, text file option. The Excel workbook used for this is in the directory used for running MODPATH, d:\uarc\sp\gw90s\mpss90s\ArPath90.xls.

Results for two cases are processed in this way: particles starting along the river in the alluvial aquifer (layer 1) and along the 500-mg/L sulfate contours in the High Plains aquifer (layer 2). Paths are shown by charts in both grid and projected coordinates for these two sets of results on spreadsheets ArkR and SO4C, which provides a reliable check on this intermediate step to prepare results for displaying in ArcView.

The postprocessing steps of importing particle paths into Excel, transformation to projected coordinates and writing to a file might be reduced if ArcView could be tricked into recognizing the particle path file written by MODPATH as a CAD dxf file, for which ArcView can be directed to apply the transformation that was computed using the spreadsheet program Excel. For the transient cases, however, Excel was called on to perform more than simply transforming from grid to projected coordinates. The postprocessing procedure followed in Excel for the transient cases is outlined here.

1. Import particle path results written by MODPATH into an Excel spreadsheet. The number of starting particles was adjusted so that the number of records corresponding to particle coordinate pairs on the resulting particle path file is less than 64k, assuming that Excel may be unable to handle 64k records or more.

Steps 2-4 apply to transient cases and not steady-state cases:

2. Sort the records based on the following three keys, all in ascending order: a) particle ID, b) particle travel time, and c) MODFLOW simulation time step.
3. Eliminate duplicate coordinate pairs corresponding to the end of each time step (n) and the beginning of the following time step (n+1) for all time steps and particles. This eliminates about half the records. Do this by calculating a field, Duplicates, that has a value of 0 for non-duplicates and a value of 1 for duplicates. Once this has been calculated, convert the formulas to values (copy and paste-special by value). Then sort the entire file based on the following three keys, all in ascending order: a) Duplicates, b) particle ID, and c) particle travel time.
4. Reduce the number of particle locations used to define paths. Select particle locations at appropriately spaced intervals; an interval of 200 m was chosen, which delineates the paths more than adequately for a grid cell size of 804.6 m. This was implemented as follows:
  - a) calculate the distance traveled between each particle locations according to

$$ds = (dx^2 + dy^2 + dz^2)^{1/2}$$

- b) accumulate distance traveled along particle path,  $s = \Sigma(ds)$ ;
- c) take the modulus of accumulated distance for 200 m [ $\text{mod}(s, 200)$ ];
- d) calculate a selection field (values of 1 or 0) to identify records for which the modulus of the accumulated distance has turned over. Once this has been calculated, convert its formulas to values and again sort the table by selection field, particle ID, and time step to select out the unneeded intermediate particle locations for elimination.

Steps 5-10 apply to both transient and steady-state cases:

5. Calculate an additional field to provide a sequence ID for each location of each particle. The sequence ID will be used within ArcView as a necessary input field for a script to convert particle path representations from a set of points to a line (step 8).
6. Transform grid coordinates to projected coordinates (see section below).
7. Make a copy of the spreadsheet; convert the spreadsheet to values, and reduce the set of fields to those of interest for import into ArcView. The fields listed below are included, the first five of which are used in step 10 for a point-to-line shapefile conversion:

X_coord	x-coordinate in projected frame;
Y_coord	y-coordinate in projected frame
Part_ID	particle ID
Part_Seq	sequence for a given particle

Years	travel time (years)
Z_global	z-coordinate (in both grid and projected frame, assuming both are in meters)
Modstep	index to MODFLOW solution time step
Node_ID	global node number
Layer	index to model layer
Uagrid_ID	index to grid cell (function of row and column; same for every layer)
Ds	cumulative distance traveled by particle (m)
V	mean particle speed

- Write out the spreadsheet produced in step 7 as a comma-delimited text file (extension .csv).
- Rename the resulting text file extension from .csv to.txt to be recognized by ArcView as a comma-delimited text file.
- In ArcView, import the comma-delimited file to your project as a text table; then add the table to a view as an event theme and convert it to a shapefile.
- Use the ArcView extension PT2L2PL.avx to convert particle path representations from a point shapefile to either a line or polyline shapefile. This extension was downloaded from ESRI, and operates on the first five fields defined in Step 7 (above).

### **Point-to-Polyline Shapefile Conversion**

A further postprocessing step within ArcView is to convert the particle path shapefile from a point coverage to a polyline coverage using the ArcView extension pt\_ln\_pl.avx according to the following procedure:

- Prepare a comma-delimited file with the following fields:

X Y ID Order Attribute

These fields correspond to the first five fields defined in Step 7 of the procedure shown above for postprocessing MODPATH's particle path results.

```
0 0 1 1 My line
1 1 1 2 My line
1 2 1 3 My line
```

- In the ArcView Table, add this file.
- Add this new table as an event theme in a view and have this theme active
- Use the extension to convert the event theme to a line shapefile.

### Notes on point-to-polyline shapefile conversion

- The point shapefile representation of the particle paths contains the attributes of interest that are derived from the MODPATH output and from the Excel postprocessing. The extension produces a polyline shapefile that does not contain these attributes.
- The format for the comma-delimited text files shown above includes a field for the order of loci, or coordinate pairs for the sequence of locations for a given particle. This field

was added as Step 2 of the procedure outlined above for postprocessing MODPATH's particle path results from within Excel.

## **B8. ArcView Project: Spatial Decision Support System (SDSS), Upper Arkansas River, 1990's**

This section of the report is also provided with the ArcView sdss project as a separate Word document, c:\sdss\Readme.doc.

### **ArcView GIS Version 3.2a; Assumed Extensions: 3D Analyst, Spatial Analyst**

Among other capabilities, these extensions provide support for the triangulated irregular network (TIN) shapefiles included in the sdss ArcView project that are used to represent average (wintertime) water-level conditions in the alluvial and High Plains aquifers in the 1990s, and the change in water levels in the High Plains aquifer from 1991-2000.

### **Spatial decision support system project: c:\sdss\uark90s.apr**

#### ***Model: Upper Ark River basin: alluvial and High Plains aquifers***

The sdss project version is a subset of the project used for model development. Projection: default is Lambert; parameters are shown below.

<u>Coverage</u>	<u>Shapefile (Type)</u>
Cities	c:\sdss\city.shp (Polygon)
Counties	c:\sdss\cnty.shp (Polygon)
Township-ranges	c:\sdss\tr.shp (Polygon)
Sections	c:\sdss\secualam.shp (Polygon)
Alluvial valley boundary	c:\sdss\alluvy.shp (Polygon)
High Plains boundary	c:\sdss\hp.shp (Polygon)
Bear Creek fault	c:\sdss\fault.shp (Arc)
Ditches	c:\sdss\ditch.shp (Arc)
Arkansas River	c:\sdss\ark_riv.shp (Arc)
Stream gages	c:\sdss\gage_lam.shp (Point)

Sulfate concentration contours in alluvial and High Plains aquifers:

[SO4] contours, alluvial	c:\sdss\SO4_Contours\qa_so4arc.shp (Arc)
	c:\sdss\SO4_Contours\qa_so4pol.shp (Polygons)
[SO4] contours, High Plains	c:\sdss\SO4_Contours\hp_so4arc.shp (Arc)
	c:\sdss\SO4_Contours\hp_so4pol.shp (Polygons)

### *1990's water levels*

Time-averaged point observations distinguished as alluvial (layer 1) or High Plains (layer 2):

DWR water levels	c:\sdss\wl_dwr90pj.shp (Point)
KGS water levels	c:\sdss\wl_kgspj.shp (Point)
KGS water levels (Haskell)	c:\sdss\wl_haskell.shp (Point)

TINs (triangulated irregular networks derived from time-averaged point observations):

Alluvial WL (layer 1)	c:\sdss\wl90stin_1
High Plains WL (layer 2)	c:\sdss\wl90stin_2
HP WL change 1991-2000	c:\sdss\wl91-00

Contour lines (derived from TINs):

Alluvial WL (layer 1)	c:\sdss\wl90cnt1.shp (Arc)
High Plains WL (layer 2)	c:\sdss\wl90cnt2.shp (Arc)

### **Projection parameters used for Upper Ark R. model ArcView project**

Ellipsoid:	Clarke_1866
Equatorial radius:	6,378,206.40 m
Polar radius:	6,356,583.80 m
Flattening ratio:	0.003390075304089
Eccentricity:	0.082271854224939
Local datum:	North American Datum 1927 (NAD27)
Projection:	Lambert Conformal Conic
Projection parameters:	

Parameter	Units (dd: dec. deg.)	Units (DMS: deg min sec)
Central meridian	-101.0 DD	-101 00 00
Reference latitude	37.5 DD	37 30 00
Standard parallel 1	37.9 DD	37 54 00
Standard parallel 2	38.2 DD	38 12 00
False easting	0 m	0 m
False northing	0 m	0 m

### **Projection Parameters Used for Standard KGS Projections**

KGS coverages and maps are typically provided in a Lambert Conformal Conic projection with the parameters shown below. Although the ellipsoid and local datum

projections are shown to be the same as above and appear repetitive, these will likely change to more recent standards in the near future.

Ellipsoid: Clarke\_1866  
 Equatorial radius: 6,378,206.40 m  
 Polar radius: 6,356,583.80 m  
 Flattening ratio: 0.003390075304089  
 Eccentricity: 0.082271854224939

Local datum: North American Datum 1927 (NAD27)

Projection: Lambert Conformal Conic

Projection parameters:

Parameter	Units (dd: dec. deg.)	Units (DMS: deg min sec)
Central meridian	-98.25 DD	-98 15 00
Reference latitude	36 DD	36 00 00
Standard parallel 1	33 DD	33 00 00
Standard parallel 2	45 DD	45 00 00
False easting	0 m	0 m
False northing	0 m	0 m

### Notes on Using the Projection Utility Wizard in ArcView GIS v. 3.2a

From the File -> Extensions menu, activate the Projection Utility Wizard. This action adds an item to the File menu that enables running the Projection Utility.

Example: Project the PLSS section grid from geographical coordinates to the above projection.

In an ArcView project, set up a view as a reference frame in geographical coordinates. Add the shapefile secua.shp to the view. In the File menu, click on the projection utility to run it; if such an item is missing, see the above instructions. Follow directions given by the Projection Utility Wizard once it is running. Notes on the procedure follow.

Step 1. Select the shapefile(s): secua.shp

Step 2. Identify the current coordinate system of the shapefile(s): geographical. For this shapefile, assume the Clarke 1866 ellipsoid for Earth-centered datum, and North American Datum of 1927 (NAD27) for the local datum. Once you've identified the current coordinate system, you're given the option to save the coordinate information with your shapefile.

Step 3. Select the new coordinate system for the new shapefile(s). Select Projected coordinate system. Under Name, choose Custom (at bottom of list). Choose Meters for Units. Check "Show Advanced Options" if the box is not checked. Go to the Parameters page. In the Base Projection box, select Lambert Conformal Conic [43020]. Fill in boxes for

Central Meridian, Central\_Parallel (Reference Latitude), and Standard Parallels 1 and 2 as shown in the Table above. For Geographic Coordinate System, select Clarke\_1866 [4008]. Use default values of (0,0) for False Easting and Northing. Keep Greenwich as the Prime Meridian. Once the new coordinate is selected, answer “No” to the next question about going back one step unless you intended to change geographical coordinate systems. Here, we keep the same system (Clarke 1866, NAD27).

Step 4. Specify the new shapefile name (Secualam.shp) and location. Check transformation summary table and press the Finish button. The projection utility will eventually display a “Processing...” window and then display a “Finished” window that requires closing.

### **Conversion of PLSS Locations to Geographic Coordinates**

Locations of some features were available in terms of the Public Land Survey System (PLSS), given by township, range, section, and subsection. Transformations from PLSS-coded locations were applied in two steps. The KGS program Leo was first applied to convert PLSS to geographical coordinates, which were then projected using the ArcView Projection Utility.