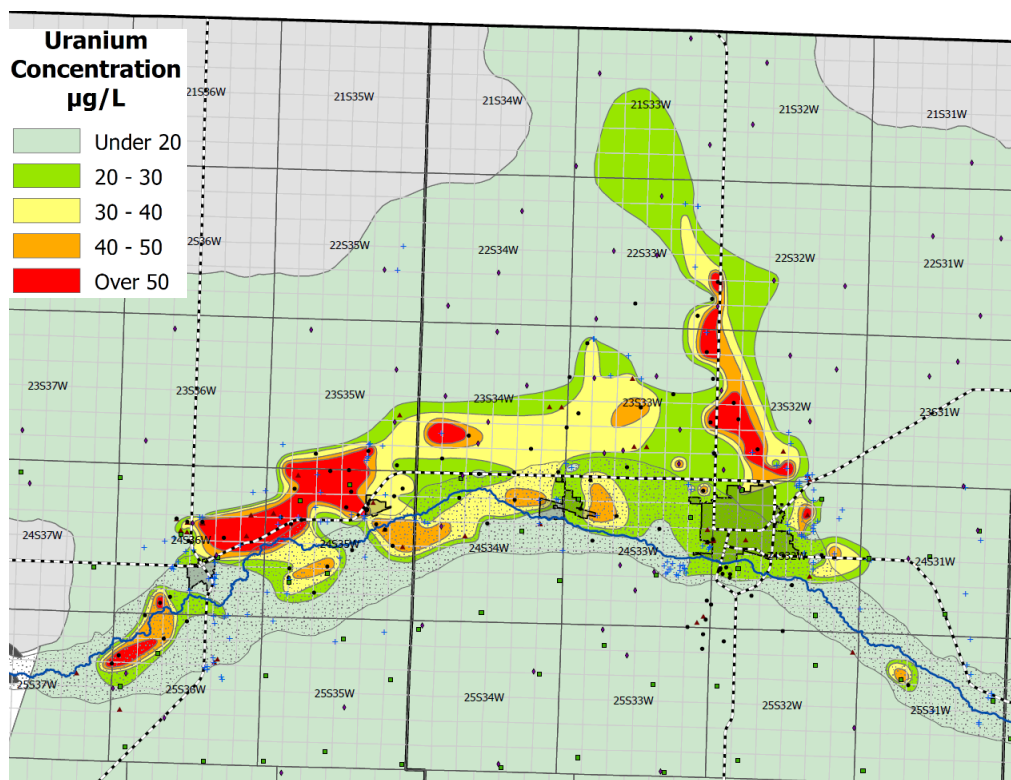


Kansas Geological Survey

Assessment of Groundwater Mineralization in the Upper Arkansas River Corridor

2023 Final Project Report

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Uranium Concentration in Arkansas River Corridor from Lakin to Garden City.

Kansas Geological Survey Open-File Report No. 2023-21
April 2023

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Acknowledgments

We are grateful for the support, assistance, and cooperation of the staff of the Kansas Water Office; for the collaboration of Southwest Kansas Groundwater Management District No. 3 for collection and transfer of well, river, and canal waters identified by the Kansas Geological Survey for sampling locations, including the cooperation of the many landowners for making their wells available for sampling; and for the assistance of the Kansas Department of Health and Environment for use of voluntary private well data and for their laboratory analyses of samples collected in this study. The State of Kansas Water Plan Fund provided partial financial support for this project.

Executive Summary

Arkansas River water entering Kansas from Colorado is saline and has been contaminating the alluvial aquifer for more than a century and the Ogallala-High Plains aquifer (HPA) for the last several decades in the river corridor in southwest Kansas. In addition to being saline, the river water typically contains a uranium concentration that exceeds the maximum contaminant level (MCL) of 30 µg/L for public supplies of drinking water. Infiltration of the saline river water from the river channel, irrigation ditches, and areas irrigated with diverted water has increased the salinity and uranium concentration of the alluvial aquifer and the HPA, affecting public and private drinking water as well as agricultural and industrial groundwater supplies.

The Kansas Department of Health and Environment (KDHE) conducted a voluntary sampling program in fall 2019 for private well waters in the area of high groundwater salinity in the river corridor. The KDHE analyzed the samples for uranium concentration and selected other constituents; a key issue that needed clarification was the distribution of domestic wells producing water with a uranium concentration above the drinking water standard for public water supplies. The Kansas Geological Survey (KGS) then conducted a study for the Kansas Water Office, with the collaboration of the KDHE, that included mapping the current distribution of salinity and uranium concentrations in the groundwater of the river corridor; determining spatial and temporal changes in the concentrations; assessing geographical factors, lithologic influences, and hydrogeochemical controls affecting the distributions of salinity and uranium; and estimating the future accumulation and spread of the aquifer contamination based on river loads entering the corridor. Southwest Kansas Groundwater Management District No. 3 collaborated with the KGS by sampling domestic, municipal, irrigation, and stock wells selected by the KGS to fill in gaps in the spatial coverage. The KGS sampled multilevel observation wells to determine changes in the vertical distribution of salinity and uranium concentrations since the wells were installed during the late 1990s in an earlier Kansas Water Plan investigation.

Salinity, as indicated by the sulfate concentration, has increased in the HPA in the river corridor since previous mapping. The sulfate concentration now exceeds 1,500 mg/L in some areas of the HPA in Kearny and Finney counties. Uranium concentration exceeded the MCL in about 18% of the 227 well water samples from the alluvial aquifer and the HPA that were voluntarily submitted by private well owners in the KDHE project. In the current KGS study, uranium exceeded the MCL in almost half of the 103 wells of different types sampled from the HPA. The reason for the higher percentage in the KGS compared to the KDHE study is that the KGS project focused on sampling wells in the highest salinity and uranium areas to better define these zones. The areas of high uranium concentration in the HPA extend from east-central Kearny County through west-central Finney County as well as along the depression called the White Woman Bottoms that extends from the east side of Garden City to about 12 miles to the north-northwest. Although high sulfate concentrations occur in the HPA on both the north and south sides of the Arkansas River and are primarily in the ditch-irrigated areas, the high uranium areas are distributed mainly to the north of the river. Water tables are generally deeper to the south of the river than the north, and some saline groundwater has migrated to the south of the river due to the southward slope in the water table. The greater travel distance of saline waters through the unsaturated zone to the water table and within the formerly uncontaminated aquifer south of the river has apparently decreased uranium concentrations due to adsorption on sediments. None of

the 19 domestic wells (18 in the KDHE study and 1 in the KGS study) in the Dakota aquifer exceeded the uranium MCL. Five well samples (approximately 2%) in the KDHE private well study and one in the current KGS study exceeded the selenium MCL. Only one well water collected during the KDHE and KGS studies exceeded the arsenic MCL. This confirmed that the main contamination issue related to metals for the aquifer is uranium. About 15% of the well waters sampled in the KDHE study and approximately 5% of the well waters in the current KGS study exceeded the MCL for nitrate-nitrogen concentration.

The prior Upper Arkansas River Corridor Study included a model of the migration of salinity from 2000 to 2040. Although the general change in the sulfate concentration from 2000 determined in the current study showed some predicted migration in Kearny and western Finney counties, the predicted migration south of the Arkansas River valley east of Garden City has not occurred. The reason is that when the model was made in 1999, the river was flowing all through western Kansas. However, no substantial river flow has extended beyond Garden City since 2001. The primary change in the aquifer salinity since 2000 is the increase in concentration in the main contaminated area of eastern Kearny and western Finney counties. Vertical migration of saline water has increased the sulfate and uranium concentrations in parts of the HPA at multilevel observation well sites at Deerfield, Garden City, and near Dodge City. In addition to vertical transport, lateral groundwater flow from the high uranium area to the north in Kearny County has increased the uranium in the lower HPA at the Deerfield site such that the concentration is greater than in the shallow aquifer.

Uranium concentrations and loads in Arkansas River water entering Kansas were estimated from a uranium and specific conductance relationship based on river water samples coupled with the real-time conductance measurements of river water at the U.S. Geological Survey gaging station near the Colorado-Kansas state line. The mean annual uranium concentration in the river water decreases with increasing flow, as expected. However, the variation in annual load is much greater due to the even larger variation in year-to-year mean flow. The average of the mean annual uranium concentrations, river flows, and uranium loads during the last decade are approximately 59 µg/L, 137 ft³/sec, and 6.0 tons/yr, respectively. These values were used to estimate the future accumulation of uranium in the HPA based on various assumptions of the contaminated area, the background concentration of uranium, evapotranspiration losses, and mixing with aquifer water. Background uranium concentrations range from less than 5 µg/L to more than 15 µg/L in the HPA in the river corridor, with the highest concentrations in parts of Kearny and Finney counties where the HPA overlies Upper Cretaceous shales and chalky limestones.

The salinity of most of the shallower portions of the HPA underlying the river valley and the ditch-irrigated area is generally expected to be greater than in the deeper portions of the aquifer because the saline water source is from the surface. However, saline water flow down the gravel packs of unsealed wells, especially large-diameter wells such as those constructed for irrigation, can allow shallow saline groundwater to penetrate to the screened intervals of the wells and produce pockets of saline groundwater in the deeper parts of the aquifer. Pumping by wells near those pockets of deep saline groundwater can cause migration of that water toward those wells. Thus, the vertical distribution of salinity and uranium is uneven and complex across the contaminated region of the HPA, especially in locations of wells with different depths,

construction, and pumping rates. These conditions indicate the critical importance of a grout seal in the annulus of a well across a clay layer above the screened interval, not only for those wells from which water is pumped for drinking purposes but also for other wells that can be potential avenues for rapid transport of saline water with high uranium concentration from the near surface down to the producing zones of the HPA. Sealing selected intervals of the gravel pack in abandoned irrigation wells located within the alluvial aquifer boundaries and in ditch irrigation areas could prevent those wells from being constant point sources of contamination to the HPA; usual plugging of a well involves placing a grout seal within the casing but not in the annulus.

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Historical Context and Previous Research

Saline water has been accumulating in the upper Arkansas River corridor in southwest Kansas since the late 1800s, when ditch irrigation using diverted Arkansas River water began. The Arkansas River entering Kansas from Colorado is one of the most saline rivers in the United States. The average total dissolved solids concentration near the state line for 1963–2010 data was 3,260 mg/L compared to the recommended level (secondary standard) for drinking water of 500 mg/L. The chemical water type is usually sodium, calcium-sulfate; the average sulfate concentration for the same period was 1,960 mg/L in comparison with a chloride content of 137 mg/L. The river water also has been found to be high in uranium; the average concentration based on 27 samples collected near the state line by the Kansas Geological Survey (KGS) and the Kansas Department of Health and Environment (KDHE) during 2009–2010 was 63.5 µg/L, which is more than twice the maximum contaminant level (MCL) of 30 µg/L for public supplies of drinking water.

The salinity and uranium in Arkansas River water entering Kansas are nearly all naturally derived, whereas the high concentration of dissolved constituents is caused by human actions. Cretaceous shales in the plains of eastern Colorado contain sulfide minerals that weather to produce secondary gypsum and release uranium, selenium, and other elements, which are ultimately leached and transported into the Arkansas River. A substantial amount of river water is diverted for irrigation in the Colorado plains; most of this water is consumed by evapotranspiration, leaving behind the salts in irrigation return flow and soil moisture. The return flow and flushing of soils by rainfall brings the saline water into the river either in drains entering the river or as groundwater discharge.

Diversion of Arkansas River water for irrigation in the river corridor started in 1883 in Kansas. Although a few ditch irrigation areas developed along the floodplain of the river in Hamilton County, the main ditch irrigation areas were formed in Kearny and Finney counties, which were fed by the Amazon, Great Eastern, Garden City, and Farmers canals on the north side of the river and the South Side canal to the south of the river (Figure 1). The water is typically diverted at moderate to high flows and is saline (although not as saline as low-flow water) but can be used for irrigation because it is a sulfate- rather than chloride-rich water. Saline water infiltrates to the groundwater of the High Plains aquifer (HPA) from the canals and ditches and from return flow in the irrigated fields. The saline water infiltrating from the fields is even more saline than the diverted river water as a result of evapotranspiration. Pumping of groundwater from wells is also used for irrigation in the ditch-irrigated areas. Evapotranspiration concentration of dissolved salts in this irrigation water along with the pumping of groundwater affected by the infiltration of saline river water and return flow continues to add to the salinity of the HPA.

Since the early 1990s, the KGS has been studying the river and groundwater quality in the upper Arkansas River corridor. Much of the work has been partially funded by the Kansas Water Plan, including the Upper Arkansas River Corridor study during 1995–2000 for the Kansas Water Office (KWO). As a part of that study, the KGS generated maps of the sulfate concentration distribution in the alluvial aquifer and the HPA; the map for the HPA is shown in Figure 2. The map indicates that the area of high sulfate content (more than 500 mg/L) correlates well with the ditch irrigation area (Figure 1). The zone of highest sulfate concentration mapped for the HPA in

2000 was greater than 1,000 mg/L. Zones of even higher sulfate concentration were mapped for the alluvial aquifer in 2000 (greater than 2,000 mg/L in Hamilton County and greater than 1,500 mg/L through Finney County into parts of the alluvial aquifer in Gray County).

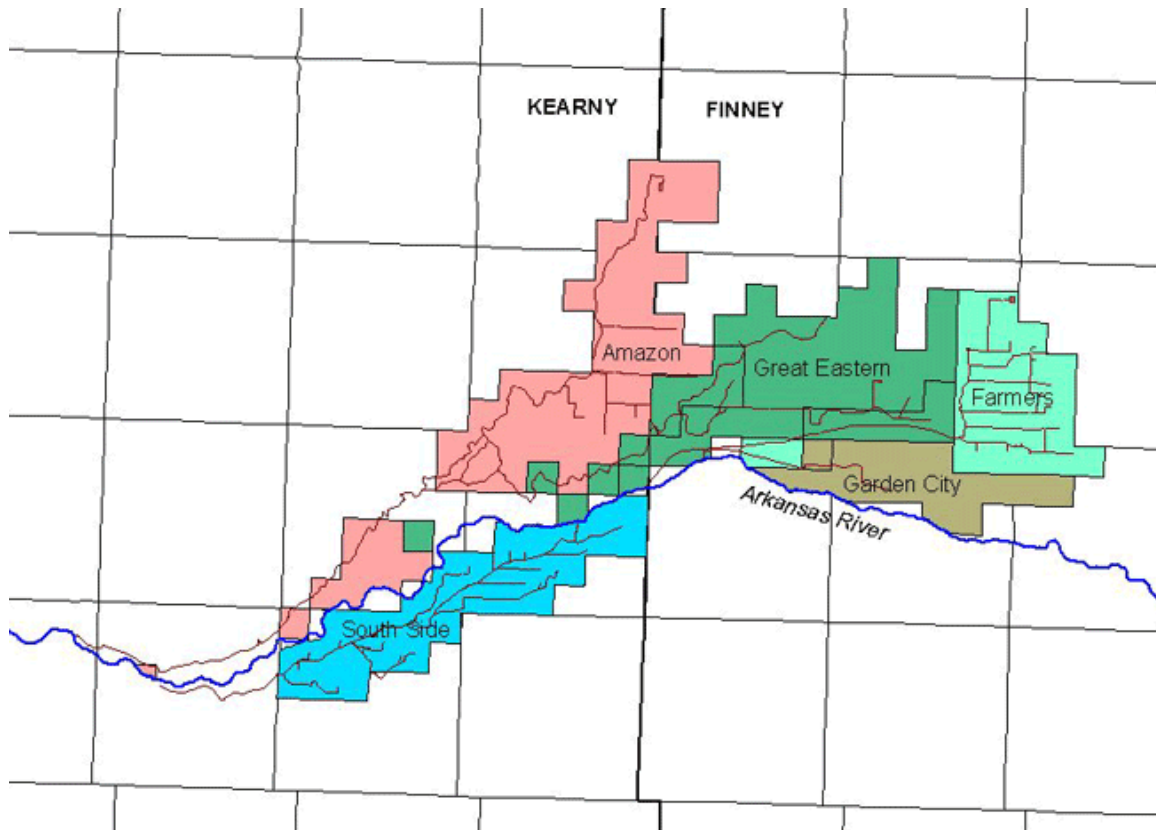


Figure 1. Map of historic ditch service areas in Kearny and Finney counties.

The KGS also conducted simplified modeling of groundwater flow in the river corridor and used particle tracking of points along the 500 mg/L sulfate concentration contour (Figure 3). The particle tracking showed that due to substantial declines in HPA water-table levels south of the Arkansas River, groundwater flow directions changed from predominantly eastward to mainly south-southeastward. Thus, the model predicted the future migration of saline groundwater to the year 2040 to be south of the river. North of the river, where water-level declines in the HPA were not as substantial due to recharge of diverted river water and less groundwater use, the saline groundwater migration was predicted to be predominantly to the east (Figure 3).

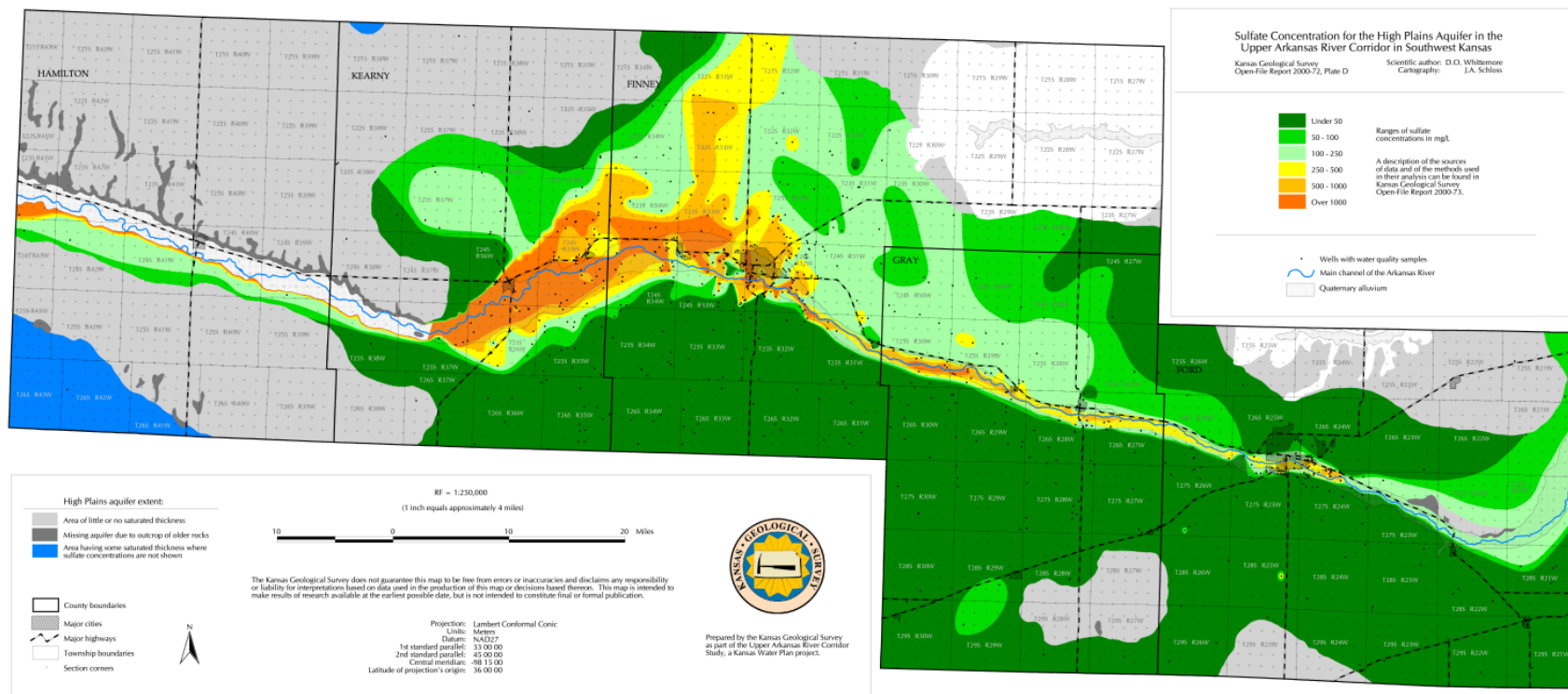


Figure 2. Distribution of sulfate concentration in the High Plains aquifer in the upper Arkansas River corridor from Hamilton to Ford counties (Whittemore, 2000).

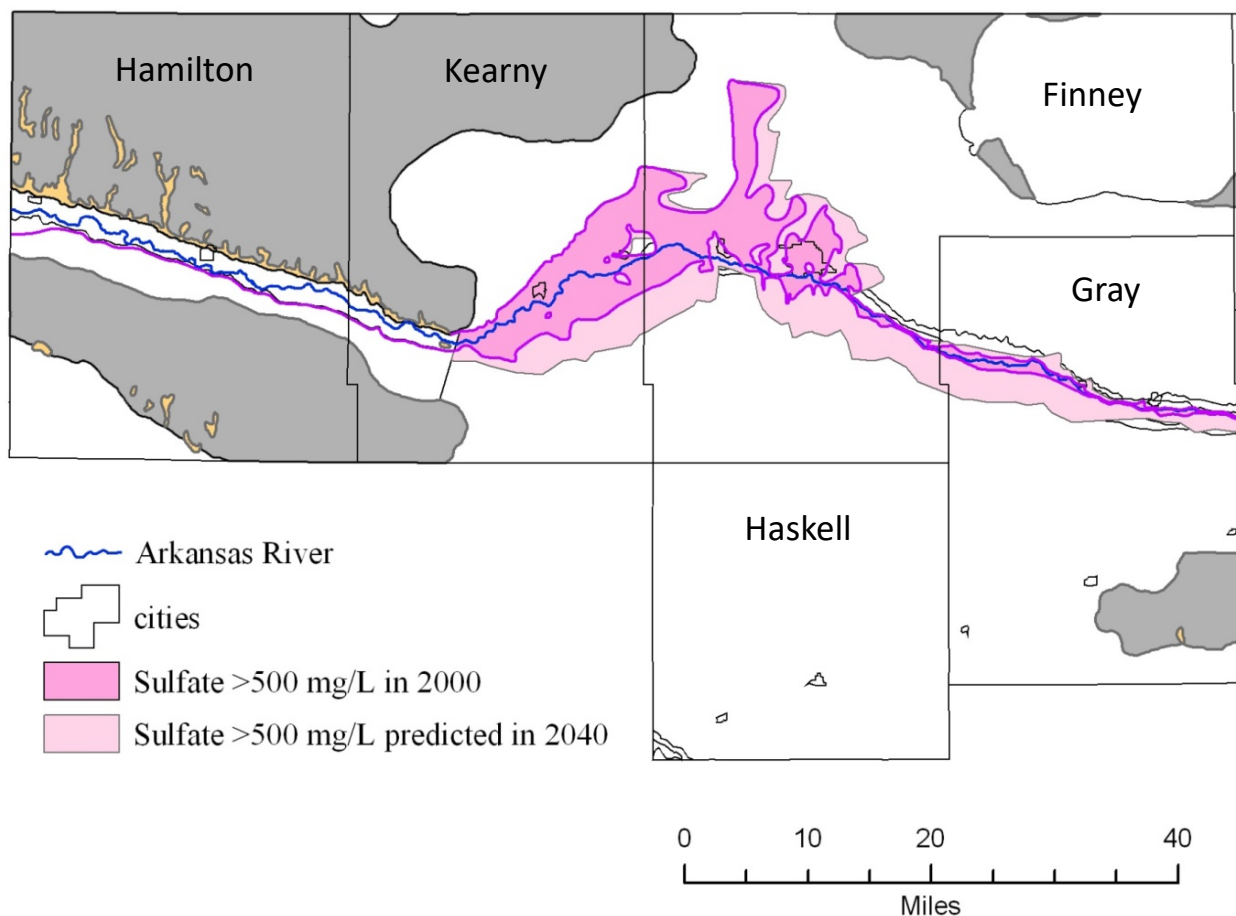


Figure 3. Prediction of migration of greater than 500 mg/L sulfate concentration area within the High Plains aquifer in the river corridor from 2000 to 2040 (Whittemore et al., 2001). Gray shaded areas have little or no saturated thickness and yellow indicates outcropping bedrock.

The KGS continued study of the Arkansas River and groundwater in the corridor after 2000. This work included a study for the U.S. Environmental Protection Agency (EPA) on uranium in the river water (for the Total Maximum Daily Load program of the KDHE, investigations under the Ogallala–High Plains Aquifer Technical Assistance program of the Kansas Water Plan for Southwest Kansas Groundwater Management District No. 3 (GMD3), and a Kansas Water Resources Institute study on uranium distribution in soils and crops irrigated with saline groundwater. The KDHE began examination of uranium in public water supplies after the EPA finalized the rule for the MCL of 30 $\mu\text{g/L}$ for public supplies of drinking water in 2003. The KDHE started monitoring uranium in the Arkansas River in southwest Kansas in 2009. The determination of uranium levels above the MCL in the Lakin public supply from the HPA in 2007 led to the construction of a treatment plant that became operational in January 2015.

Current Study

As a result of the findings of uranium exceeding the MCL in public supply systems, the KDHE, in the late summer of 2019, embarked on a program of voluntary sampling of private wells used for drinking in the area with saline water delineated in Figure 2. At the same time, the KWO requested that the KGS consider a study on the current state of mineralized groundwaters in the HPA in the river corridor, with a focus on uranium and other elements and radioactivity for which MCLs exist. The KGS prepared a scope of work for the KWO for a two-year study that included 6 objectives and 12 tasks; the project was funded under the Kansas Water Plan. The project was extended by more than a year due to the Covid-19 situation that slowed travel, affected personal contacts involved in KGS and GMD3 cooperative sampling of wells, and required remote computing that was not ideal until better communications software was installed. This report presents the results of the study. The original six objectives are listed below along with two additional objectives added to encompass all of the tasks under the project.

Study Objectives:

1. Determine the current distribution of salinity and uranium, selenium, and arsenic concentrations and gross alpha and gross beta radioactivity in groundwater of the High Plains aquifer (HPA) (including the alluvial aquifer) in the upper Arkansas River corridor from the state line with Colorado to Dodge City.
2. Compare the current chemical concentration distributions with past distribution data to determine concentration differences and spatial and temporal changes.
3. Determine the current input of chemical concentrations and loads in Arkansas River water in the river channel and major irrigation canals.
4. Assess the geographic factors controlling the chemical concentration distributions and changes in time, including distance from the Arkansas River channel and major irrigation canals, and the area underlying historic and current ditch irrigation areas.
5. Assess the vertical lithologic controls on the chemical concentration distributions, including depth to sampling intervals and the distribution of thick clay layers based on lithologic information in well logs.
6. Assess hydrogeochemical factors controlling the chemical concentration distributions, including precipitation of sulfate minerals in irrigated soils and adsorption of uranium, selenium, and arsenic on sediment surfaces during transport in groundwater flow, both of which can alter uranium/sulfate ratios in the groundwater.
7. Estimate the future accumulation and redistribution of salinity, uranium, and other contaminants of concern in the study area as implied by the data and information obtained from the above objectives.
8. Communicate the results of the study to state and local agencies and the public.

Results and Discussion for Objectives

Objective 1: Determine distributions of salinity, uranium, and other constituents in the High Plains aquifer in the upper Arkansas River corridor

Tasks 1 and 2: Sample collection and analysis

We used two primary datasets to address the study objectives. The first is the dataset generated from the 2019 KDHE voluntary private wells sampling campaign. In August 2019, surveys were sent to landowners in Finney and Kearny counties to solicit samples of domestic well water and corresponding information about the well. The deadline for sample submission was December 2019. The KDHE received 247 samples that were subsequently analyzed for a suite of chemical parameters, including (1) concentrations of sulfate, uranium, nitrate, chloride, arsenic, selenium, iron, and manganese, (2) specific conductance, and (3) gross alpha and beta radiation.

The KGS received the chemistry data from the KDHE in March 2020 and reviewed it to remove a duplicate sample record and one with an analysis that had an unrealistically low dissolved solids content that indicated that the water was not natural but treated such as by reverse osmosis. We combined the chemistry data from the 245 remaining wells with existing KGS well water databases to build a robust database of well chemistry and relevant hydrogeologic information. We cross-referenced the KDHE private well sampling campaign database with the KGS WWC5 database to obtain (where records existed) additional information (to that already entered by the KDHE) on well age, screened intervals, construction type, and gravel pack and grout intervals. We also used location information from the WWC5 database and satellite imagery to improve the accuracy of location estimates (latitude and longitude of the wells), which is critical for accurate contouring and assessment of spatial patterns. Using well depth information for those wells with well logs (obtained from the WWC5 database) and location relative to hydrogeology (aquifer thicknesses and typical wells in the area, particularly important for those wells without logs), we classified the aquifer source as either the Dakota aquifer (n=18 samples), High Plains aquifer (n = 219 samples), Dakota and/or alluvial aquifer (n = 4 samples), or alluvial aquifer (n = 4 samples). In this study, we focused on wells in the alluvial and High Plains aquifers.

In addition to the KDHE private well sampling, we leveraged data from studies conducted by the KGS during 2009–2015. One set of studies was for GMD3, conducted under the Ogallala–High Plains Aquifer Technical Assistance program funded by the Kansas Water Plan. These studies involved samples collected by GMD3 from domestic, municipal, irrigation and stock wells located in the Dakota and High Plains aquifers. Another study, funded by the Kansas Water Resources Institute, focused on the fate of uranium in soils and crops and included groundwater sampling of irrigation wells in the HPA. When combined with information from the KDHE voluntary sampling campaign and the samples collected by the KGS and GMD3 for this project during 2020–2022, these datasets provide information about the current chemical distribution within the upper Arkansas River corridor (objective 1) and can be compared with baseline data from the late 1990s (from the Upper Arkansas River Corridor Study described above) to address objective 2 (determining changes between past and current chemical distributions).

The data collection during this current KGS study for the KWO involved identifying areas where additional well sampling was needed to supplement the domestic well samples obtained by the KDHE in 2019 and recent (2009–2015) samples from different well types obtained by the KGS/GMD3. The sampling included a total of 103 domestic, municipal, irrigation, stock, and observation wells from the HPA to better characterize the groundwater quality in the study area.

The focus was on the High Plains aquifer. To select wells to be sampled, we prepared initial maps using the KDHE and recent KGS well water data to determine where gaps were located that would be priority locations for well selection and provided these lists of different well types to be sampled by GMD3. GMD3 sampled 50 domestic (one of which was industrial/domestic), 18 municipal/public water supply, 20 irrigation, and 5 stock wells during 2020–2022. The KGS sampled 11 wells at the three multilevel observation well sites (at Deerfield, Garden City, and near Dodge City) installed in the HPA during 1997 and 1998 as a part of the Upper Arkansas River Corridor Study for the KWO. The KGS was able to sample all five observation wells at the Deerfield site but only three out of the five wells at the Garden City site and three out of the four wells at the Dodge City site; the groundwater levels had dropped below the well depths of the two shallowest wells at Garden City and the shallowest well at Dodge City.

This study also included sampling of the Arkansas River at irrigation canal headgates or at major points along the canals to supplement prior data of the KGS and KDHE for river water. GMD3 collected 11 samples during 2019–2022, all of which were analyzed by the KGS and 8 of which were also analyzed by the KDHE laboratory.

The study contract with the KWO called for collecting at least 100 total samples; 107 well and 11 river water samples (for a total of 118 samples) were collected and analyzed. Three of the observation wells at the Deerfield site were sampled at different times about a half year apart, so the total number of different wells sampled was 104. One of the domestic wells sampled by GMD3 was constructed in the Dakota aquifer and was a replacement of a previous HPA well that had produced saline water. Thus, the number of wells in the HPA was 103. The ranges of the number of wells to be sampled as anticipated in the contract was 30–40 domestic, 25–30 municipal, 5–10 stock, 5–10 irrigation, and 14 monitoring wells; at least 10 river or irrigation canal samples were to be collected. The actual number of different types of wells sampled was adjusted during the study to better fit the distribution of locations that would fill in gaps in the areal distribution. The final numbers for the types of wells sampled were greater than anticipated for domestic and irrigation wells, within the range for stock wells, and less than anticipated for municipal and monitoring wells; the number of river or canal samples slightly exceeded the anticipated number. As indicated above, three of the monitoring wells could not be sampled because the water level was below the well depth.

Samples were collected in 1 L bottles for the KDHE laboratory and 500 mL bottles for the KGS laboratory and placed in ice chests for preservation before transfer to the laboratories. The KDHE measured specific conductance and concentrations of chloride, sulfate, nitrate, uranium, selenium, arsenic, iron, and manganese. Although the KWO contract indicated that radium and gross alpha radioactivity would be determined by the KDHE, based on the low values of radioactivity in the results for the KDHE voluntary sampling program for private wells and the first 16 well samples from the KGS study, the KDHE did not determine radium concentration and discontinued analyses for gross alpha radioactivity for the rest of the samples. Thus, these radioactivity-related parameters are not discussed in this report. The KGS determined specific conductance and alkalinity and concentrations of calcium, magnesium, sodium, potassium, strontium, silicon, boron, chloride, sulfate, nitrate, fluoride, and bromide. The chemical data obtained in both the KDHE private well study and this study are provided in spreadsheets available on the project website.

Summary of Results for Groundwater Samples

Table 1 summarizes key parameters of the analyses of waters sampled from the alluvial aquifer or the HPA related to drinking water quality standards for both the KDHE voluntary private well study and the current study arranged by well type, including the number and percentage of samples that exceeded secondary and primary standards for drinking water. As indicated earlier, a total of 219 of the 245 wells sampled in the KDHE private well study were screened in the HPA, 4 wells were completed in the Arkansas River alluvial aquifer, and 4 wells were installed in either the alluvial aquifer or the Dakota aquifer or in both (3 of these wells had no well log, so it was unclear as to which aquifer they represented). The alluvial and potentially or partly alluvial wells in the KDHE study were included with the 219 HPA wells in the KDHE study. Accordingly, Table 1 presents the results of analyses for 227 wells in the KDHE study. A total of 103 of the 104 wells sampled in the current KGS investigation were completed in the HPA; the other well was installed in the Dakota aquifer.

The salinity of the groundwaters in the alluvial aquifer and the HPA in Table 1 ranged substantially from fresh to appreciably saline. The chemical water type is mixed cation-sulfate; the sulfate concentration is typically more than 7 times the chloride concentration in most of the groundwaters and can be about 14 times the chloride concentration in the most saline waters. Most of the wells sampled exceed the secondary (recommended) standards for total dissolved solids and sulfate concentrations for drinking water; 61% of the domestic wells in the KDHE private well study and 88% of the wells in the current KGS study exceeded the secondary standard for sulfate. The primary reason for the greater percentage in the current study is that the focus was on sampling wells in the high salinity and uranium areas shown by previous KGS studies and the KDHE private well study. None of the samples in the KDHE private well study and only about 2% of the well waters sampled in the current study exceeded the secondary standard for chloride concentration.

About 15% of the samples from the alluvial aquifer and the HPA in the KDHE private well study and approximately 5% of the well waters sampled from the HPA in the current KGS study exceeded the MCL for nitrate-nitrogen concentration (Table 1). None of the samples in the current study exceeded the MCL for fluoride concentration; fluoride was not determined in the KDHE private well study. Only one sample out of the 227 wells sampled in the KDHE study exceeded the MCL for arsenic and none exceeded the MCL in the current KGS study. Five samples (approximately 2%) exceeded the MCL for selenium in the KDHE private well study, and only one exceeded the selenium MCL in the current KGS project. Nearly 18% of the waters in the KDHE study exceeded the uranium MCL, and almost half of the wells in the KGS study exceeded the uranium MCL (Table 1). Again, the main reason for the higher percentage in the KGS study is that the focus of the project was on sampling wells in the high salinity and uranium areas to better define those zones. The percentages of samples with uranium above the MCL from domestic, irrigation, stock, and irrigation wells were all relatively high in the KGS study; the percentage was the lowest for the public water supply wells sampled.

Table 1. Summary of groundwater chemistry for all wells in the KDHE voluntary and KGS mineralization studies that yielded water from the alluvial aquifer or HPA relative to secondary and primary standards for drinking water and categorized according to different well types. SS = secondary (recommended) standard; MCL = maximum contaminant level (primary standard) for public supplies of drinking water. For the current study, KGS analyses are used for conductance through fluoride values and KDHE analyses are used for arsenic, selenium, and uranium values.

Property or constituent	SS or MCL		KDHE Voluntary Private Wells	KGS Mineralization Study				
		Well type	Domestic	Domestic	Public water supply	Irrigation	Stock	Observation
		Number of wells	227	49	18	20	5	11
Specific conductance		Range, $\mu\text{S}/\text{cm}$	380–3,800	437–4,650	400–2,870	1,553–4,200	1,048–3,280	485–3,660
Total dissolved solids	SS 250 mg/L	Range, mg/L	n.d. ¹	278–3,880	242–2,290	1,107–3,300	692–2,560	298–2,910
Chloride	SS 250 mg/L	Range, mg/L	4.1–250	6.9–326	4.2–178	65.6–259	30.8–152	12.9–135
Sulfate	SS 250 mg/L	Range, mg/L	19–1,900	43.8–2,330	24.3–1,361	547–1,885	306–1,533	42.9–1,796
Nitrate-nitrogen	MCL 10 mg/L	Range, mg/L	<0.5–38	0.02–24.6	2.1–9.6	0.90–12.0	3.4–7.8	2.1–8.2
		No. >MCL	34	3	0	2	0	0
		% >MCL	15.0	6.1	0	10.0	0	0
Fluoride	MCL 4 mg/L	Range, mg/L	n.d.	0.16–2.08	0.17–1.08	0.29–1.71	0.43–0.74	0.17–0.63
		No. >MCL	-	0	0	0	0	0
Arsenic	MCL 10 $\mu\text{g}/\text{L}$	Range, $\mu\text{g}/\text{L}$	<1–12	<1–9.4	<1–3.8	<1–7.4	<1–3.1	<1–1.8
		No. >MCL	1	0	0	0	0	0
		% >MCL	0.4	0	0	0	0	0
Selenium	MCL 50 $\mu\text{g}/\text{L}$	Range, $\mu\text{g}/\text{L}$	<1–97	<1–42	<1–22	4.8–69	12–29	7.2–30
		No. >MCL	5	0	0	1	0	0
		% >MCL	2.2	0	0	5.0	0	0
Uranium	MCL 30 $\mu\text{g}/\text{L}$	Range, $\mu\text{g}/\text{L}$	<2.3–120	<1–130	<1–58	12–110	13–46	4.8–61
		No. >MCL	40	25	2	14	3	6
		% >MCL	17.6	51	11.1	70	60	55

¹not determined

Only 2 of the 18 domestic wells sampled in the KDHE private well study that are believed to be completed only in the Dakota aquifer (11 have well logs) yielded water with more than the secondary standard for sulfate concentration in drinking water. None of these well waters exceeded the MCL for nitrate, arsenic, selenium, and uranium. The sample collected from the one domestic well screened in the Dakota aquifer in the KGS current study did not exceed any secondary or primary standards for drinking water.

Relationships of key parameters of water quality to specific conductance are a useful approach to estimating concentrations of those parameters using the simple analytical tool of conductivity. Graphs for total dissolved solids (TDS) and sulfate concentrations versus conductance for water samples from the HPA are displayed in Figures 4 and 5 based on KGS analyses from the current study. The plot of uranium concentration versus conductance for the HPA shown in Figure 6 is based on KDHE values for uranium and KGS conductance values from the current study. The very high coefficient of determination (R^2) and P value for Figures 4 and 5 indicate that both TDS and sulfate concentrations are statistically highly correlated with specific conductance, such that an accurate conductance measurement is an excellent predictor of these parameters in HPA groundwaters in the study area. Although the P value is very low for the uranium concentration versus conductance relationship (Figure 6), the low R^2 and visual scatter of the points indicates that conductance is not nearly as strong of a predictor of uranium as it is for TDS or sulfate. However, the plot indicates that if the conductance is less than about 1,400 $\mu\text{S}/\text{cm}$, the uranium concentration ought to be less than the MCL of 30 $\mu\text{g}/\text{L}$, and at a conductance greater than 3,500 $\mu\text{S}/\text{cm}$, the probability of uranium exceeding the MCL is high.

Task 3: Maps of current chemical distributions

We prepared initial maps documenting the current spatial distribution of sulfate and uranium concentrations in the HPA within the upper Arkansas River corridor based on a combination of pre-2000 sample data (for sulfate) and recent (2009–2022) KGS and KDHE sample data (for sulfate and uranium). The salinity of the aquifer water is represented by the sulfate concentration; sulfate is the constituent in highest concentration in the saline waters. The procedure involved modifying contours on the historical sulfate map (Figure 2), constructed for the HPA during the prior Upper Arkansas River Corridor Study, using recent KGS and KDHE data. The re-contouring process involved comparing the sulfate contours from the 2000 base map to the new chemistry data and then manually drawing new contours in areas where change has occurred or retaining the old contours where there are not enough recent data to justify changes. This manual re-contouring allowed for incorporation of knowledge about the location of irrigation canals, the river, and aquifer boundaries that influence the salinity distribution. Where data points for the 2000 map are close to those for 2009–2022, contouring was biased toward the more recent data. The modified contours were then traced using ESRI GIS software, followed by filling the intervals between the contours with colors similar to those in the 2000 map for the HPA (KGS Open-File Report 2000-72, Plate C). ArcMap was then used to edit the contours.

After the first version of the sulfate map was completed, data were added from the National Uranium Resource Evaluation (NURE) program of the 1970s that was initiated by the Atomic Energy Commission (now the U.S. Department of Energy) to identify uranium resources in the United States. The program included sampling and chemical analysis of groundwater. The USGS

assumed the responsibility for the data set and reformatted the data for improved accessibility (<https://mrdata.usgs.gov/metadata/nurehssr.faq.html>). The NURE database contains a total of 227 records for wells in Kearny, Finney, Gray, and Ford counties; these samples were collected during the summers of 1978 and 1979. Wells identified in the database as deriving water from bedrock aquifers (essentially all Dakota) and the alluvial aquifer of the Arkansas River were removed. The location of each of the remaining wells identified as being the Tertiary or Pleistocene aquifer (the HPA) in the database was examined relative to the boundaries of the High Plains aquifer and the depth of the well listed in the database. Thirteen of the remaining wells were removed in the area just outside or near the boundaries of the HPA because they were assessed to primarily derive water from the Dakota aquifer. The final number of wells representing water in the HPA totaled 190. Contours in the sulfate map were then adjusted using ArcMap in areas where the sulfate concentration was greater than indicated by the concentration contours in the first map version. This adjustment was based on nearly all of the NURE wells sampled being irrigation wells, which tend to be drilled into deeper parts of the aquifer, and the assumption that saline water in the deeper aquifer is not likely to have become less saline. Figure 7 shows the final version of the sulfate map.

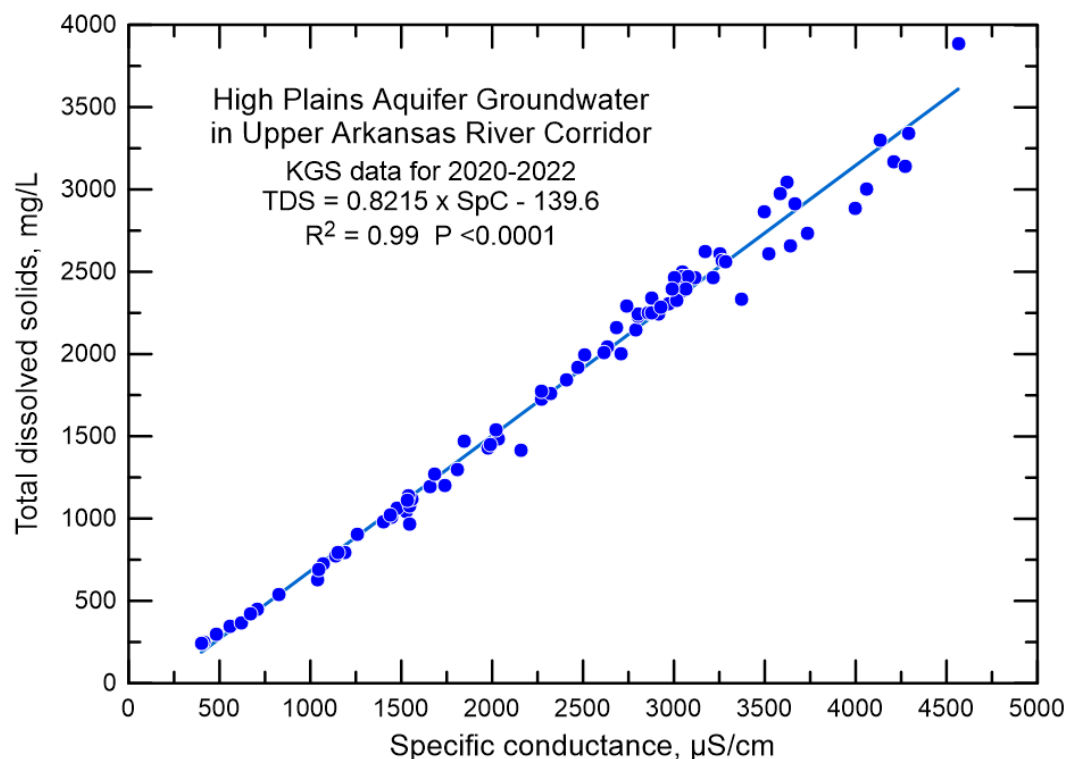


Figure 4. Total dissolved solids concentration versus specific conductance for groundwaters in the HPA based on KGS analyses from the current study.

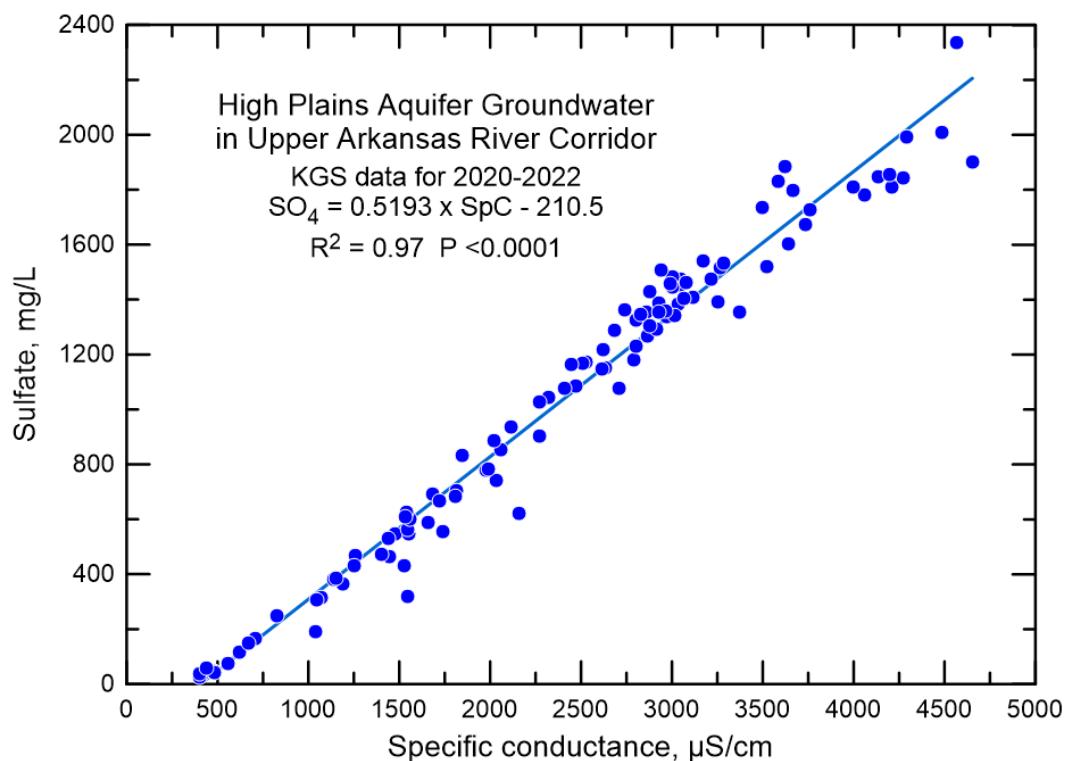


Figure 5. Sulfate concentration versus specific conductance for groundwaters in the HPA based on KGS analyses from the current study.

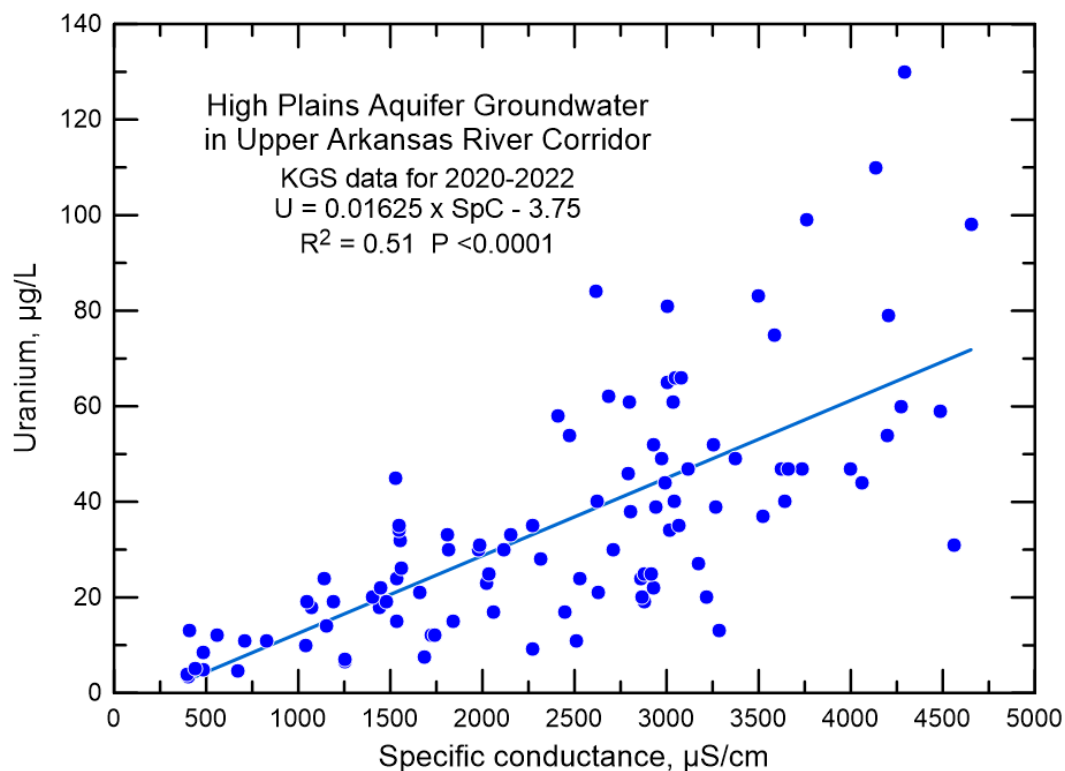


Figure 6. Uranium concentration versus specific conductance for groundwaters in the HPA based on KDHE (uranium) and KGS (conductance) analyses from the current study.

We produced a map of uranium concentration using the 2019 KDHE dataset, the existing KGS data for 2009–2015, and the 2020–2022 data from the current study (Figure 8). The map was generated using Photoshop Elements to manually draw contours on a .jpg image saved from a file produced using ESRI GIS software. These contours were then traced using ESRI GIS software, followed by filling the intervals between the contours with colors similar to those in the sulfate map. The contours were drawn manually to allow for incorporation of information about aquifer boundaries and river and canal location as was done for the sulfate distribution map. ArcMap was then used to edit the contours.

After the first version of the uranium map was completed, data were added from the NURE database as described above for the creation of the final sulfate map and from a KGS study of uranium concentrations in unconsolidated aquifers of western Kansas (Berendsen and Hathaway, 1981). The KGS study on uranium used samples collected during the 1970s for investigations of the chemical quality of irrigation wells in western and south-central Kansas. These data had already been incorporated in the values used for the 2000 map of sulfate concentration. Each of the 183 wells in Kearny, Finney, Gray, and Ford counties listed in Berendsen and Hathaway (1981) were examined to determine the groundwater source based on the aquifer identification in the KGS Irrigation Series publications for the irrigation water quality studies; wells in the alluvial aquifer and Cretaceous bedrock aquifers were removed, leaving 170 records. These samples were collected during the last week in July of 1975–1977. Contours in the uranium map were then adjusted for the NURE 1978 and 1979 and KGS 1975–1977 data using ArcMap in areas where the uranium concentration was greater than indicated by the concentration contours in the first map version. As for the sulfate map, this adjustment was based on the assumption that saline water in the deeper aquifer, as represented by irrigation wells, is not likely to have become less saline. Figure 8 shows the final version of the uranium map.

Figure 9 displays the main area of high sulfate and uranium concentration distributions in the HPA in the Arkansas River corridor. The areas of greater than 500 mg/L sulfate concentration in Figure 9a are located along the river corridor in east-central Kearny County to west-central Finney County and extend to the north between Holcomb and Garden City. Nearly all of the area with greater than 1,000 mg/L sulfate south of the river lies within the boundary of the alluvial aquifer, whereas to the north of the river this area lies both within and outside of (directly over the HPA) the alluvial aquifer. The areas of greater than 30 µg/L uranium concentration, the MCL for public supplies of drinking water, (Figure 9b) are generally distributed within the areas of greater than 1,000 mg/L sulfate, although the prong to the north of Garden City has higher uranium than would be expected based on the sulfate concentration distribution. Unlike the high sulfate area (greater than 1,500 mg/L) that is distributed both north and south of the river corridor, the areas of high uranium concentrations (greater than 50 µg/L) occur predominantly to the north of the river. The background uranium concentrations outside the contaminated area are also substantially greater north of the river (usually in the range of 8–16 µg/L) in comparison to south of the river (generally in the range of 3–6 µg/L). These higher background levels help explain the elevated uranium concentrations north relative to south of the river in the main contaminated area.

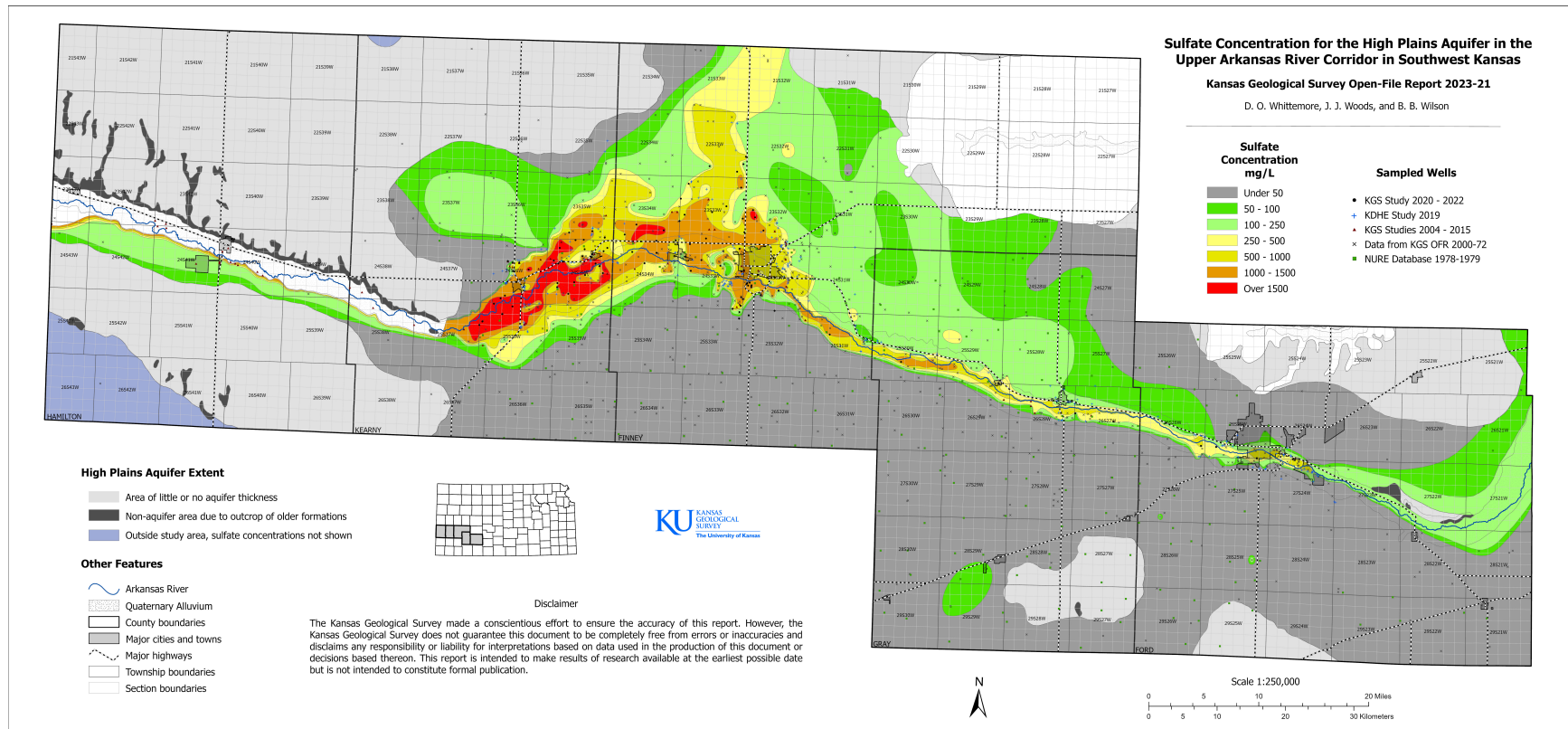


Figure 7. Distribution of sulfate concentration in the HPA in the upper Arkansas River corridor based on data used in the 2000 map for the prior Upper Arkansas River Corridor Study and data in the NURE database (1978–1979 samples), 2004–2015 KGS studies, the 2019 KDHE private well study, and the current KGS 2020–2022 project.

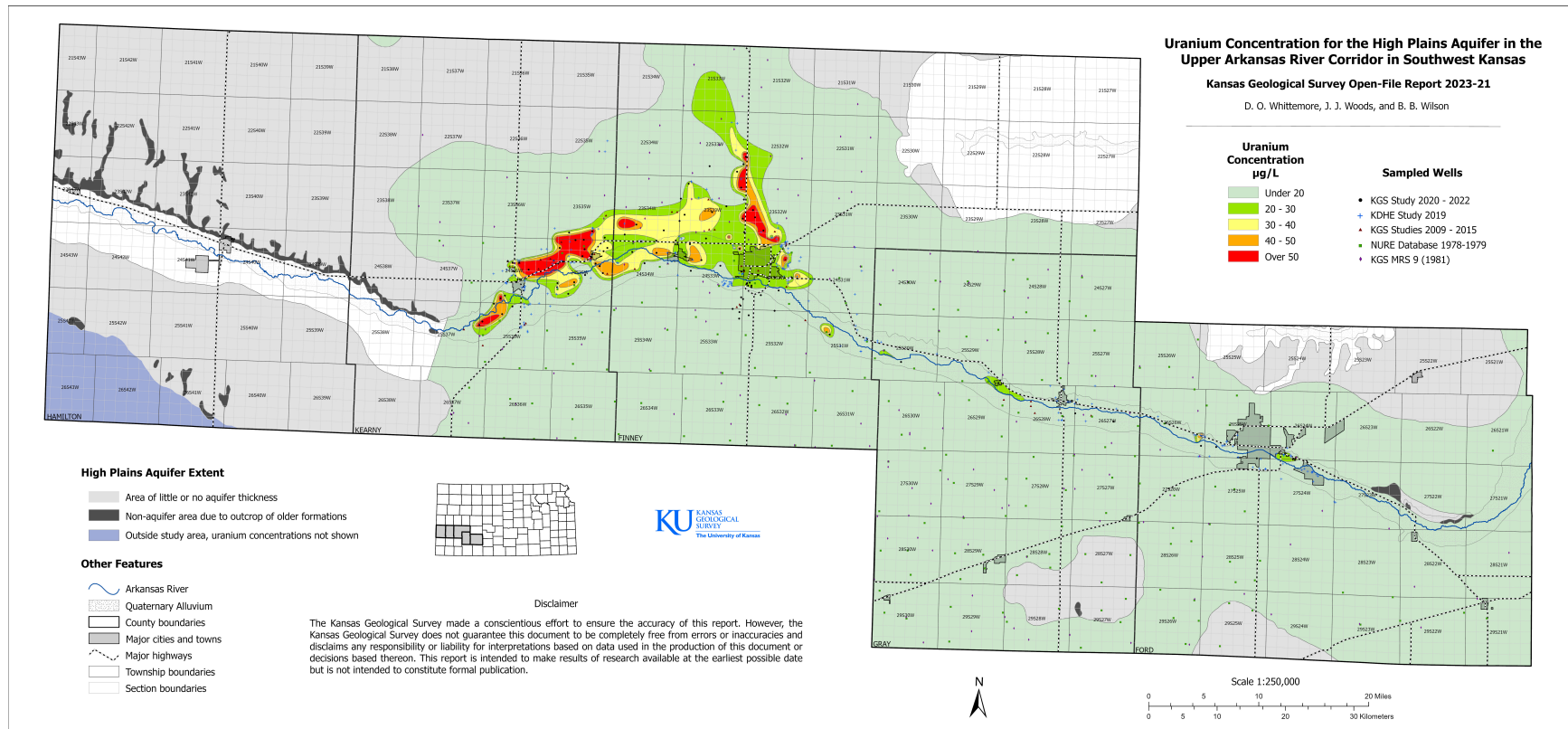


Figure 8. Distribution of uranium concentration in the HPA in the Upper Arkansas River corridor based on data from KGS studies for 1975–1977 samples (Berendsen and Hathaway, 1981), the NURE database (1978–1979 samples), 2009–2015 KGS studies, the 2019 KDHE private well study, and the current KGS 2020–2022 project.

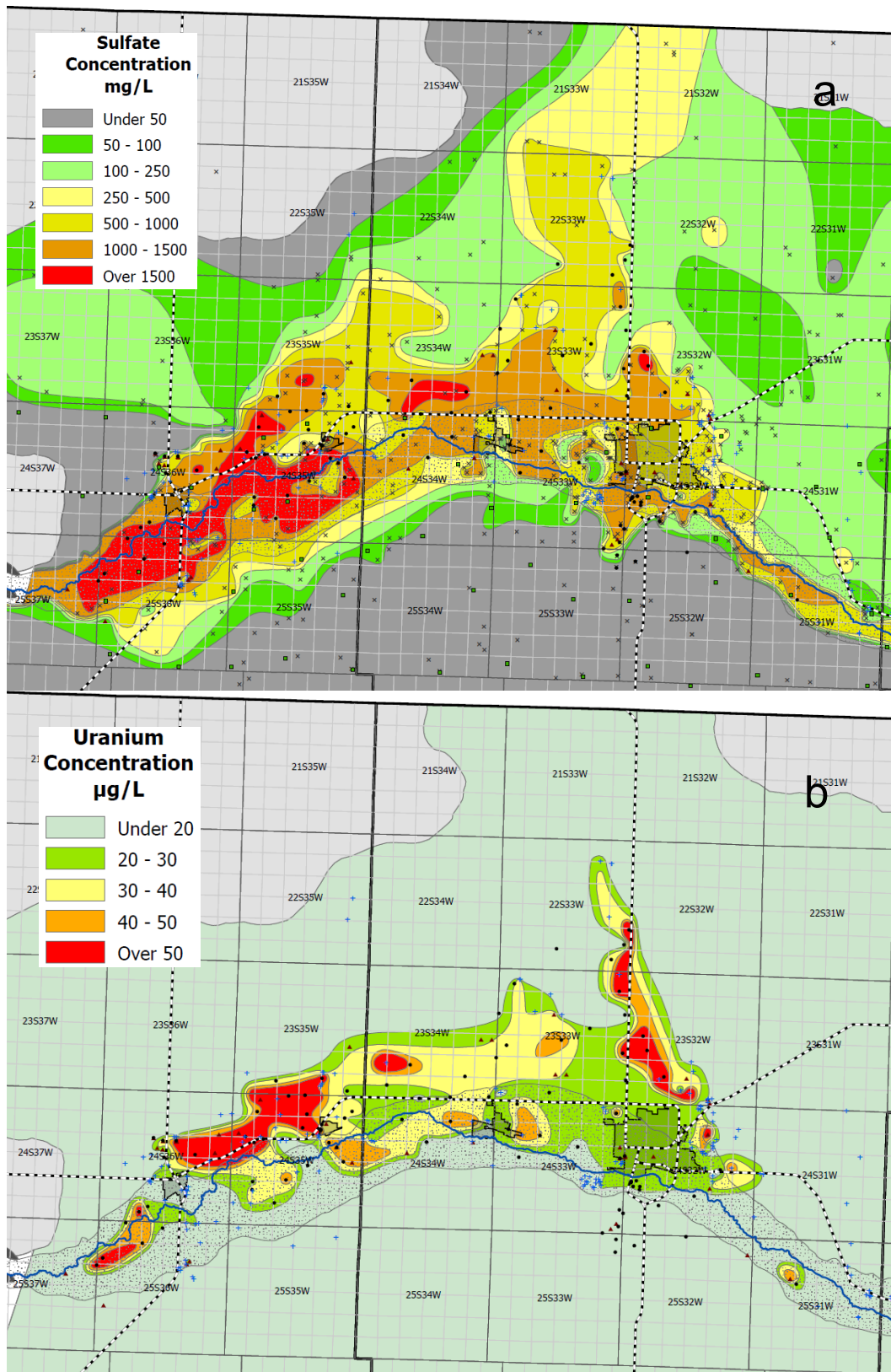


Figure 9. Main map area of (a) high sulfate and (b) high uranium concentrations in eastern Kearny and western Finney counties. The Arkansas River is the dark blue line.

Objective 2 (Task 4): Determine changes between current and past chemical distributions

We compared the distribution of sulfate concentration in the HPA displayed in Figure 7 with the distribution in the 2000 map (Figure 2). Sulfate concentration increased in the core areas of saline aquifer water such that a new contour interval (greater than 1,500 mg/L) was warranted in Figure 7. The additional sampling locations resulted in more complex contours indicating substantial spatial heterogeneity in the areal sulfate distribution.

Figure 10 shows an enlarged portion of the sulfate concentration map of 2000 (Figure 2) and the same portion of the updated (2022) map that covers the main area of greater than 1,500 mg/L concentration in east-central Kearny County. The current high concentration area is distributed both north and south of the Arkansas River, as well as north of the alluvial aquifer boundary to the north of the river. The high sulfate concentration area in Figure 10 is located in the historic parts of the service areas of the South Side ditch, southern portion of the Amazon ditch, and westernmost parts of the Great Eastern ditch (Figure 1). As a result of canal leakage and return flow in the ditch irrigation area, a large portion of the HPA in 2000 had sulfate concentration greater than 1,000 mg/L interval. Although a few wells in the greater than 1,000 mg/L interval sampled before 2000 yielded water with sulfate concentration greater than 1,500 mg/L in the area of Figure 10a, the additional wells with greater than 1,500 mg/L sulfate content based on the 2009–2022 data justified adding the interval of greater than 1,500 mg/L. The closely spaced, wavy concentration contours in the northwest portion of the images in Figure 10 represent the location of the Amazon Canal. Because the subregional groundwater flow direction is generally to the east, seepage from the earthen canal infiltrated to the groundwater in this area and migrated eastward. Seepage from the Arkansas River channel and alluvial aquifer and infiltration of irrigation return flow from HPA groundwater pumped from below the river valley is also expected to have contributed to the salinity.

The updated distribution of sulfate concentration (Figure 7) shows some of the predicted salinity migration displayed in Figure 3 in the area from Kearny County to just to the east of Garden City in Finney County but not in the river corridor farther east of Garden City in Finney County and in Gray and Ford counties. For example, the band of salinity extending to the north in Finney County has expanded as predicted. The model used to generate Figure 3 incorporated greater flow of the Arkansas River than what has occurred. When the model was made in 1999 and 2000, the river was flowing all through western Kansas. Because no substantial river flow has extended beyond Garden City since 2001, the predicted migration of salinity to south of the river valley downstream of Garden City has not occurred. The general change in the sulfate concentration illustrated in Figure 7 is not as much the lateral migration but the increase in concentration in the main contaminated area of eastern Kearny and western Finney counties.

Figure 11 shows the spatial distribution of uranium over the same enlarged portion of the map of Kearny and Finney counties as in Figure 10. As indicated earlier, the areas of highest uranium concentrations (greater than 50 µg/L) occur mainly to the north of the Arkansas River, whereas the high sulfate area (greater than 1,500 mg/L) is distributed both north and south of the river. However, the main area of high uranium concentration covers part of the area with greater than 1,000 mg/L sulfate concentration to the north and northeast of Lakin. Many of the wells for which 1978 and 1979 NURE data and 1975–1977 KGS data exist in the main areas of uranium

contamination had lower concentrations than for samples collected during 2009–2022. Just as for sulfate concentration, this indicates the increase in uranium concentration in the river corridor. The difference in uranium and sulfate concentration distributions is discussed further in the Objective 4 section of this report on geographic factors controlling chemical distributions and temporal changes.

Objective 3 (Task 5): Determine chemical concentrations and loads of Arkansas River water into the study area

Chemical loads of uranium in the Arkansas River entering Kansas from Colorado were estimated using KGS and KDHE water-quality data for samples collected from the Arkansas River and U.S. Geological Survey (USGS) specific conductance and flow data for the stream gaging station at Coolidge near the Colorado-Kansas state line. The USGS monitors both flow and conductance at the station and reports values at 15-minute intervals. Figure 12 is a plot of uranium concentration versus specific conductance measured in the laboratory by the KGS and KDHE for river water samples collected from Coolidge to the Amazon canal headgate during 2009–2022. The correlation between uranium and conductance is statistically highly significant based on best-fit lines for both linear ($R^2 = 0.85$) and power functions ($R^2 = 0.92$). The power function in Figure 12 was used to estimate the mean uranium concentration for each day in a year based on the mean daily specific conductance for the USGS gaging station. The uranium load for each day was calculated by multiplying the mean uranium concentration times the mean daily flow; the load for a year was computed by summing the values for each day.

Uranium loads, along with mean annual flows and uranium concentrations, of the Arkansas River entering southwest Kansas are listed in Table 2 for 2012–2021. As expected, the mean annual uranium concentration decreases with increasing flow from release of water from John Martin Reservoir in eastern Colorado that has been affected by rainfall runoff and snowmelt and from dilution by rainfall runoff into the river downstream of the reservoir. Although the mean annual uranium concentration varies substantially from year to year (50–75 $\mu\text{g/L}$), the variation in annual load (1.6–9.1 metric ton) is much greater due to the even larger variation in year-to-year mean flow (26.9–235 ft^3/sec).

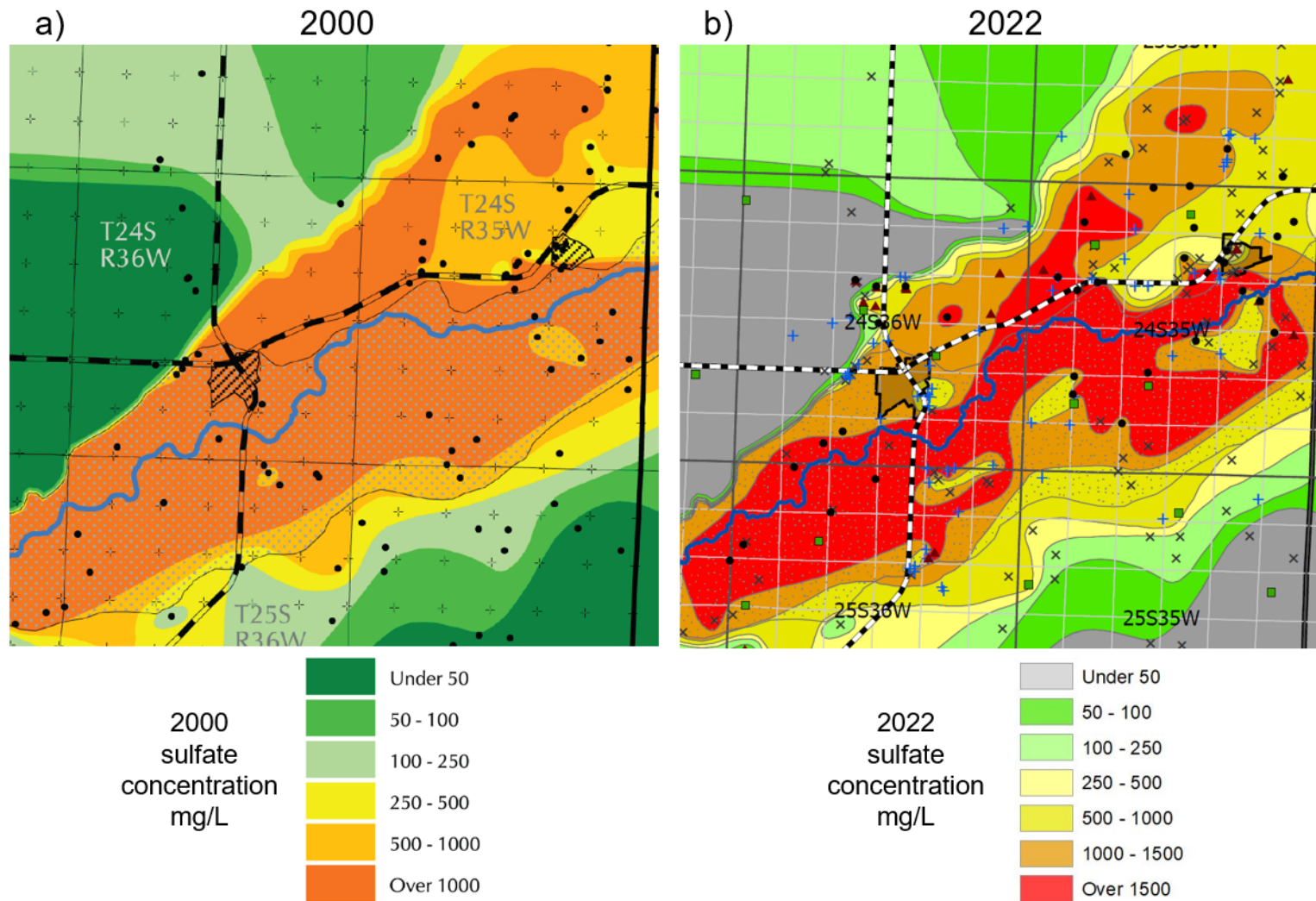


Figure 10. (a) Portion of the sulfate concentration map for the HPA for 2000 (Figure 2) and (b) the same area from the updated map (Figure 7) that includes the main area of greater than 1,500 mg/L concentration in east-central Kearny County. The thick blue line is the Arkansas River. The area of the alluvial aquifer overlying the HPA is denoted by the stippled area with a black border. The cities of Lakin and Deerfield are in T24S-R36W and T24S-R35W, respectively. The sampled well locations in (a) are black circles and in (b) are listed in the legend of Figure 7.

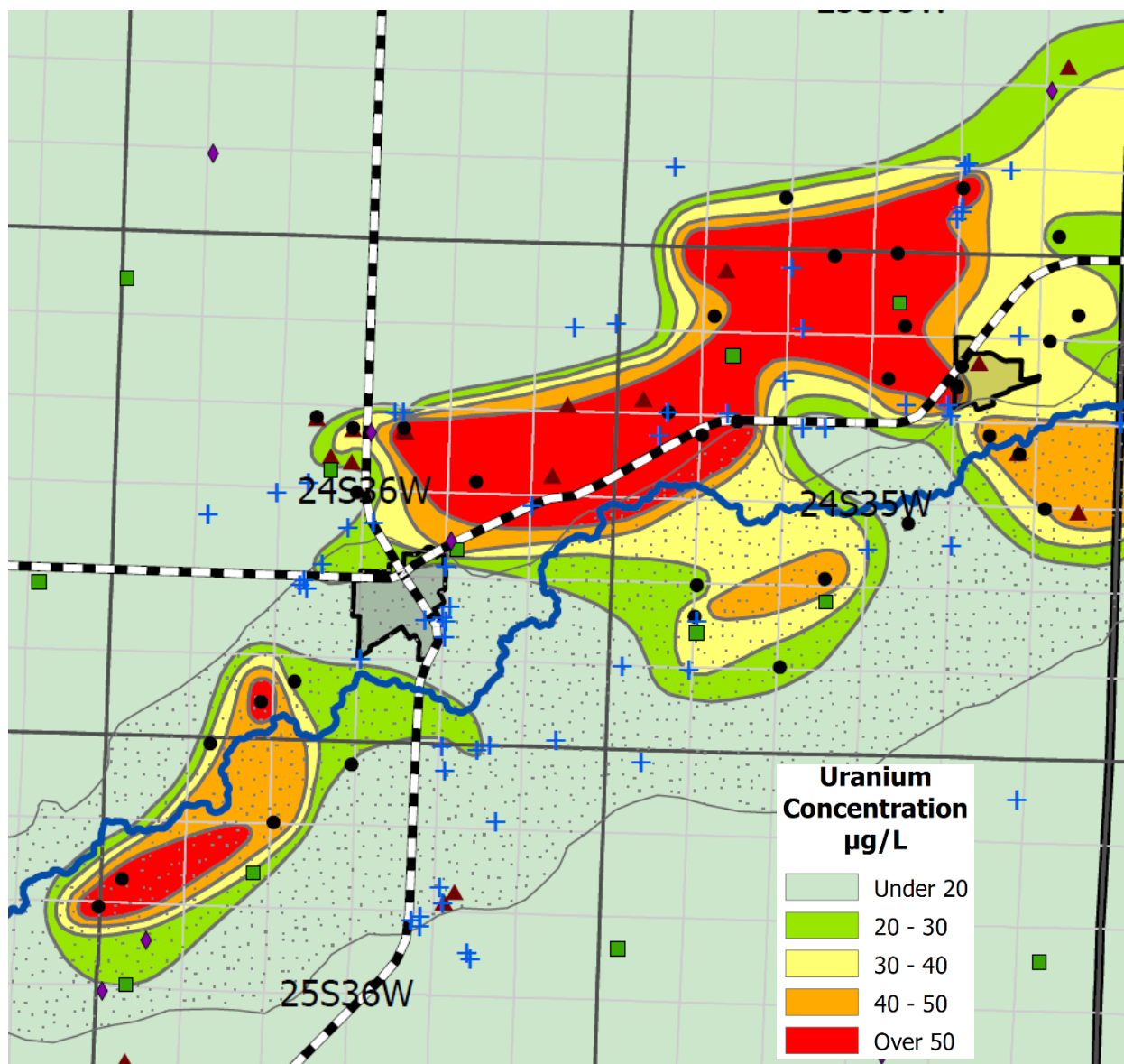


Figure 11. Portion of the uranium concentration map (Figure 8) covering the same area as shown in Figure 10. The map features are described in the caption for Figure 10 and the sampled well locations are identified in the legend of Figure 8.

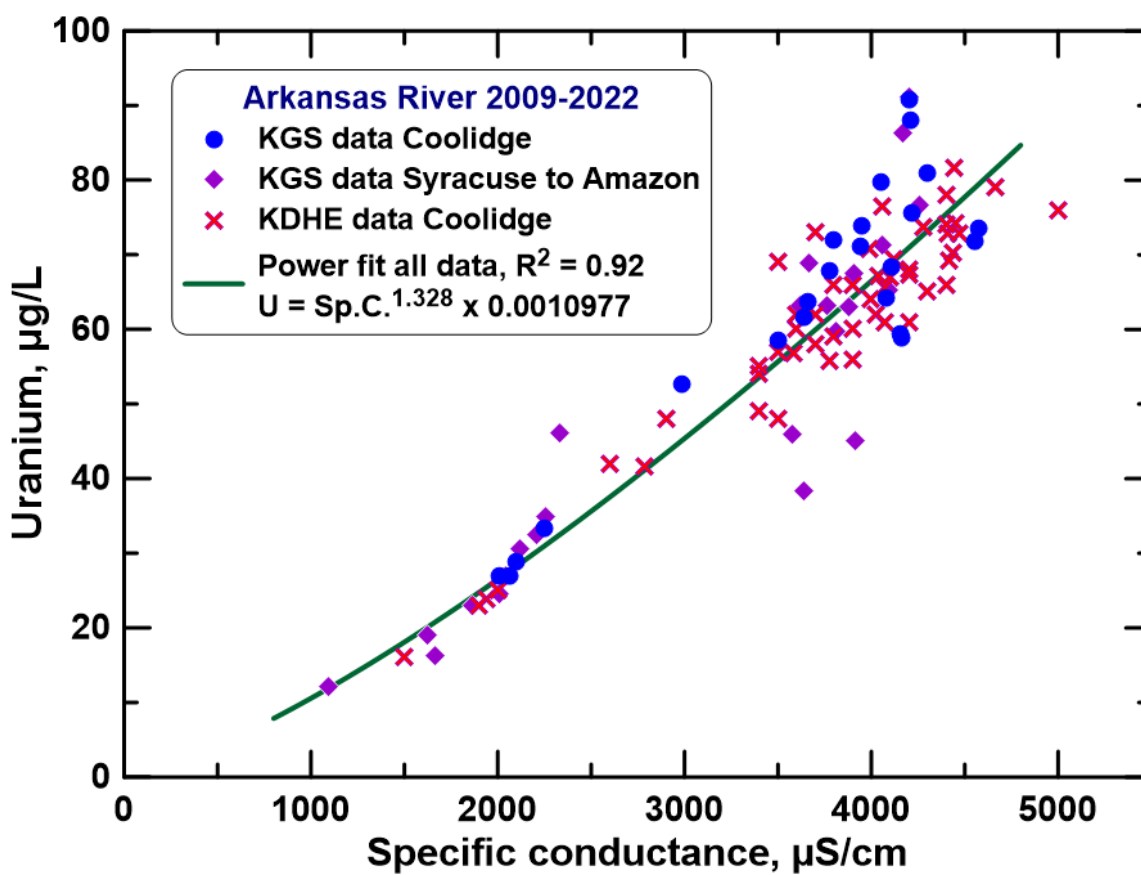


Figure 12. Uranium concentration versus laboratory specific conductance for water samples collected from the Arkansas River from Coolidge to the Amazon canal during 2009–2022 and analyzed by the KDHE and KGS.

Chemical loads and flows in the Arkansas River do not usually change substantially from the Colorado-Kansas state line (Coolidge) downstream to the headgate of the Amazon canal because the river channel is located within a floodplain underlain by alluvium resting on bedrock in a paleovalley, i.e., the alluvial valley is not underlain by the HPA. River flow can decrease downstream from the state line when the flow is rising because river water enters the alluvial aquifer (bank storage) and can increase downstream from groundwater discharge into the river during the recession of higher flow. These flow changes can cause some decrease and increase, respectively, in the chemical load. The groundwater in the alluvium is very saline (see Plate C for the alluvial aquifer in Whittemore, 2000 (KGS Open-File Report 2000-72, https://www.kgs.ku.edu/Hydro/Publications/2000/OFR00_72/plate_c.pdf); therefore, groundwater discharge into the river does not appreciably affect the river water salinity in most instances.

Table 2. Mean annual flow and uranium concentration and annual uranium load for 2012–2021 for the Arkansas River near the Colorado-Kansas state line.

Year	Mean annual Sp.C., μS/cm	Mean annual uranium concentration, μg/L	Mean annual flow, ft ³ /sec	Annual uranium load, metric ton/yr	Annual uranium load, ton/yr
2012	4,271	72.5	28.7	1.79	1.97
2013	4,395	75.3	26.9	1.60	1.77
2014	3,813	62.4	92.1	3.76	4.14
2015	3,230	50.0	196.1	6.02	6.64
2016	3,285	51.2	201.5	7.47	8.23
2017	3,324	52.0	234.6	9.09	10.02
2018	3,409	53.8	206.6	8.41	9.27
2019	3,401	53.6	186.2	7.44	8.20
2020	3,641	58.7	106.9	4.82	5.32
2021	3,564	57.0	91.9	3.90	4.30

As stated earlier, the main ditch irrigation areas are in Kearny and Finney counties and are fed by the Amazon, Great Eastern, Garden City, and Farmers canals on the north side of the river and the South Side canal to the south of the river (Figure 1). These canals divert the chemical loads in the river onto fields overlying the HPA. Out of the eleven surface water samples collected during the study, two were at the Amazon headgate during 2019 and 2020, four at three different locations near the start of the Great Eastern canal (where water from the Amazon canal is diverted into the Great Eastern canal or into Lake McKinney and thence to the Great Eastern) in 2021, and three at the Farmers canal headgate in 2021 (Table 3).

Arkansas River flow was being diverted at the Amazon headgate on August 6, 2019, when Kansas called for water from the John Martin Reservoir in Colorado, as indicated by the higher flow of 522 ft³/sec near Coolidge and the Colorado-Kansas state line. However, although online data for the National Water Information System of the U.S. Geological Survey indicated that discharge data are available, only gage height data are listed for the date. The estimated uranium concentration in the diverted river water is 29 μg/L (Table 3), just below the uranium MCL of 30 μg/L. Water was not being diverted into the Amazon canal on September 4, 2020, when the estimated uranium concentration was 66 μg/L. The uranium contents of the water carried by the Amazon ditch where water was diverted into the Great Eastern ditch and in the Great Eastern ditch below the Amazon ditch and the Lake McKinney dam during July 2021 were in a narrow range (34–35 μg/L), values greater than the uranium MCL. Headgate flow data are available for the Farmers ditch for the dates during which samples were collected during late June to mid-July 2021 (Table 3). The uranium concentration was substantially above the MCL during the initial diversion, dropped to 29 μg/L (just below the MCL), and then rose to 37 μg/L during the latter part of the diversion. The change in flow at the Farmers headgate and in the river near Coolidge for the same dates (as well as for the Coolidge flows for the Amazon/Great Eastern sample dates in Table 3 during July 2021) give a general idea of the call for irrigation water from Colorado during summer 2021. Uranium loads in the irrigation water diverted from the Farmers ditch

during the peak of the diversion were three to four times as great as in the early and later stages of the summer diversion.

Objective 4 (Task 6): Assess geographic factors controlling chemical distributions and temporal changes

The difference in the geographic distribution of the high uranium concentration compared to that for sulfate concentration in east-central Kearny to west-central Finney counties is discussed under Objective 2 (Task 4). Possible reasons for the high uranium only on the north side of the river (compared to high sulfate on both sides of the river) include proximity to the river channel and major canals, the historic amount of ditch water applied to the different areas, the depth to the water table and its changes with time, the lithology of the aquifer, and the direction and rate of groundwater flow. For example, saline Arkansas River water has substantially increased the salinity and uranium concentration in the alluvial aquifer for likely more than a century due to stream-aquifer interactions. The major impact of the infiltration of saline, alluvial groundwater to the underlying HPA is expected to have started when groundwater levels in the HPA dropped below the base of portions of the alluvial aquifer in the mid-1970s. The greater decline in groundwater levels south of the river compared to north meant that saline water on the south side of the river flowed away from the river faster than on the north side (see, for example, Figure 3). During this flow, sulfate concentration would act primarily conservatively, meaning that its concentration would be mainly affected by the amount of fresher aquifer water with which it mixed. Uranium, however, could be adsorbed during the groundwater flow.

On the north side of the river, the greater amount of ditch irrigation water and greater density of canals crossing the area, as well as the shallow reservoir storage of river water in Lake McKinney, fed more seepage water to the aquifer than south of the river. Water tables in the area north of the river have been generally shallower than to the south of the river. Adsorption of uranium in the unsaturated zone and in the upper aquifer would have occurred in the earlier history of the infiltration and may have saturated enough of the adsorption surfaces to allow more of the uranium to increase the groundwater concentration in the aquifer. In addition, the background salinity and uranium concentration in the HPA are greater north in comparison to south of the river. This is related to the geologic leaching of Cretaceous bedrock in central and northern Kearny County to the west and northwest of the high salinity and uranium area, where the HPA depths to bedrock are shallow.

Table 3. Location and selected flow and chemical data for samples collected from the Arkansas River and major irrigation canals during the study. All locations are in Kearny County and all samples were collected by GMD3. Specific conductance (Sp.C.) and sulfate concentration values are from analyses completed by the KGS, and uranium concentration values are from analyses completed by the KDHE. The first three uranium concentrations (in parentheses) were estimated from a sulfate and uranium correlation for the river.

Location description	Township-Range-Section (legal location)	Sample date	Sample time	Flow at headgate ft ³ /sec	Flow at Coolidge ft ³ /sec	Flow at Deerfield ft ³ /sec	Sp.C. μ S/cm	SO ₄ mg/L	U μ g/L	U load kg/sec
Amazon ditch headgate	25S-38W-12BBAB	8/6/2019	14:20	na	508	25.6	2,216	957	(29)	
Deerfield bridge	24S-35W-14ACB	4/1/2020	16:30		75.6	49.0	4,572	2,111	(69)	96
Amazon ditch headgate	25S-38W-12BBAB	9/4/2020	17:15	na	35.5	0	3,866	2,021	(66)	
Amazon ditch at Great Eastern diversion	24S-35W-06ABCB	7/16/2021			288	~2	2,366	1,067	34	
Amazon ditch at Great Eastern diversion	25S-38W-12BBAB	7/27/2021	13:00		321	0	2,400	1,097	34	
Farmers ditch headgate	24S-35W-12DACD	6/25/2021	10:30	11.2	172	23.6	2,692	1,279	43	13.6
Farmers ditch headgate	24S-35W-12DACD	7/8/2021	9:50	46.3	343	65.0	2,127	928	29	38.0
Farmers ditch headgate	24S-35W-12DACD	7/14/2021	15:00	8.39	286	14.8	2,840	1,321	37	8.79
Great Eastern ditch below dam	24S-35W-08BDCC	7/14/2021	16:00		288	14.8	2,406	1,103	35	
Great Eastern ditch below Amazon ditch	24S-35W-06ABCB	7/27/2021	13:30		321	0	2,398	1,104	34	
Lakin river bridge	24S-36W-34ACAD	4/21/2022	10:30		21.5	0	4,427	2,141	60	

na = not available

A zone of high salinity and uranium concentration in the HPA was delineated along the depression called the White Woman Bottoms and extends from the east side of Garden City about 12 miles to the north-northwest (Figure 13). Berendsen and Hathaway (1981) had previously mapped a general trend of higher uranium concentration in this area based on a much smaller distribution of well data. Figure 13 displays the uranium concentration that exceeds 50 $\mu\text{g/L}$ in parts of the zone; a few well locations in these areas yield water with near or greater than 100 $\mu\text{g/L}$, which is more than three times the MCL for public supplies of drinking water. White Woman Bottoms is a shallow depression that extends from northwest Finney County to the Arkansas River, the general zone of the depression starts from the White Woman basin in south-central Scott County where natural groundwater uranium concentrations are relatively high and exceed the MCL in parts of the center of the basin. The highest uranium concentrations in the area shown in Figure 13 are in the main part of the White Woman Bottoms as labeled on the USGS topographic map of the area and along the east edge of the Farmers ditch shown in Figure 1. A drainage that has been modified by human construction extends along the depression to the Arkansas River. The high uranium in the groundwater could be a result of a higher background concentration generated during recent geologic time by infiltration of surface runoff from the west accumulating in the depression that was affected by evapotranspiration, combined with more recent surface water flowing into the depression from irrigation ditch drainage and groundwater-irrigated fields (such as return flows) that were also concentrated by evapotranspiration. Further discussion of the groundwaters in the White Woman basin is included later in this report in the assessment of hydrogeochemical controls on chemical distributions in Objective 6.

Objective 5 (Task 7): Assess vertical lithologic controls on chemical distributions and temporal changes

Factors such as depth to the water table, depth to the screened interval(s) of sampled wells, well construction (especially annular seals and type of well), the distribution of thick clay layers relative to the well construction, and the current thickness of the HPA are important considerations in the assessment of vertical lithologic controls on the distribution of salinity, uranium, and other elements. The travel distance of high uranium water to the water table and during groundwater flow, as mentioned in the Objective 4 discussion, is important because it appears that uranium is being adsorbed on sediments during saline water migration through the unsaturated zone and within the aquifer. This is discussed in more depth under Objective 6 (Task 8) on geochemical controls.

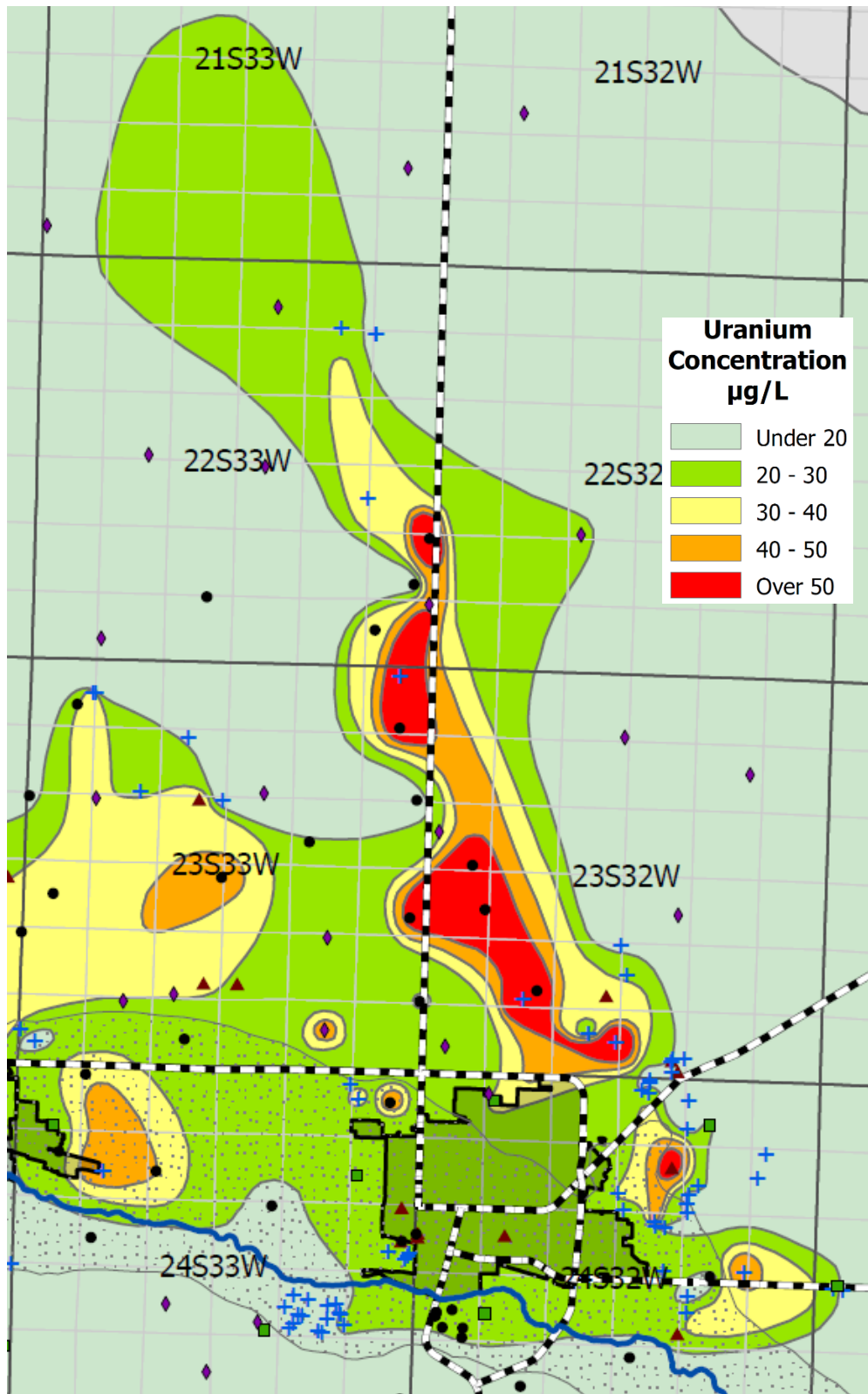


Figure 13. Zone of high uranium concentration that extends along the depression named the White Woman Bottoms to the east and north of Garden City. The map features are described in the caption for Figure 10, and the sampled well locations are identified in the legend of Figure 8.

In general, the salinity of the aquifer decreases with depth as shown by the vertical distribution of sulfate in the multilevel wells in Figure 14. These wells were installed in the late 1990s as a part of a KGS study of salinity in the upper Arkansas River corridor (Whittemore et al., 2000). The Deerfield site is located on the west side of the city to the south of the Garden City ditch and to the north of the Arkansas River. The Garden City site is approximately one-fourth of a mile south of the river channel and a little over a tenth of a mile east of Highway 83. The Dodge City site is three miles west of 14th Avenue and a little over a tenth of a mile south of the river channel. The vertical concentration change can be gradual, as it was at Deerfield in 1999, where a number of clay units are interspersed throughout the aquifer thickness and result in slow vertical migration. A clay layer underlying the alluvial aquifer at a location a few miles upstream of Dodge City was a key control on preventing the saline water in the alluvial aquifer from penetrating to the underlying HPA in 1999. The sediments at the Garden City site do not include as many or as thick substantial clay layers as at Deerfield, resulting in vertical migration of salinity to all depths from 1961 to 1999. The migration at the Garden City site was facilitated by the decline of groundwater levels after the mid-1970s to levels near the bottom of or below the alluvial aquifer for many years. The increase in sulfate concentration from the shallowest to the next depth in 1999 is related to the amount, concentration, and timing of saline river water infiltration; the infiltration of water during 1997–1999 was greater and of lower salinity than for most of the prior two decades due to the high river flows during the late 1990s.

The salinity of the groundwater in the HPA at the Deerfield multilevel well site increased appreciably from 1999 to 2022, while the salinity in the alluvial aquifer and the shallow HPA did not change substantially (Figure 14). The entire aquifer system at the Deerfield site is now saline. The sulfate concentrations of samples from the three deepest wells were in a similar range (1,326–1,384 mg/L).

At the Garden City multilevel well site, the sulfate concentration decreased at the second deepest depth in the HPA from 1999 to 2022, whereas the concentrations in the middle and the bottom of the HPA did not change significantly (Figure 14). The groundwater level had dropped to below the depth of the two shallower wells such that no samples could be collected in 2022. The less saline water at the second deepest depth in 2022 probably represents vertical migration of the lower salinity Arkansas River water during the high flows of the late 1990s. The sediments at the Garden City site contain fewer and thinner clay units than at the Deerfield site, such that vertical migration is expected to occur at a greater rate. The lower salinity in the middle of the HPA at Garden City in 2022 compared to 1999 could have been caused by the infiltration of freshwater runoff from the city into the river valley during the period when no significant flows of saline river water reached Garden City. Nearly continuous flow that began at Garden City during the summer of 1995 ceased in early 2002. Since early 2002, the only significant flow (greater than 50 ft³/sec) at Garden City that was derived from river flow originating at the state line occurred as pulses from the latter half of 2017 to the first quarter of 2019. The sulfate concentration of two samples collected by GMD3 at the Main Street bridge (near the multilevel well site) on different dates in May 2017 and analyzed by the KGS contained 1,620–1,860 mg/L, and two additional samples collected at the same location on different days in August 2017 had 1,300–1,330 mg/L. The average of these sulfate concentrations was lower than those in the middle of the aquifer in 1999. Infrequent, lower flow pulses of river water generally contained higher salinity; for example, a sample collected at the Main Street bridge in March 2010 when the flow was 16

ft³/sec contained a sulfate concentration of 2,370 mg/L. The volume of these flows may not have been great enough to offset the lower salinity of higher flows.

The groundwater level had dropped to below the depth of the shallowest well (screened in the alluvium) at the Dodge City multilevel well site when samples were collected in 2022. In the wells screened in the HPA, the sulfate concentration increased substantially from 1999 to 2022 in the shallowest and next deepest wells at the Dodge City site (Figure 14). Vertical migration of the salinity had not reached the screened interval of the deepest well; the sulfate concentration (43.7 ± 0.8 mg/L) was essentially the same in 1999 and 2022. This interval was the only one of the multiwell intervals in the HPA that still contained freshwater in 2022.

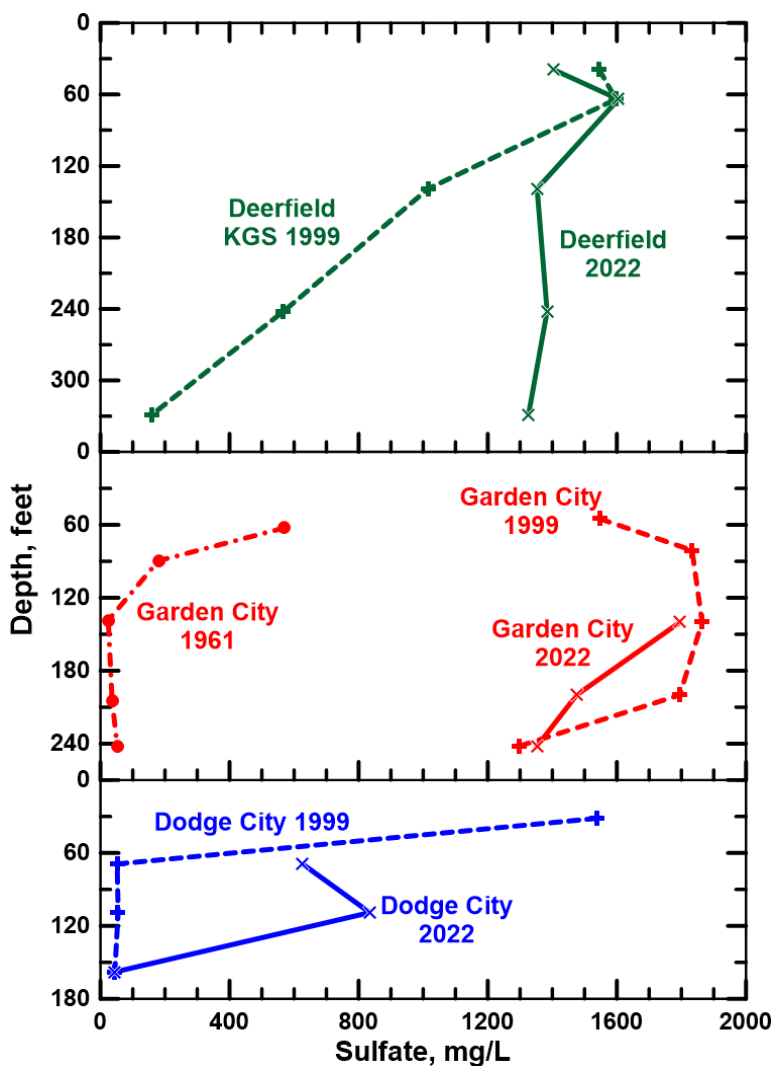


Figure 14. Change in sulfate concentration with depth in the alluvial aquifer and HPA at different locations near the Arkansas River from Deerfield to Dodge City. The data are based on multilevel observation wells installed by the KGS in 1997 and 1998 and by the USGS in 1961.

The uranium concentration at the two shallow depths of the Deerfield multilevel well site did not change appreciably from 1999 to 2022 (Figure 15). In contrast, the uranium concentration at deeper depths increased substantially during this time such that the two deepest intervals screened in the HPA at the site yielded water with a significantly greater concentration (61 $\mu\text{g/L}$) than all of the shallower depths. The groundwater at the deepest well depth was fresh in 1999 but contained about 20 $\mu\text{g/L}$ uranium, a relatively high background concentration for the HPA in the upper Arkansas River corridor. This higher uranium background is most likely derived from the leaching of Cretaceous shales underlying HPA sediments in that area and to the northwest. The next deepest depth yielded water with a uranium concentration of 29 $\mu\text{g/L}$. Even though the middle well at the Deerfield site is at a shallower depth than the two deeper wells, and therefore closer to surface infiltration of Arkansas River water, the uranium concentration in 1999 (16.4 $\mu\text{g/L}$) was lower than in the two deeper well waters.

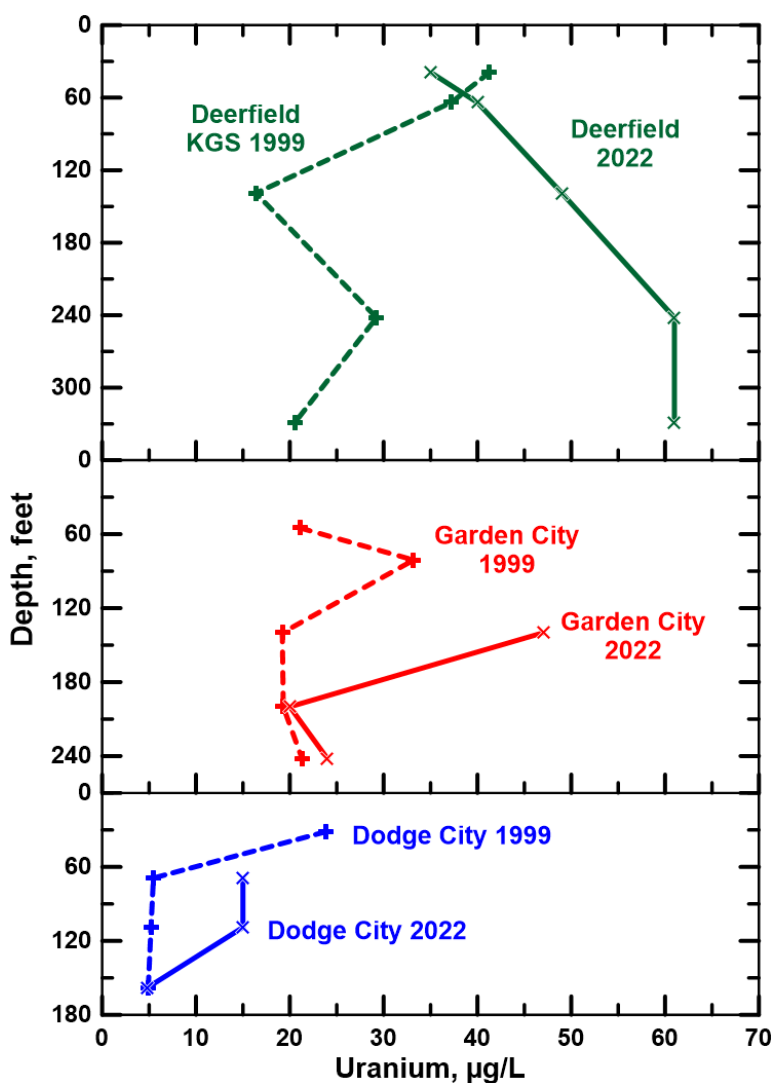


Figure 15. Change in uranium concentration with depth in the alluvial aquifer and HPA at different locations near the Arkansas River from Deerfield to Dodge City. The data are based on multilevel observation wells installed by the KGS in 1997 and 1998.

The high uranium in the two deepest wells in 2022 (Figure 15) provide evidence for a probable explanation of the 1999 results for the middle well. Mixing of the uranium concentrations of 1999 in the two shallowest well waters with the two deepest well waters could not produce the high uranium concentration of 2022 at the two deepest intervals sampled in the HPA at the Deerfield site. The well logs for the Deerfield multilevel wells indicate that a number of substantial clay units separate permeable sand and gravel units (Figure 3 in Whittemore et al., 2000). The probable cause of the high uranium concentrations at the two deepest depths in 2022 is the lateral migration of groundwater in the deeper portions of the HPA from the high uranium area to the north-northwest displayed in Figure 11. The similar sulfate concentration of water from the three deepest wells, for which the uranium concentration was similar and higher than in the middle well water, indicates that the background uranium concentration in the middle zone of the aquifer was lower than in the deeper part of the aquifer. The mass concentration ratio for uranium/sulfate in Arkansas River water is usually a little over $3 \times 10^{-5} \pm 1 \times 10^{-5}$. The uranium/sulfate ratios in 1999 were in the lower part of the river water range for uranium/sulfate for the two shallowest Deerfield well waters, lower than river water for the middle well, and higher for the two deeper wells (especially the deepest well) (Figure 16). In 2022, the uranium/sulfate ratio increased from the two shallowest well waters to the deepest well water, even though the sulfate concentrations were similar. The sulfate and uranium concentrations and uranium/sulfate ratios suggest that different zones of the HPA in the area contained groundwater with different background uranium concentrations and that various mixtures of the waters in these zones with alluvial groundwater affected by Arkansas River water, as well as shallow groundwater in the HPA affected by the infiltration of irrigation water derived from river water diversion, produced different water chemistries in the zones. As the salinity of the aquifer system increased from additional river water added to the system, along with concentration of dissolved constituents (including uranium) from evapotranspiration with continual irrigation, the groundwater with different chemistries migrated more laterally within the permeable zones between the clay layers than vertically to generate the observed water quality. The more saline and higher uranium concentration water in the shallow aquifer water in the area to the north probably penetrated to the background water in the different aquifer zones by flow down continuous gravel packs in the annular space of wells without grout seals or with only 10–20 ft seals (especially in the case of large diameter boreholes of irrigation wells). Otherwise, local windows in the HPA without substantial clay layers would have to exist to allow the vertical migration of saline water.

At the Garden City multilevel well site, the uranium concentration in 1999 increased from the alluvial aquifer to the underlying HPA aquifer, as did the sulfate concentration (Figure 15). The uranium/sulfate ratio increased in 1999 from the shallowest (alluvial aquifer) well water to the underlying shallow HPA well water in the direction of the ratio in Arkansas River water (Figure 16), supporting the higher impact of river water in the shallow HPA at that time as described above for sulfate concentration for the Garden City site. The uranium concentrations were lower in the middle to deep HPA than in the shallow HPA at the site in 1999. The uranium increased substantially in the middle well interval from 1999 to 2022 but changed only a little in the next to deepest well water and increased by a small amount in the deepest well water in 2022. The uranium/sulfate ratios in the saline waters at the Garden City site were lower and ranged less than the saline waters at the Deerfield site in 1999 (Figure 16), although the ratios for the saline waters in the shallowest and deepest HPA well waters were similar to that of the middle Deerfield well. The uranium concentration increased appreciably in the middle well at the Garden City site from 1999 to 2022; the uranium/sulfate ratio also increased in the well interval during that time to a value within the range for Arkansas River water. As indicated earlier, the sediment

lithology of the Garden City site is characterized by fewer and thinner clay units than at Deerfield. It appears that the main control on salinity and uranium concentration at the Garden City site is now vertical migration and mixing of Arkansas River water of varying salinity with saline alluvial aquifer water (when groundwater levels are within the alluvial sediments) and HPA groundwater previously affected by river water. The much higher uranium concentration and uranium/sulfate ratio in the middle well interval in 2022 than in 1999 (Figures 15 and 16), even though the sulfate concentration was a little less in 2022 than in 1999 (Figure 14), suggests that uranium adsorbed on sediments during earlier contamination of the aquifer by river water has reduced the capacity of the sediments to adsorb more uranium such that the groundwater chemistry is now approaching that of river water. The factor of uranium adsorption on sediments is discussed further for lateral migration of Arkansas River water south of the river channel in the next section of this report.

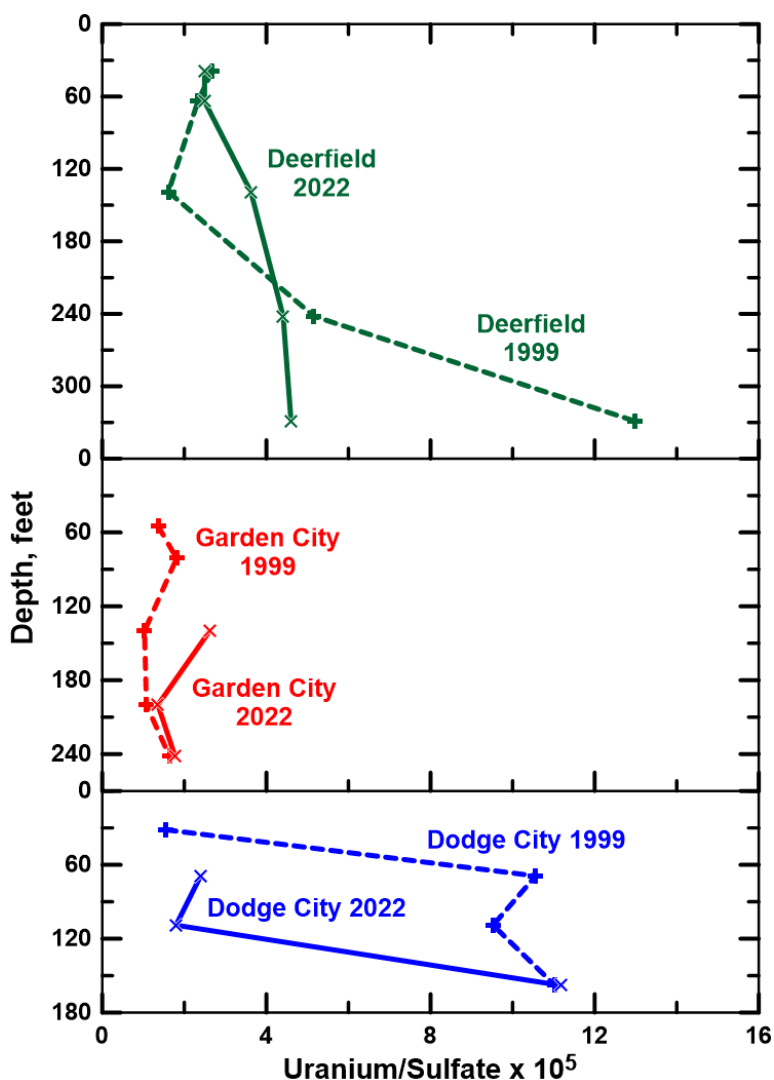


Figure 16. Change in uranium/sulfate concentration ratio with depth in the alluvial aquifer and HPA at different locations near the Arkansas River from Deerfield to Dodge City. The data are based on multilevel observation wells installed by the KGS in 1997 and 1998.

Vertical migration of saline groundwater is also the probable cause of the increase in uranium concentration in the middle two wells at the Dodge City multilevel well site (Figure 15). The saline water in the alluvium, below which the water level had dropped at the time of sampling in 2022, is expected to have mixed with water in the underlying HPA between 1999 and 2022 to raise the salinity and uranium concentrations of water from the two middle wells at the site. The uranium levels in the three HPA wells in 1999 represented background concentration (4.9–5.6 µg/L) in freshwater at that location. The uranium concentration in the deep well remained essentially the same in 2022 as in 1999 (4.8 µg/L and 4.9 µg/L, respectively), as did the sulfate concentration. The uranium/sulfate ratios in the middle two wells substantially decreased from 2022 as the groundwater was affected by infiltrating saline alluvial aquifer water. The shallowest HPA well had a uranium/sulfate ratio at the lower ratio range for river water, whereas the next deepest HPA well had a ratio just below the ratio range (Figure 16). This indicates adsorption of uranium on the aquifer sediments as described for the Garden City site.

The distributions in selenium concentration with depth at the multilevel well sites (Figure 17) generally fit the explanations for the uranium concentration variations. The range in background selenium levels in freshwaters in 1999 was about 9 µg/L in the deepest well at Deerfield to 2.4–6.4 µg/L in the freshwaters at the three HPA intervals at Dodge City. The selenium concentrations in the three deepest wells at the Deerfield site in 2022 were the highest observed, just as for uranium at that site. The selenium/uranium ratio range in 2022 (1.9×10^{-5} – 2.2×10^{-5}) for these three well waters was also greater than the range for Arkansas River water ($1.0 \pm 0.3 \times 10^{-5}$). This supports the lateral groundwater flow of saline water with high uranium and selenium concentrations to that location rather than vertical migration. The selenium increase in the middle well at Garden City relative to sulfate concentration mirrors that of uranium in that well, suggesting that adsorption may also affect selenium concentration during saline water migration.

Objective 6 (Task 8): Assess hydrogeochemical controls on chemical distributions and temporal changes

Although uranium and sulfate concentrations are well correlated in Arkansas River water across a wide range of salinities, their relationship in groundwater from the HPA varies substantially across the river corridor (Figure 18). Many groundwaters contain uranium concentrations appreciably greater than what would be expected at given sulfate concentrations, and many waters have much lower uranium concentrations than expected. This pattern exists for groundwaters with uranium both above and below the MCL.

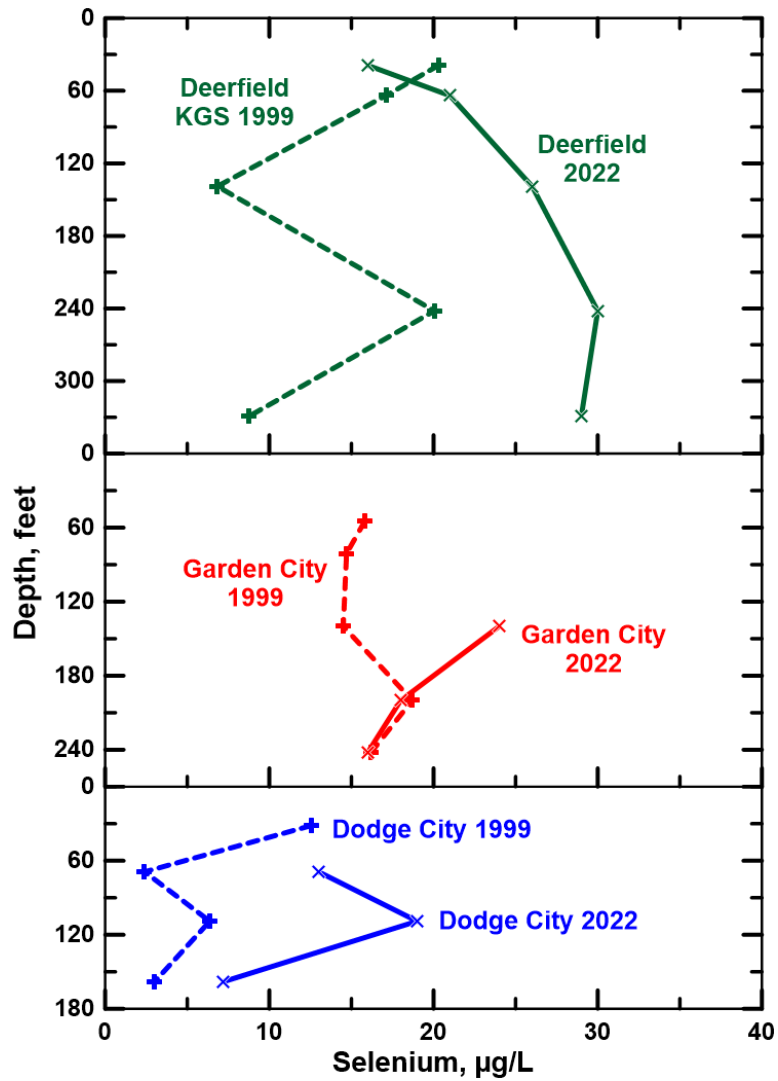


Figure 17. Change in selenium concentration with depth in the alluvial aquifer and HPA at different locations near the Arkansas River from Deerfield to Dodge City. The data are based on multilevel observation wells installed by the KGS in 1997 and 1998. The maximum contaminant level for selenium in drinking water is 50 µg/L.

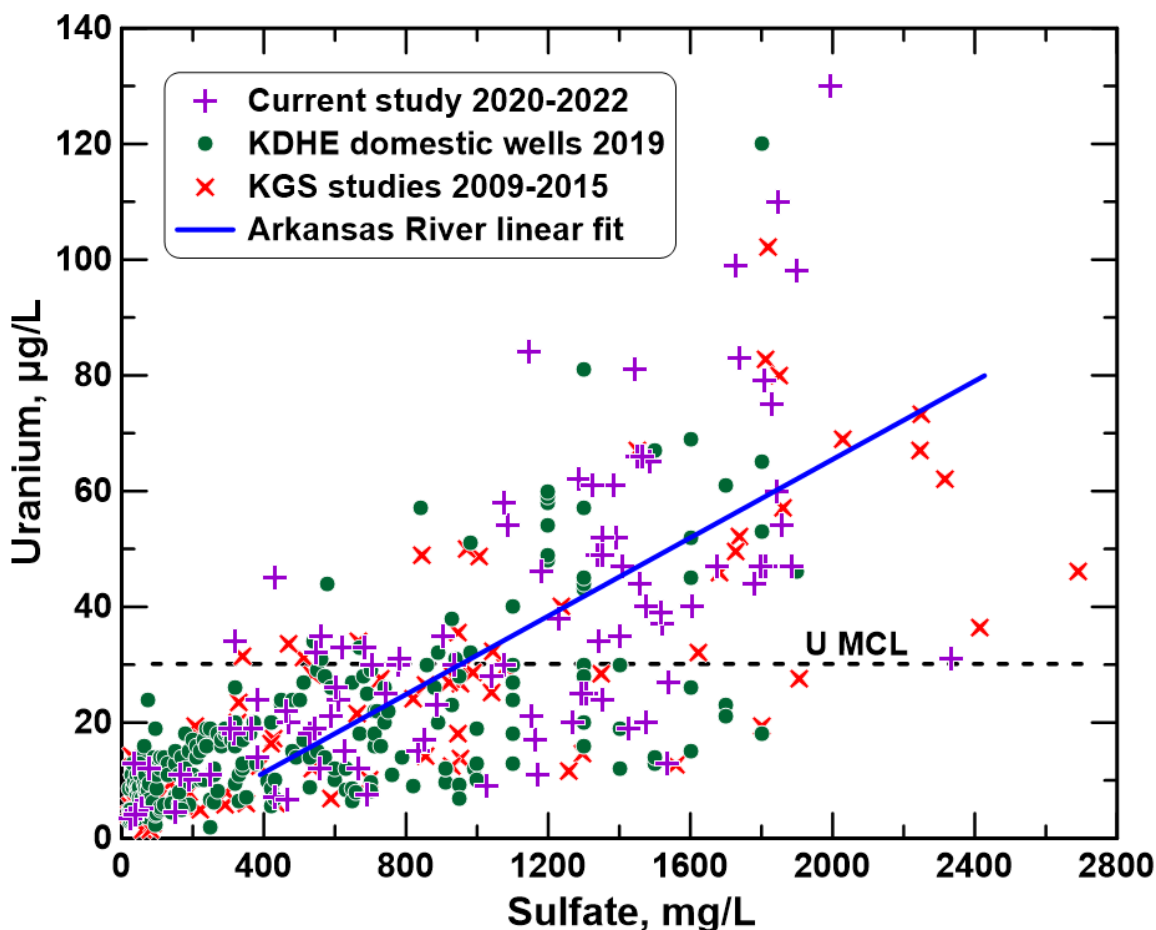


Figure 18. Uranium versus sulfate concentration for Arkansas River water and for groundwaters in the alluvial aquifer and the HPA sampled in past KGS studies, the KDHE voluntary private well program, and the current KGS study.

Uranium and sulfate concentrations are well correlated for groundwater within local HPA areas but have linear regressions that greatly differ from each other as well as from the linear regression for the Arkansas River. For example, Figure 19 displays uranium and sulfate concentration data since 2009 for municipal wells of the City of Lakin, which are located north of the city and the Arkansas River, and of the City of Garden City in the Sand Hill wellfield, which are south of the city and the river. Uranium concentration at a given sulfate concentration is greater in groundwaters of the Lakin wellfield than in Arkansas River water and much higher than in the Garden City Sand Hill wellfield. Uranium concentration at a given sulfate concentration is lower for the Sand Hill wellfield than for river water with sulfate concentration around 400 mg/L and above. The background sulfate (about 30 mg/L) and uranium (12–14 µg/L) concentrations in 2009–2012 were higher at the Lakin well farthest to the west than at the Sand Hill wells farthest to the south (about 20–40 mg/L and 3.4–4.6 µg/L, respectively, in 2010–2021) because groundwater flow from the west of Lakin is affected by leaching of Cretaceous strata similar to those in the Colorado plains that weather to supply dissolved sulfate and uranium to the Arkansas River. The depths of wells in the HPA in the Lakin wellfield are on the order of a little over 200 ft; in the Sand Hill wellfield they range from 340 ft to more than 400 ft.

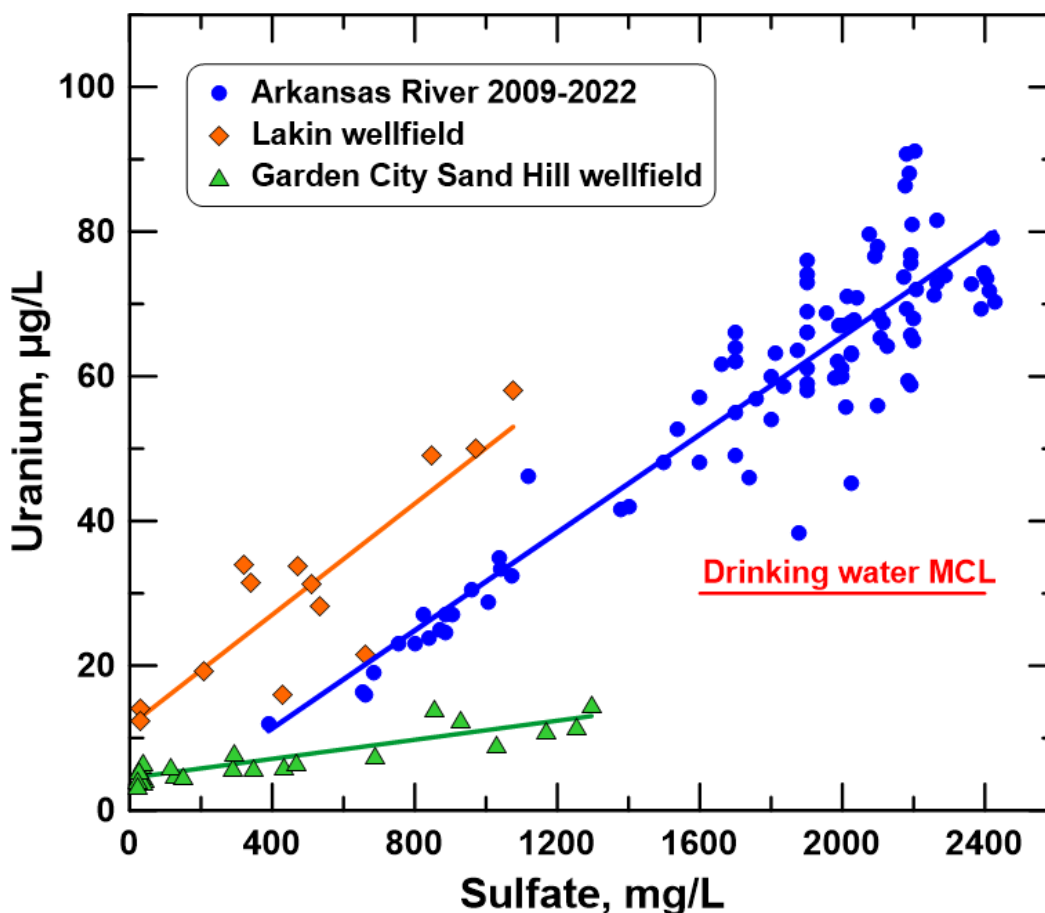


Figure 19. Uranium versus sulfate concentration for Arkansas River water, Lakin and Garden City Sand Hill wellfields.

The Lakin wellfield (five wells) is located just to the west of the Amazon canal. In general, the closer the wells in the Lakin wellfield are to the canal, the greater the salinity and uranium concentration. The distances from the canal to the four Lakin wells affected by the saline water are in the range of 0.4–0.7 mi; two of these wells had been operating since 1972 and the other two since 1978. The fifth well is farther west and has not been substantially affected by canal water. Pumping by the wells close to the canal appears to have created drawdown cones that have induced lateral flow of saline groundwater seepage from under the canal. The Amazon canal was constructed in 1883; thus, seepage of saline river water into the HPA has occurred for well over a century. This extended time has allowed uranium adsorption to occur on sediments in the unsaturated zone and the aquifer near the canal for a sustained period such that additional sorption capacity for uranium has likely been reduced and less adsorption would be occurring today. It is expected that since the start of pumping of the Lakin wells, some uranium was adsorbed on aquifer sediments during the migration of saline water toward the wells farther to the west of the canal such that less removal of uranium during groundwater transport would have occurred during the last one and a half decades.

However, the uranium/sulfate ratio of the well waters with the greatest sulfate and uranium concentrations is still higher than expected, i.e., there is no more saline source with a high uranium/sulfate ratio to produce the observed values. Thus, an additional mechanism is needed to explain the ratios for the most saline well waters. The simplest explanation is removal of sulfate relative to uranium in the water recharging the aquifer in the area to produce the high ratios. This could be expected from the more than a century of conveyance of Arkansas River water in the canal and irrigation with that river water in fields in the ditch irrigation area. Evapotranspiration of the water in the soil near the canal and in the ditch-irrigated fields could concentrate dissolved constituent concentrations in the residual moisture until they exceed the solubility of selected minerals, gypsum (hydrated calcium sulfate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) being the most prominent. Gypsum could then precipitate in the soil, thus removing sulfate from the soil moisture, while the uranium could remain in solution in a form complexed with carbonate, thereby increasing the uranium/sulfate ratio. This soil moisture can then infiltrate through the unsaturated zone to the HPA with canal leakage water, irrigation return flow, or precipitation recharge.

The Garden City Sand Hill wellfield south of the Arkansas River has seven wells. In general, the closer a well is to the river channel, the greater the salinity of the water pumped (Figure 20). Background sulfate concentrations in the HPA in the wellfield area were once less than 50 mg/L. The two wells closest to the river channel (1.7–1.8 mi distance) began to experience increases in salinity in the 1990s; sulfate concentrations began to increase at another well (2.4 mi distance) around 2004 and at a fourth well (2.8 mi distance) before 2010. Water at the next closest well (3.0 mi distance) started to increase in sulfate before the latest sample in 2021. The other two wells are 3.2–3.6 mi from the river and have not shown sulfate increases as of 2021. Although the first uranium data for the well waters start in 2009, a similar pattern exists, i.e., the closer to the river, the higher are the uranium concentrations. Overall, the Garden City wells are farther from the river (or a major irrigation canal), deeper, and have had less time for salinity to affect the wells than at the Lakin wellfield. This is expected to have allowed a substantial percentage of the uranium in the induced plume of salinity from the river and its alluvial aquifer to be adsorbed during the last two decades of transport to the Garden City wellfield. Thus, uranium/sulfate ratios in the HPA water at the wellfield started lower than at the Lakin wellfield and significant adsorption of uranium kept the ratios lower than the river water during the saline groundwater migration to the south.

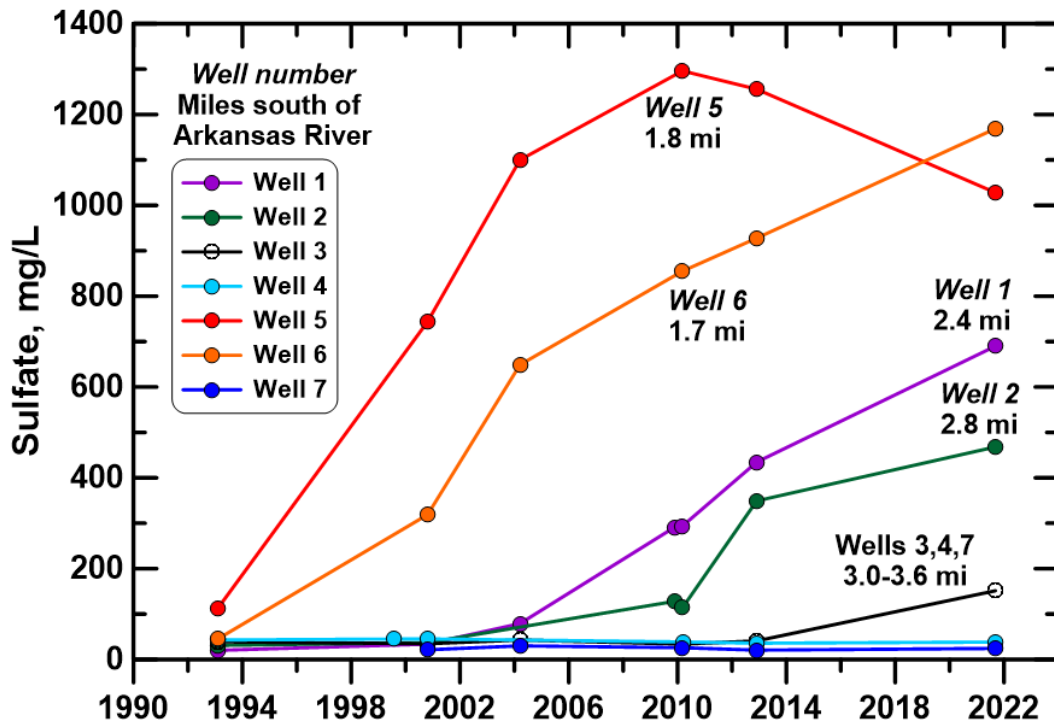


Figure 20. Change in sulfate concentration with time for wells in the Sand Hill wellfield of Garden City south of the Arkansas River.

Points for waters sampled from all well types in the HPA based on data from studies during 2009–2022 plot both higher and lower than the linear regression for the Arkansas River for all the counties over the HPA as shown in Figure 21. The plot shows that the sulfate and uranium concentrations are substantially greater in the groundwaters in Kearny and Finney counties than in Gray and Ford counties. However, the relative magnitude of the deviations from the river line are not significantly different for the four counties at sulfate concentration less than 1,000 mg/L and not different for Kearny and Finney counties within the entire sulfate concentration range. Thus, county location does not by itself explain the deviations from the river line.

Figure 22 displays uranium versus sulfate concentration data for groundwaters from the HPA according to water supply well type. Just as for classification according to county location, no clear difference appears for the position of points above or below the best-fit line for Arkansas River water based on well types.

In contrast to Figures 21 and 22, classification of the HPA wells according to location north or south of the Arkansas River does show a pattern differentiating many of the well waters (Figure 23). Most of the wells south of the river (symbols in green) plot either below or along the regression line for river water. Although many points for the wells north of the river (symbols in red) also plot below the river water line, most plot above or along the river line.

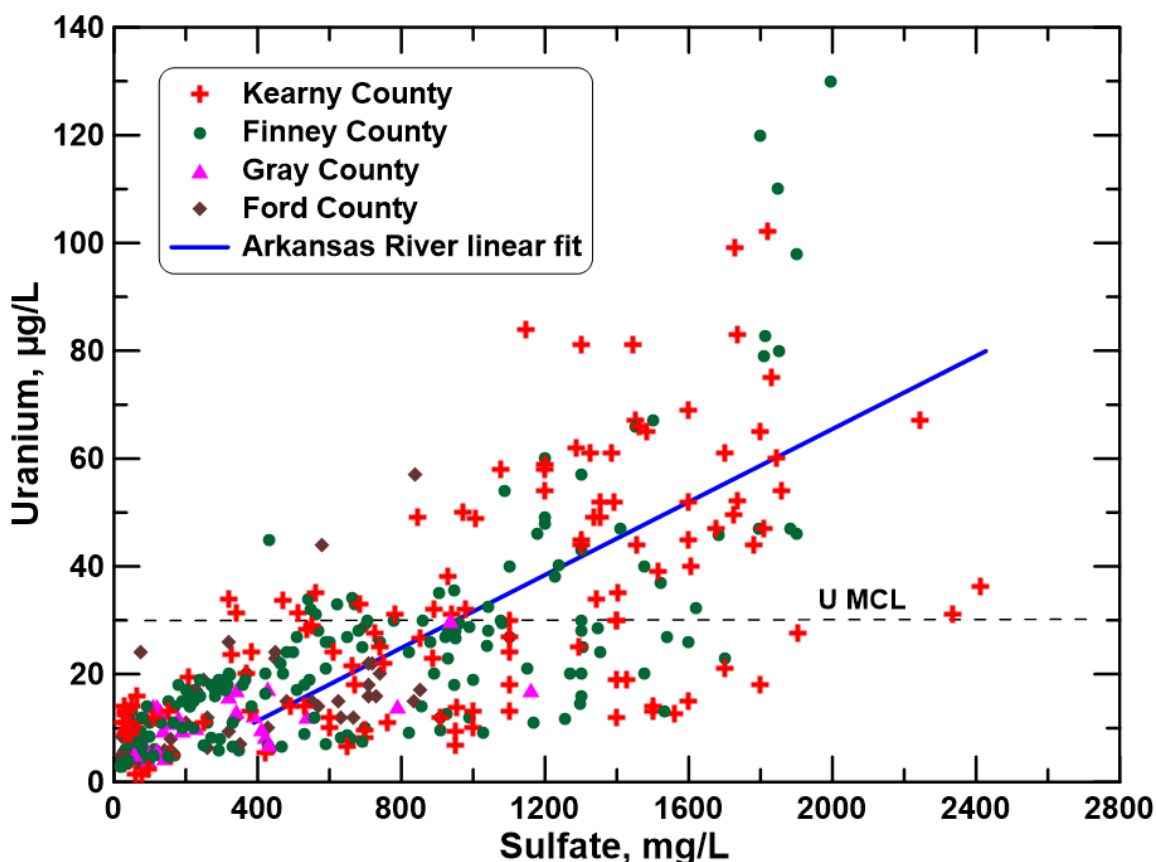


Figure 21. Uranium versus sulfate concentrations for groundwater from the HPA in four counties based on data from KGS studies of 2009–2015, the KDHE voluntary private well program of 2019, and the current KGS study of 2020–2022.

The uranium/sulfate ratio can indicate differences between much of the groundwater in the HPA north compared to south of the river, as well as influences on the chemistry relative to river water due to such effects as uranium adsorption and precipitation of sulfate minerals in soils while uranium remains in solution. A plot of the sulfate/uranium ratio versus sulfate concentration improves the differentiation of the chemistry in the north-south areas along with the effect of mixing of groundwaters of different salinity (Figure 24). The graph indicates that the uranium/sulfate ratio of fresh groundwaters is appreciably greater than that of saline waters. As the freshwaters are affected by mixing with saline river waters, the uranium/sulfate ratio generally decreases as the sulfate concentration increases within the mixing zone boundaries such that the ratio of many of the groundwaters changes to within the range of the ratio for saline river waters. However, the ratios of many of the groundwaters north of the river and most of those south of the river decrease below their respective mixing zones. The main process that is thought to cause this, as indicated before, is adsorption of uranium on sediments during vertical flow of water in the unsaturated zone and in the aquifer and lateral flow in the aquifer. The observation that more of the groundwaters south of the river plot below the mixing zone than north of the river supports the greater potential for adsorption because the depth to groundwater is greater and lateral groundwater flow generally moves into areas where fresher waters had recently existed in comparison with north of the river where lateral flow can often carry those

groundwaters into areas already contaminated by river water that infiltrated below irrigation ditches. In addition, lateral groundwater flow rates are expected to be usually higher south of the river due to the greater gradient in the water table caused by larger declines to the south; the groundwater levels in much of the area of the high salinity north of the river do not decline as much due to the recharge by ditch diversions.

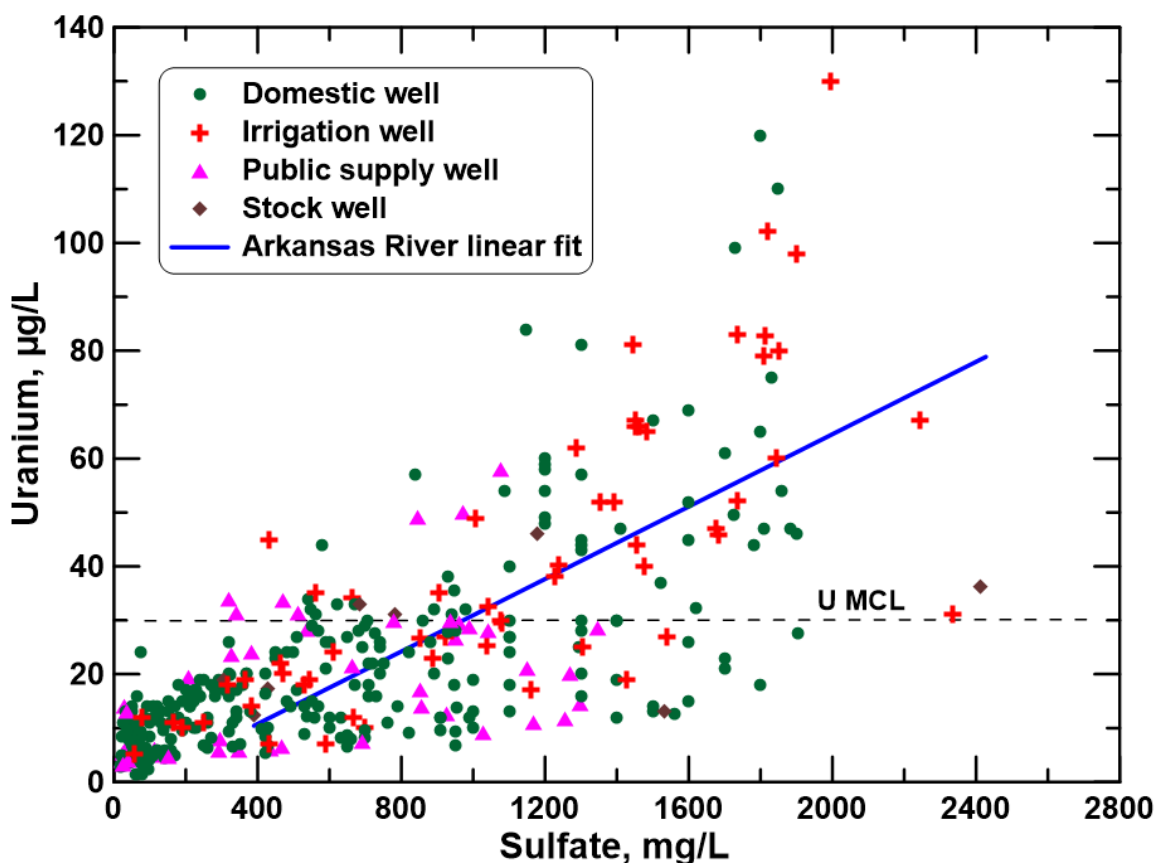


Figure 22. Uranium versus sulfate concentrations for groundwater from different types of water supply wells in the HPA based on data from KGS studies of 2009–2015, the KDHE voluntary private well program of 2019, and the current KGS study.

None of the groundwaters south of the river plot at higher uranium/sulfate ratios than the mixing zone between fresh and saline groundwaters (Figure 24). In contrast, many groundwaters north of the river contain uranium/sulfate ratios above the fresh and saline mixing zone for that area. Several of the groundwaters with a sulfate concentration greater than 1,000 mg/L that plot above the mixing zone are located in the zone of the White Woman Bottoms. A process that is thought to be responsible for the higher uranium/sulfate ratio than expected for the conservative mixing zone is the removal of sulfate relative to uranium in soil moisture such as the precipitation of gypsum during dry periods, followed by infiltration of soil moisture with a higher uranium/sulfate ratio by irrigation return flow or rainfall/snow melt without complete dissolution of the precipitated gypsum. For example, a heavy rainfall could initially provide water for driving soil moisture deeper in the soil to eventually reach the underlying water table until the

soil was saturated, followed by surface runoff or shallow soil interflow to drainages. The surface runoff and shallow interflow could then have time to dissolve more gypsum and move water with a lower uranium/sulfate ratio from the area. The infiltration of soil moisture coupled with runoff or interflow during substantial rain events within the depression of the White Woman Bottoms and then out of the area into the Arkansas River valley could be an explanation for the high uranium/sulfate ratio of groundwater underlying the Bottoms. Similarly, past ditch irrigation return flow from the eastern side of the original extent of the Farmers ditch into the Bottoms could be part of the cause of the high uranium/sulfate ratios in the underlying groundwater; some gypsum could have been precipitated in the surface soil within the ditch-irrigated area, and irrigation return flow with a higher uranium/sulfate ratio at the east end of the area could have entered the Bottoms and then infiltrated to the underlying aquifer.

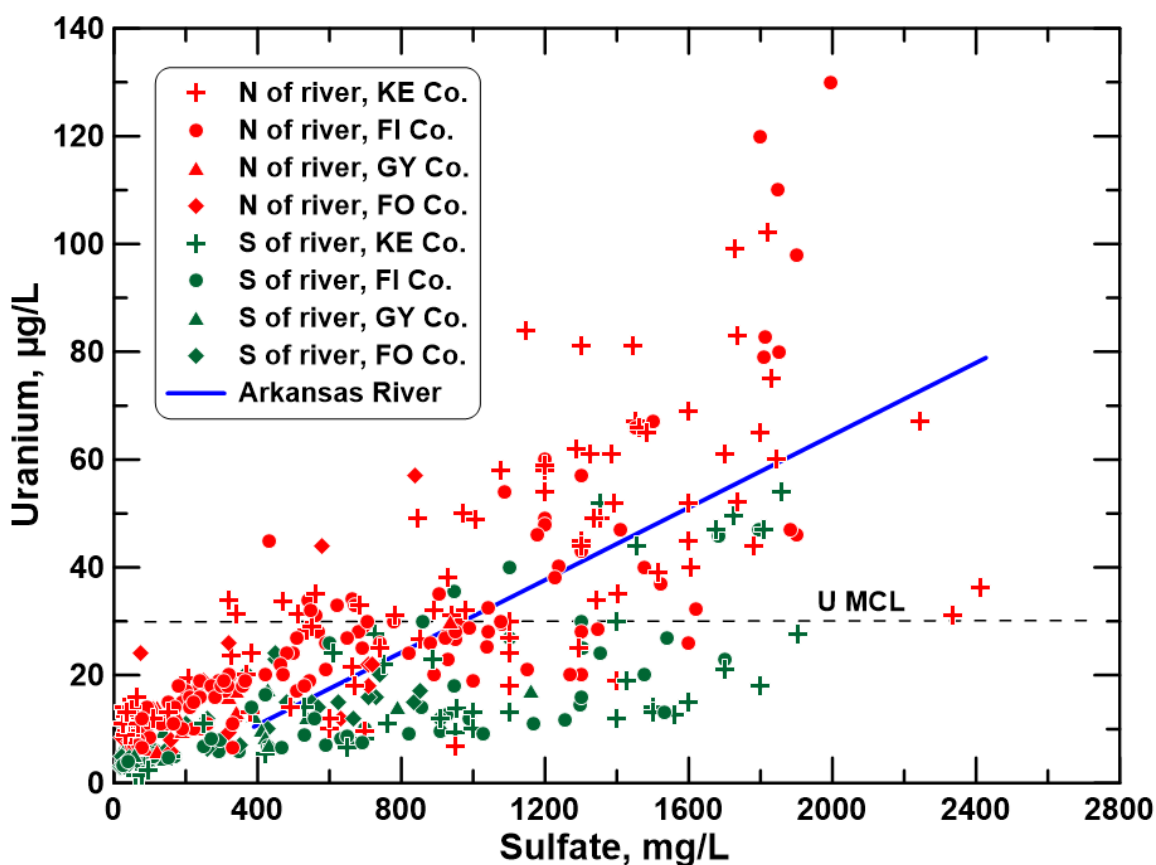


Figure 23. Uranium versus sulfate concentrations for groundwater from wells in the HPA classified as located either north or south of the Arkansas River based on data from KGS studies of 2009–2015, the KDHE voluntary private well program of 2019, and the current KGS study.

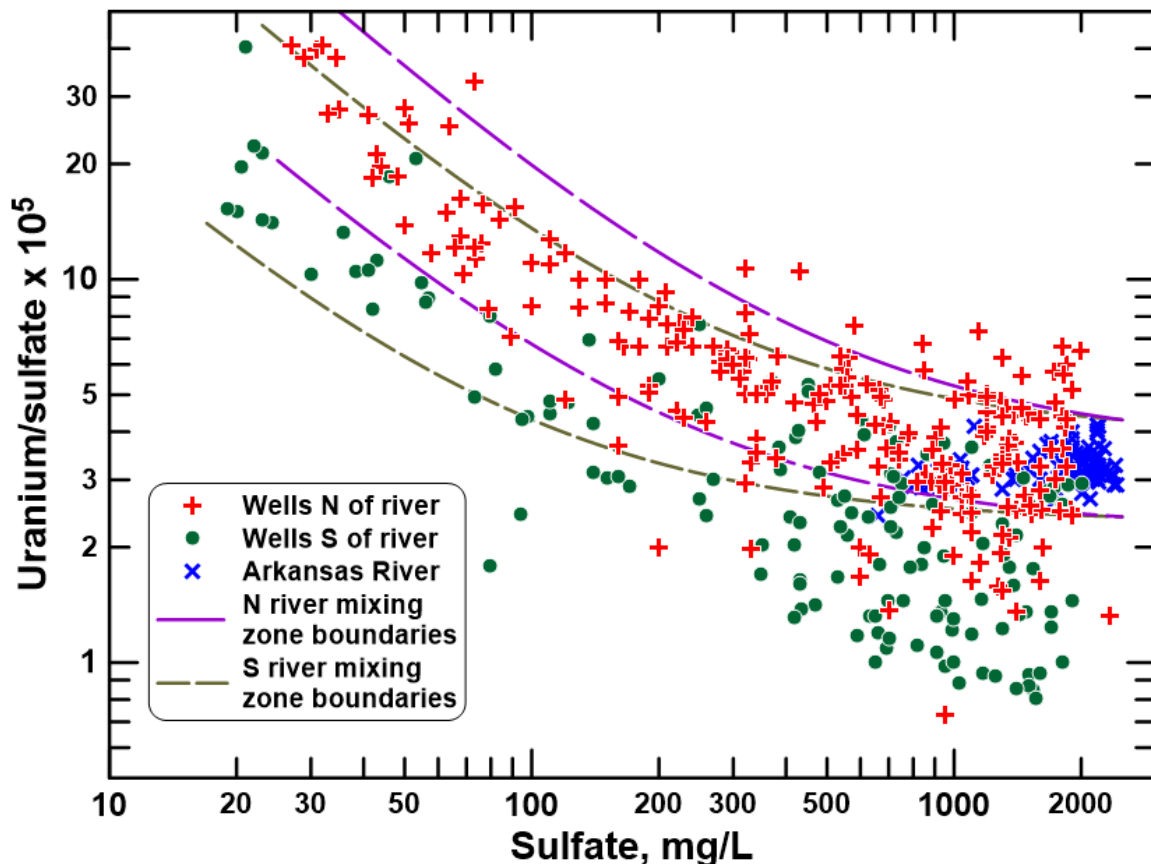


Figure 24. Uranium/sulfate mass ratio versus sulfate concentration for groundwater from wells in the HPA classified as located either north or south of the Arkansas River based on data from KGS studies of 2009–2015, the KDHE voluntary private well program of 2019, and the current KGS study. The curves represent the conservative mixing of freshwater and saline water end members; two curves are plotted as the upper and lower boundaries of a mixing zone. The freshwater end members for the zones of mixing for waters north and south of the river were selected such that the mixing zone would bracket nearly all of the freshwaters (less than 100 mg/L sulfate) in that area. The saline water end members for both the zones of mixing for waters north and south of the river are the same and bracket the saline Arkansas River waters.

As indicated earlier, the background uranium concentration in the HPA in the upper Arkansas River corridor could be greater in parts of Kearny and Finney counties due to leaching from the weathered upper Cretaceous bedrock underlying the HPA. Stratigraphic maps of southwest Kansas (Macfarlane et al., 1993) indicate that the Dakota Formation underlies the HPA in southern Kearny County (all ranges in the southern two townships and T. 24 S., R 35–36 W.) and part of southwest Finney County (most of T. 24 S., R.34W.; T. 25 S, R 33–34 W. and the southwest half of R. 32 W.; and T. 26 S., R 32–35 W. and the southwest half of R. 31 W.). In the rest of Kearny and Finney counties, and in most of Gray and Ford counties, the bedrock underlying the river corridor is Upper Cretaceous shale and limestone (Graneros Shale, Greenhorn Limestone, Carlile Shale, and Niobrara Chalk) based on test hole logs in Waite (1942), McLaughlin (1943), Latta (1944), and Stramel et al. (1958). Plate 2 of Berendsen and Hathaway (1981) displays the division between the Niobrara Chalk and the strata group Carlile

Shale–Greenhorn Limestone–Graneros Shale in western Kansas. The Niobrara Chalk underlies the HPA in northern Hamilton, Kearny, and Finney counties. The Carlile Shale underlies the HPA in the northern part of central Kearny and Finney counties. The bedrock under the HPA then transitions to the Greenhorn Limestone in central Kearny County and in parts of southwest Finney County around Holcomb. Farther to the south, the bedrock underlying the HPA changes to the Graneros Shale along the Arkansas River valley and then to the Dakota Formation.

Bern and Stoger (2017) examined a stretch of the Arkansas River corridor in the plains of central Colorado where weathering of Upper Cretaceous bedrock is believed to be the source of high dissolved solids, sulfate, selenium, and uranium concentrations in the Arkansas River. The bedrock in their study area included the Pierre Shale that overlies the Niobrara Formation (the Niobrara unit is named as a formation in Colorado and a chalk in Kansas) in addition to the other units named above for the river corridor in Kansas. Although the literature review in their paper indicated parts of all of the Upper Cretaceous strata could contribute to the poor water quality of the river, their investigation of the relative contributions of dissolved solids, sulfate, selenium, and uranium concentrations in inflows influenced by the different strata found that the Niobrara Formation contributed a disproportionately larger amount than the other bedrock units. They cited Kulp and Pratt (2004) as explaining why the Niobrara could release more selenium than the Pierre: selenium in the Pierre is primarily associated with organic matter whereas it is in selenide minerals and pyrite in the Niobrara. Based on Kulp and Pratt (2004), Bern and Stogner (2017) stated that “Selenium is more easily released to the environment from oxidation of inorganic reduced forms than from organic Se...” (p. 188). The higher permeability of the chalk than that of shale is thought to be another factor that could lead to greater leaching of selenium (Kulp and Pratt, 2004).

The Niobrara Formation/Chalk includes the Fort Hays Limestone Member and the Smoky Hill Chalk Member; the latter of these two would be the unit contributing more uranium based on the description in Bern and Stoger (2017). Other Upper Cretaceous strata in Kansas also include chalky layers; all four members of the Greenhorn Limestone include chalky limestone or chalky shale, and the Fairport Chalk Member of the Carlile Shale includes chalky limestone and chalky shale. The Graneros Shale contains selenite crystals (a crystalline form of gypsum) that most likely formed from the weathering of pyrite in the presence of a calcium source such as dissolution of calcite. Pyrite nodules and selenite occur in parts of the Blue Hill Shale Member of the Carlile Shale.

The original source of the uranium in the Upper Cretaceous strata is probably ash beds. Selected types of igneous and volcanic rocks can contain higher uranium concentrations than other rock types. Volcanic ash was deposited in many Upper Cretaceous strata in the United States during their formation. Weathering of the ash in the rocks produced bentonite. Bentonite layers are common in the Niobrara Formation in the Arkansas River basin in Colorado as well as in the Niobrara Chalk in Kansas (especially the Smoky Hill Chalk Member). Thin beds of bentonite occur in the Fairport Chalk Member of the Carlile Shale, the Jetmore Chalk Member of the Greenhorn Limestone, and the Graneros Shale (Latta, 1944; Zeller, 1968). Uranium released during alteration of the ash to bentonite could have been precipitated as uranium IV containing minerals within the Cretaceous strata because slow oxidation of organic material present in the deposits would have produced a reducing environment resulting in uranium IV. Volcanic ash

deposits are found in the Ogallala Formation and Pleistocene sediments (Carey et al., 1952). Partial leaching of these ash deposits could be a potential source of low background levels of uranium in the HPA but not the high background concentrations, otherwise higher background levels would be observed south of the Arkansas River where river water has not affected the groundwater quality. The presence of Cretaceous bedrock, especially chalky units containing bentonite that underlie the HPA north of the Arkansas River in Kearny and Finney counties, is therefore a probable explanation for the higher background concentrations of uranium and higher uranium/sulfate ratios in groundwater of the HPA north of the river in these counties.

Nitrate is known to exacerbate the leaching of uranium during the weathering of bedrock by facilitating the oxidation of uranium in the reduced state to its more soluble oxidized state (Nolan and Weber, 2015). Nitrate has been found to be an important predictor of groundwater uranium concentrations within the High Plains aquifer and the Central Valley of California (Nolan and Weber, 2015; Lopez et al., 2021). However, the relationship between uranium and nitrate concentrations in the High Plains aquifer in the Arkansas River corridor is not statistically significant as shown in Figure 25; high uranium concentration exists in the presence of low nitrate concentration and low uranium concentration occurs in groundwater with high nitrate concentration. The uranium-nitrate relationship for groundwater also bears no resemblance to the linear regression for the Arkansas River from the Colorado-Kansas state line to the Amazon ditch, which is displayed in Figure 25 and is statistically significant ($R^2 = 0.41$, $P < 0.0001$).

The high concentrations of uranium in Arkansas River water and HPA groundwater exist primarily as oxidized uranium (VI) complexed with carbonate species and calcium-carbonate species (Lopez et al., 2021). Ample calcium and carbonate are present in the river water due to drainage from areas of bedrock containing limestone and calcareous shale and in groundwater in the HPA from dissolution of carbonate minerals in the sediments, including as calcareous zones known as caliche, as well as interaction with limestone and calcareous shale bedrock. Figure 26 illustrates the importance of the carbonate complexing of uranium; the correlations between uranium concentration in both Arkansas River water and HPA groundwater are statistically significant and the position and slope of the linear regressions are also close to each other. Although the correlation between uranium and calcium concentrations in HPA groundwater is statistically significant based on the P value, the R^2 value indicates that calcium concentration only explains about a quarter of the variation in the uranium concentration in contrast to bicarbonate explaining a little over half of the uranium variation (Figures 26 and 27). This also is in contrast to the higher R^2 for the correlation between uranium and calcium concentrations than between uranium and bicarbonate concentrations for Arkansas River water. In addition, the slopes of the linear regressions for the uranium and calcium concentrations relationships are markedly different. The correlation between uranium and sulfate concentrations is about the same as that for uranium and bicarbonate concentrations for the same set of sample records (Figure 28). Thus, the dissolved constituent concentrations of bicarbonate and sulfate in HPA groundwater appear to explain the variation in uranium concentration better than calcium concentration.

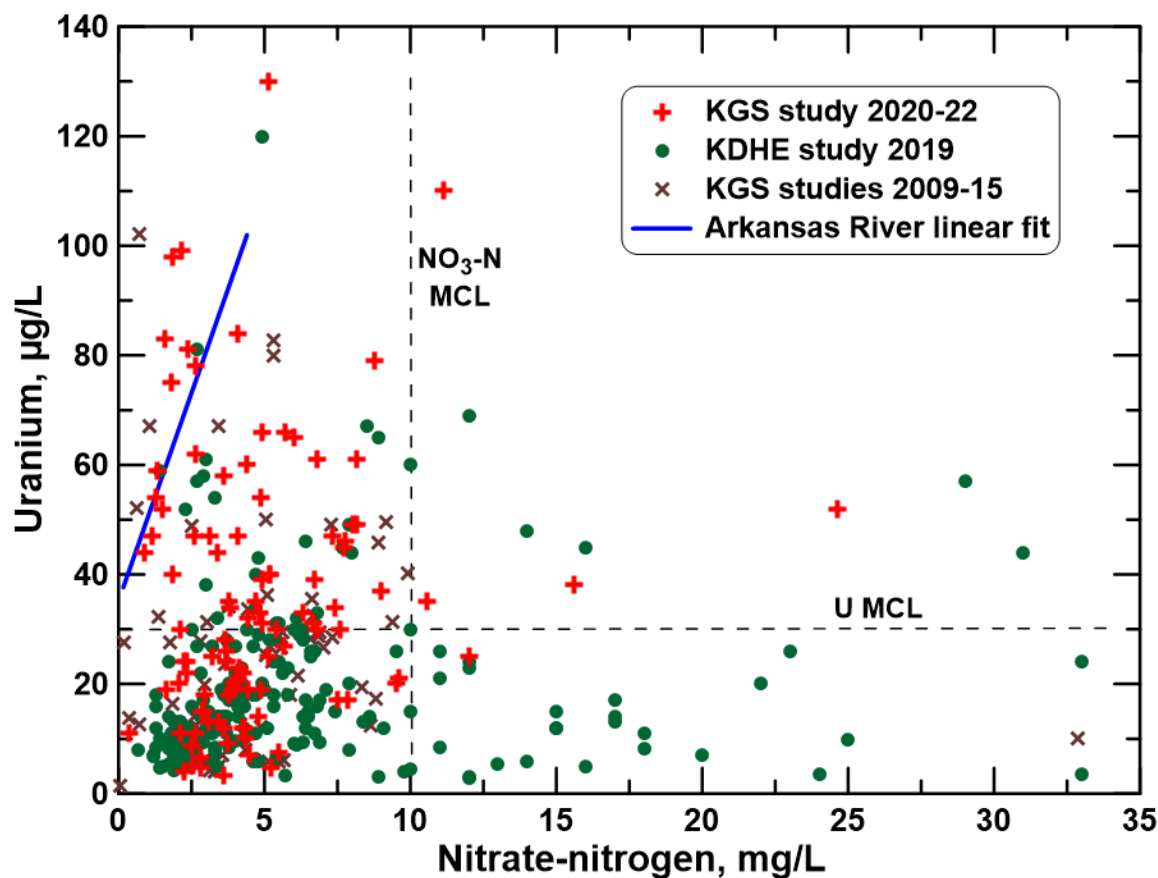


Figure 25. Uranium versus nitrate-nitrogen concentrations for groundwater from wells in the HPA based on data from KGS studies of 2009–2015, the KDHE voluntary private well program of 2019, and the current KGS study.

Objective 7 (Task 9): Estimate future accumulation and redistribution of chemical loads within the study area

The annual uranium loads (1.77–10.0 ton/yr) of the Arkansas River listed in Table 2 for 2012–2021 can be used to estimate an increase in the concentration in the HPA. The annual average uranium concentration in the river water was 58.6 µg/L for the past decade. If the uranium mass for each year is used to calculate an aquifer volume in which the groundwater has a uranium concentration of 50 µg/L, and the river water completely replaces the existing groundwater, the range in annual volumes would be equivalent to areas covering 2.0–11.5 mi² for a 100 ft thickness of the HPA, assuming an aquifer porosity of 20%. The total area for the last decade would be approximately 69 mi². However, the river water entering the HPA mixes with the existing groundwater in the aquifer. The uranium concentration in the aquifer prior to each year of river water addition must be considered in the mixture. If the existing uranium concentration is 30 µg/L, then the concentration would increase to 40 µg/L and the total volume of groundwater would double, assuming a 50–50% volume mixture (either twice the area or twice the aquifer thickness or something in between). If the prior uranium concentration of the recipient groundwater were about the background concentration of 5–10 µg/L in the

uncontaminated aquifer, the concentration would be raised to 27.5–30 µg/L for a 50–50% volume mixture for an aquifer area double that of 115 mi² or an aquifer thickness of 200 ft. Subsequent mixing by another decade of river water infiltration would raise the uranium concentration to 38.7–40 µg/L for a 50–50% volume mixture in an even larger area or greater saturated thickness.

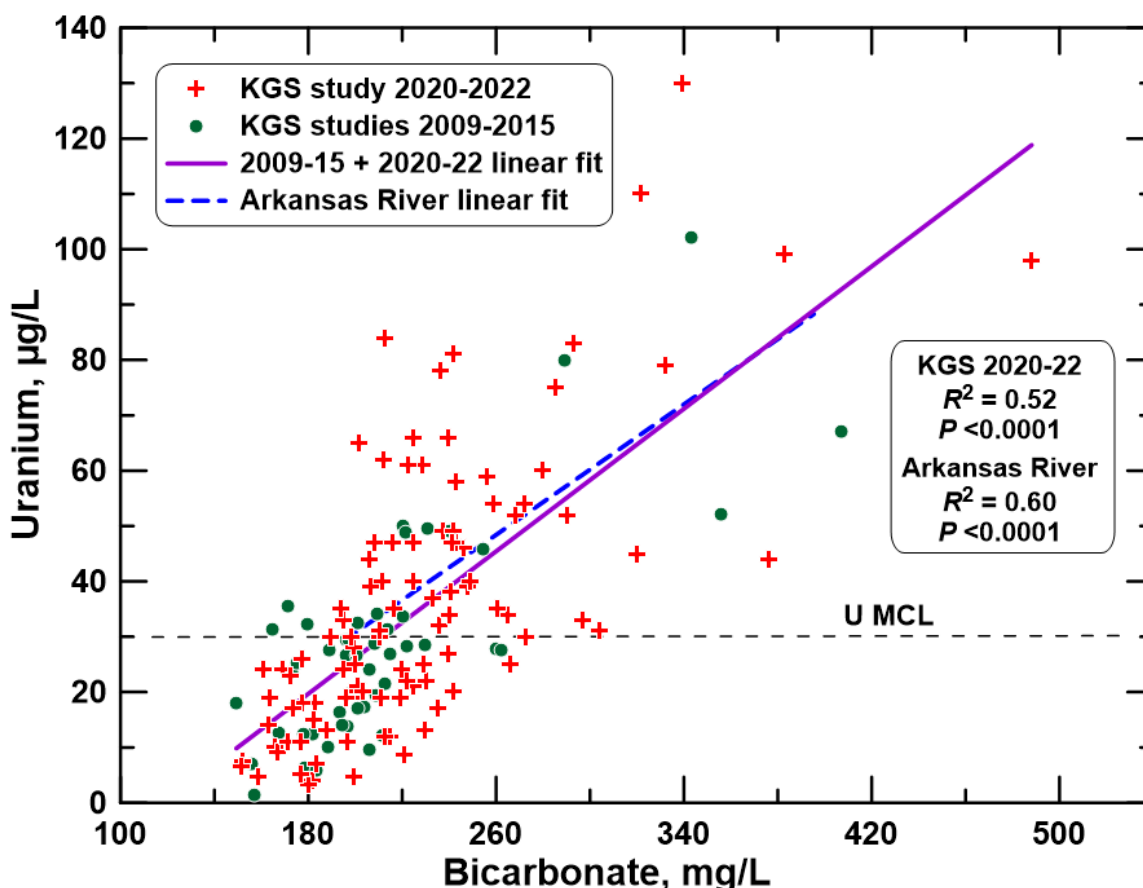


Figure 26. Uranium versus bicarbonate concentrations for groundwater from wells in the HPA based on data from KGS studies during 2009–2015 and the current KGS study.

The river loads are delivered as dissolved uranium in water that enters the unsaturated zone and the aquifers. This includes river flow, which seeps from the channel into the underlying alluvial aquifer and subsequently to the HPA aquifer where it underlies the alluvial aquifer, leakage from the earthen canals and ditches, and infiltration below fields irrigated with ditch water. The area where this water seeps into the alluvial aquifer and HPA in the upper Arkansas River corridor is roughly equivalent to somewhat more than four to five townships (about 150–180 mi²); nearly all of this area is located in Kearny and Finney counties. During high flows, river water enters the alluvial aquifer and then a relatively small amount flows into parts of the paleovalley aquifer south of the alluvium in Hamilton County. However, during low flows following high flows, the saline water from the alluvial aquifer can discharge back into the river. The average of the mean annual flows of the Arkansas River at the state line during 2012–2021 was 137 ft³/sec. This

volume spread over 150–180 mi² would be equivalent to about 10–12 inches of annual recharge without evapotranspiration. The leakage from the river channel and the main canals is affected by a small amount of evaporation during travel before infiltration, whereas the irrigation return flow from fields irrigated with ditch water would be a much smaller recharge due to substantial evapotranspiration. For a rough calculation, the average annual recharge for river, canal, ditch, and field recharge from ditch service areas might be assumed to be 5–6 inches (half of 10–12 inches).

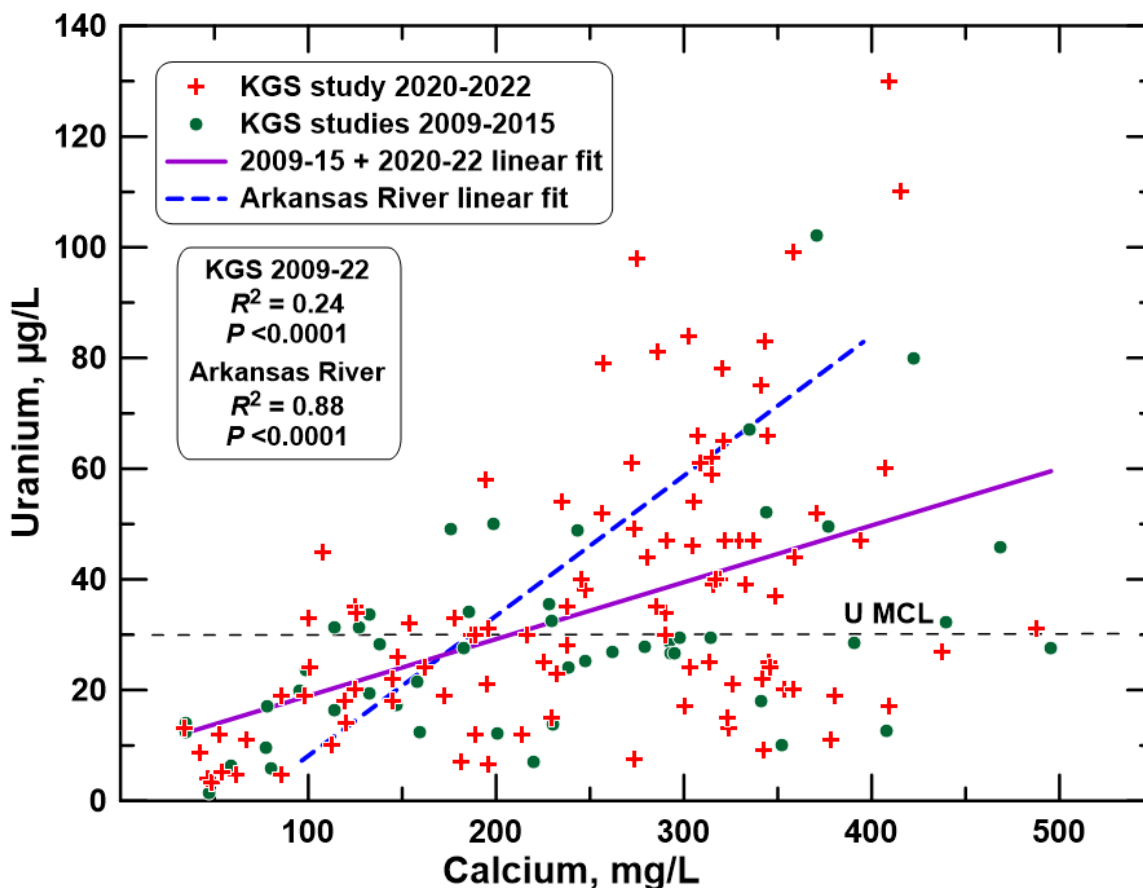


Figure 27. Uranium versus calcium concentrations for groundwater from wells in the HPA based on data from KGS studies during 2009–2015 and the current KGS study. The sample records used in the plot are the same as for Figure 26.

The average uranium concentration in Arkansas River flow across the state line was 62.5 µg/L for 1963–2010 data, which is a little more than the average of the mean annual concentrations in Table 2 (58.6 µg/L) for 2012–2021. If approximately half of the water were lost to evapotranspiration and the uranium were not adsorbed on sediments, the concentration would be doubled. Assuming an average uranium concentration of 120 µg/L, if the 5–6 inches of annual recharge conservatively mixed with an equal volume of aquifer water, the uranium concentration of the resulting aquifer water mixture would be composed of 50% Arkansas River water concentrated by evapotranspiration (120 µg/L) and 50% groundwater with the uranium

concentration of the aquifer before the mixing. For example, if the uranium content of the aquifer before mixing were 20 $\mu\text{g/L}$, the concentration in the mixture would be 70 $\mu\text{g/L}$ ($0.5 \times 120 + 0.5 \times 20$), thereby raising the uranium level by 50 $\mu\text{g/L}$ in a volume double that of the groundwater. If the recharge mixed with an aquifer volume four times that of the recharge, the uranium concentration would be raised to 40 $\mu\text{g/L}$ ($0.2 \times 120 + 0.8 \times 20$). The results would be substantially above the MCL for public supplies of drinking water. If a porosity of 20% were assumed for the aquifer, the 10–12 inches of a 50–50 mixture volume would occupy 4–5 ft of aquifer thickness; for two decades, the mixture volume would occupy 80–100 ft of aquifer thickness. If the aquifer were contaminated by a 20–80% mixture, then the aquifer thickness affected each year would be 2.5 times as great. Much of the aquifer water is pumped for irrigation, thereby redistributing saline water and further concentrating the dissolved solids after evapotranspiration consumption of the water before irrigation return flow. Thus, the uranium concentrations increase even more as a result of the return flow.

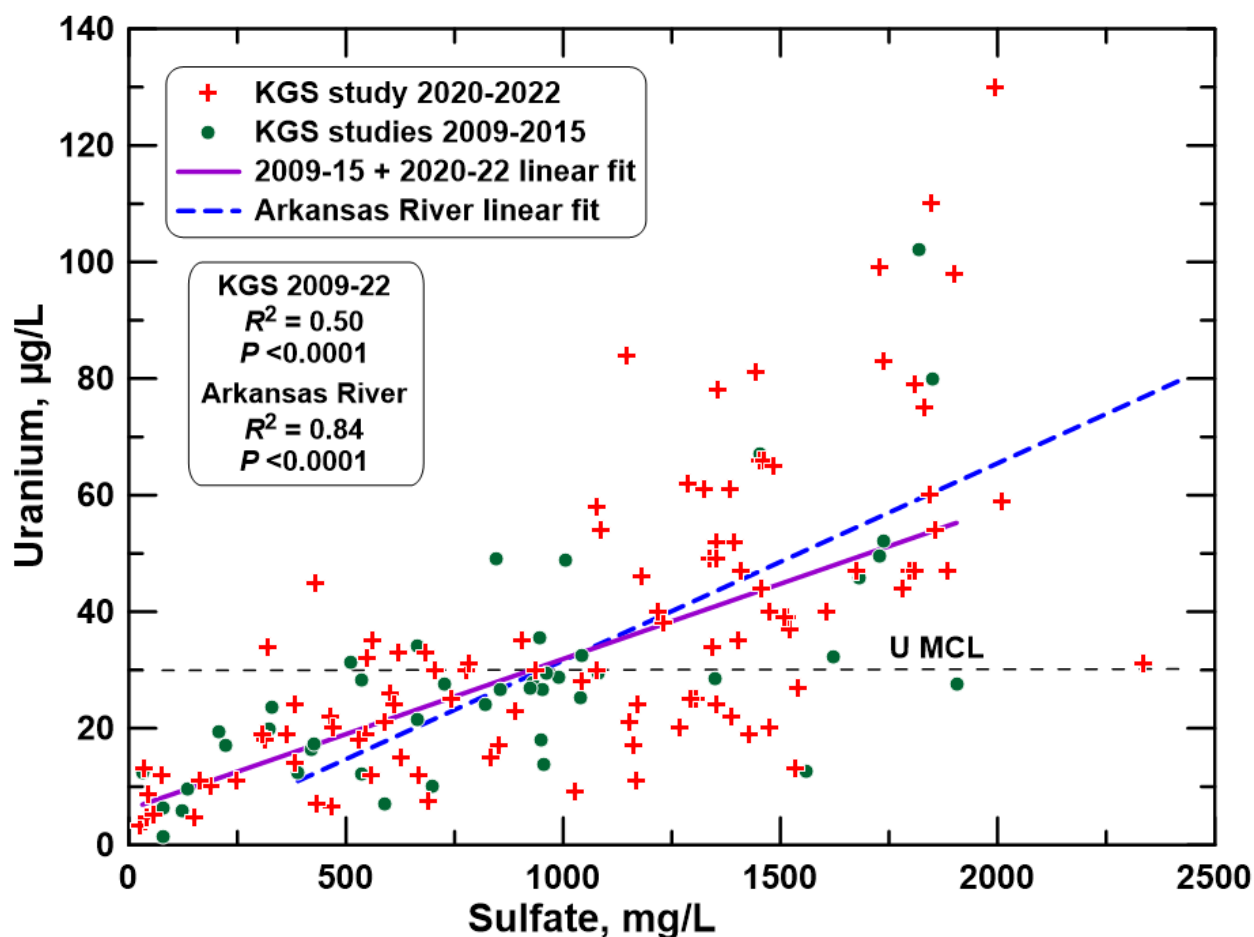


Figure 28. Uranium versus sulfate concentrations for groundwater from wells in the HPA based on data from KGS studies during 2009–2015 and the current KGS study. The sample records used in the plot are the same as for Figures 26 and 27.

Arkansas River water diverted for irrigation is usually water called for from the John Martin Reservoir in eastern Colorado under the Arkansas River Compact between Colorado and Kansas. This water generally has a uranium concentration in the range of somewhat below 20 µg/L to somewhat above 30 µg/L (see cluster of points at lower uranium values in Figures 12 and 19). However, because of the evapotranspiration consumption of that water during irrigation, the concentration of irrigation return flow to the aquifer under ditch-irrigated fields would be substantially greater. The average uranium concentration in much of the river water entering the alluvial aquifer and then the HPA via the river channel in Kearny and Finney counties would be somewhat greater than 60 µg/L because the lower salinity water is diverted into the irrigation canals in western Kearny County (Figure 1). The highest salinity water that occurs in low river flows would mainly seep into the aquifer from the Bear Creek fault zone (where the HPA begins in south-central Kearny County) to around Deerfield in western Finney County; often, there is no flow at Deerfield.

As discussed in the previous section, adsorption of uranium on sediments in the unsaturated zone can decrease its concentration in recharge reaching the aquifer and also decrease its concentration during migration of saline water within the aquifers. The longer the movement of saline water through sediment, the greater the amount of uranium that can be adsorbed due to exchange equilibria. Vertical infiltration of saline water through the unsaturated zone underlying fields irrigated with river water has been occurring for well over a century in the study area. Thus, adsorption of uranium in the unsaturated zone may no longer substantially decrease uranium concentration in the recharge reaching the water table, although some adsorption could continue as the concentration of uranium continues to increase in the recharge due to the recycling of salinity from groundwater pumped for irrigation in the same area where ditch water is used. Infiltration of saline river water into the alluvial aquifer has also occurred for many decades, and uranium adsorption in that aquifer may not remove much more uranium because the groundwater already has become saline. However, migration of saline water into the parts of the HPA with freshwater or only low salinity should result in appreciable uranium adsorption. The longer the migration path through the aquifer, the greater could be the percentage of uranium adsorption. Vertical migration within the aquifer is on the order of tens to at most a few hundred feet whereas lateral migration is on the order of hundreds to thousands of feet. Thus, the estimates of the uranium increases from uranium loads entering the study area depend on the particular conditions. Uranium concentration from the same loads could potentially increase faster in the HPA directly under the ditch service areas and in the alluvial aquifer than in areas where lateral migration is carrying the water into largely uncontaminated portions of the aquifer.

Sorption of uranium by the HPA sediments is expected to occur on different types of sites, with iron, manganese, and other metal oxides probably more important than clay minerals per unit surface area due to the negative charge of the uranium-carbonate complexes dissolved in the groundwater, although the volume of clay is substantially greater than that of the metal oxides. The rates of uranium desorption from the sediments would depend on the different types of adsorption sites if freshwaters entered a portion of the heavily contaminated aquifer with substantial uranium adsorption. A study of uranium sorption and desorption in alluvium in the Yucca Mountain area of Nevada (proposed as a nuclear waste disposal site) found that the desorption is not as fast as sorption and that some uranium remained adsorbed (Scism, 2005; Scism et al., 2006). Thus, although uranium could be released from sediments to freshwater that

was flushing a contaminated part of the aquifer, the amount would probably be lower than originally adsorbed and it would be released at a slower rate than the earlier sorption.

Objective 8 (Tasks 10–12): Communicate the results of the study to state and local agencies and the public.

Task 10: Update website for upper Arkansas River corridor

A new website was developed for the current study; it includes a link to the web pages of the prior Upper Arkansas River Corridor Study. The website is available at <https://www.kgs.ku.edu/Hydro/UARP/index.html> and will be updated to include the latest information provided in this final report along with the data for the KDHE private well study and this study.

Task 11: Progress and final reports for the study

Reports provided to the KWO included a mid-year status report in February 2020, a year 1 report in July 2020, and an update report in November 2020. This report is the final one for the study.

Task 12: Presentations and communication of study results

A presentation was given on salinity and uranium distribution and fate in the upper Arkansas River corridor at the August 1, 2019, meeting of the Kansas Water Congress at Kansas State University.

A presentation on progress during the first year of the study was given to the KWO, other state agencies, and GMD3 on June 23, 2020.

A study summary was prepared for the Arkansas River Compact Administration meeting of December 2021.

A presentation was given on Arkansas River water quality and its impact on groundwater quality in southwest Kansas at the Arkansas River Water Quality Conference at Lamar, Colorado, on May 10, 2022, attended by individuals from Colorado and Kansas in state and local agencies, non-governmental agencies, universities, advisory committees, and the Kansas legislature, as well as those involved in various water uses such as agriculture and public water supply in the two states.

A short report was prepared at the request of the Kansas Department of Emergency Management (KDEM) concerning how many wells along the Arkansas River in southwest Kansas are affected by the presence of uranium exceeding the MCL for public supplies of drinking water. The report sent to the KDEM on August 30, 2022, is included in the appendix; the tables in the report have been updated to include later data obtained during this study.

Information from this study was used during the Arkansas River Basin Water Quality Issue Panel held on November 17 at the 2022 Governor's Water Conference in Manhattan, Kansas. Don

Whittemore, a member of the panel, gave a brief summary of current surface water and groundwater quality conditions in the Arkansas River basin.

Study results were also presented at the Kansas Hydrology Seminar on November 18, 2022, at the University of Kansas.

Implication of Observations

The salinity of most of the shallower portions of the HPA underlying the river valley and the ditch-irrigated area is generally expected to be greater than in the deeper portions of the aquifer because the saline water source is from the surface. However, saline water flow down the gravel packs of unsealed wells, especially large-diameter wells such as those constructed for irrigation, can allow shallow saline groundwater to penetrate to the screened intervals of the wells and produce pockets of saline groundwater in the deeper parts of the aquifer. Pumping by wells near those pockets of deep saline groundwater can cause migration of that water toward those wells. Thus, the vertical distribution of salinity and uranium can be uneven and complex across the contaminated region of the HPA, especially in locations of wells with different construction and pumping rates.

For example, water-quality data for the study show that salinity and uranium concentrations can range substantially within a relatively small geographic area. This indicates that lithology and well construction are important controls on infiltration of saline river water (from the channel and used for ditch irrigation) to the aquifer. For example, north of the river and west of Deerfield are two domestic drinking water wells about 0.25 mi apart that yielded samples in the KDHE voluntary program of 2019 with 150 mg/L and 380 mg/L sulfate concentration and 13 µg/L (both samples) uranium concentration. Within a mile to the west and north-northwest of the well with 380 mg/L sulfate are two domestic wells sampled in 2019 for which the water contained 930 mg/L and 1,200 mg/L sulfate and 38 µg/L and 58 µg/L uranium, respectively. About a mile to the east-northeast of the well with 150 mg/L sulfate is a domestic well sampled in 2019 with a sulfate content of 1,600 mg/L and uranium of 45 µg/L. These data and the distribution of older well water-quality data in the area suggest that aquifer characteristics such as substantial clay thickness in the HPA could be retarding downward movement of salinity. No well log exists for the well with 150 mg/L sulfate but one does for the well with 380 mg/L sulfate; the screened interval for that well is 310–350 ft below land surface and the annular space in the well is grouted from 0 to 290 ft. The lithology above the well screen indicates several clay units, including some of substantial thickness. Thus, clay units appear to be retarding the downward movement of saline water while the long grout seal in the well prevents the flow of saline water down the annular space to the screened interval.

Another example is an irrigation well east of Garden City that was sampled in 2015 and yielded water with sulfate and uranium concentrations of 1,850 mg/L and 80 µg/L, respectively. Within 0.8 mi are five domestic wells sampled in 2019 with sulfate concentrations of 240–510 mg/L and uranium concentrations of 16–24 µg/L. No well log is available for the irrigation well but a well log for another irrigation well about a half mile to the south indicates that a few substantial clay layers exist in the area. The irrigation well producing high sulfate and uranium groundwater is

probably older than mid-1975, when a requirement for drillers to file well logs with the state went into effect. Older irrigation wells in the study area typically have a small grout interval (usually from the surface to a depth of 10–20 ft) or no grout and a gravel pack that extends either from the surface or below the grout interval down the annular space through the screened interval. For example, an irrigation well with a well log about two miles to the northeast of the well with high sulfate and uranium was completed in 1980 and has a screened interval of 150–278 ft, a grout seal of 0–10 ft, and a gravel pack of 10–278 ft. The borehole diameter for this well is 28 in and the casing diameter is 16 in, which are fairly typical of irrigation wells in the region. Thus, there is an annular cross section equivalent to 400 in² of gravel pack through which saline water can flow from the near surface down the well annulus. Drilling of a well usually results in fine sediment in the drilling mud invading the borehole walls. After the well casing and screen(s) are installed, the well is developed; the pumping clears the fine sediment from the screened interval but leaves most of the fines in the borehole wall opposite the casing. Thus, when water from the near surface flows down the gravel pack to the aquifer, it can bypass much of the saturated zone opposite the casing and then enter the upper zone of the screened interval.

A third example is a domestic well in the Southside ditch area south of the Arkansas River that is only about 350 feet southeast (as indicated on the domestic well log) of an active irrigation well in Finney County. The wells were drilled within the last decade, the domestic well in 2016 and the irrigation well in 2015. A former irrigation well with the same water right number was located 490 ft south of the new irrigation well according to WIMAS records, which would place it about 350 ft southwest of the 2016 domestic well. The domestic well and the prior irrigation well are each about 300 ft northwest of the Southside ditch; the new irrigation well is approximately 650 ft northwest of the ditch. The domestic well has a screened interval of 305–345 ft with grout seals of 4–24 ft and 270–280 ft across a clay at 270–285 ft. The log of the new irrigation well indicates fine to medium sand at a depth of 234–283 ft and fine sand with clay stringers at 283–314 ft, so the clay unit at 270–285 ft at the domestic well does not appear to be as significant at the irrigation well location. The irrigation well has a screened interval of 180–340 ft with a grout seal only at the upper part of the well (0–20 ft). Water reports for the former irrigation well indicated that it pumped during 1967, 1980–1985, and 1998–2012. The new irrigation well pumped during 2015–2021. The domestic well was a part of the KDHE voluntary sampling program, and the irrigation well was included in the sampling for this study. The sulfate and chloride concentrations for the domestic well sampled in the fall of 2019 was 750 mg/L, which was about half that of the concentration (1,508 mg/L) of the sample from the irrigation well collected in September 2022. The chloride concentration was also appreciably lower (81 mg/L) in the domestic well than in the irrigation well (133 mg/L) water. The uranium concentrations in the domestic and irrigation wells were also appreciably different: 22 µg/L and 39 µg/L, respectively. The new irrigation well is drawing water from about 125 ft of the HPA above the screened interval of the domestic well and that water is mixed with the deep HPA groundwater. This implies that the shallow HPA must have a salinity substantially greater than indicated by the sulfate concentration of 1,508 mg/L, a concentration that represents the mixture drawn from the 180–340 ft screened interval that includes the deep aquifer concentration of 750 mg/L. A clay with some sand is indicated at 157–180 ft on the well log of the new irrigation well. If a grout seal had been placed across this clay unit in the irrigation well, it could have potentially prevented some of the very saline groundwater in the shallow HPA above the screened interval from entering the water pumped from the well. If gravel pack flow was

important at the prior irrigation well, its effect is expected to be to the south-southeast of the well due to the water-level gradient in the area, a direction that is to the south of the domestic well. If gravel pack flow is significant at the new irrigation well, enhanced vertical movement of salinity would primarily impact the HPA in the upper part of the screened interval and not the deep aquifer. If it also affected water quality in the deep aquifer, the south-southeast direction of groundwater flow could potentially impact the deep aquifer at the domestic well in the future.

These conditions indicate the critical importance of a grout seal in the annulus of a well above the screened interval in the study area, not only for those wells from which water is pumped for drinking purposes, but also for other wells that can be potential avenues for rapid transport of saline water with high uranium concentration from the near surface down to the producing zones of the HPA. An irrigation well with a log about a half mile to the south of the irrigation well east of Garden City with high sulfate and uranium concentrations discussed above was completed relatively recently (2013) and has a grout interval of 0–80 ft, which is definitely more than most irrigation wells in the area, a gravel pack of 80–240 ft, and a screened interval of 100–240 ft. Recommendations that longer grout seals (such as in this well) be placed in new irrigation wells and other non-domestic wells and also that grout seals be placed from just above the uppermost screened interval to the land surface in domestic wells would not only help protect the aquifer from more rapid contamination but result in better quality water when the wells are pumped. Also, sealing selected intervals of the gravel pack in abandoned irrigation wells located within the alluvial aquifer boundaries and in ditch irrigation areas would prevent those wells from being constant point sources of contamination to the HPA; usual plugging of a well involves placing a grout seal within the casing but not in the annulus.

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Appendix

Report to Kansas Department of Emergency Management

In August 2022, the Kansas Department of Emergency Management (KDEM) requested information about the number of wells affected by uranium concentration of concern to drinking water. The Kansas Geological Survey (KGS) prepared a report describing the Kansas Department of Health and Environment (KDHE) voluntary private well study, the current KGS study, and the number of wells of different types with uranium exceeding the maximum contaminant limit for public supplies of drinking water. The following text and tables constitute the report sent to the KDEM on August 30, 2022.

Kansas Department of Health and Environment Voluntary Private Well Sampling Program in the Upper Arkansas River Corridor

The Kansas Department of Health and Environment (KDHE) invited owners of private wells in the upper Arkansas River corridor to voluntarily submit samples for measurement of selected constituents of interest to human water consumption. The sampling program, conducted in the fall of 2019, focused on the area of saline groundwater from Hamilton to Ford counties delineated by a 2000 map by the Kansas Geological Survey (KGS). Uranium was one of the constituents determined in the samples. The maximum contaminant level (MCL) allowed for uranium concentration in public supplies of drinking water is 30 µg/L (micrograms per liter). The domestic wells sampled in the voluntary program are not regarded as public water supplies and, thus, are not regulated by the state as are public water supplies. The following table lists the number of samples collected from different aquifers and the percentage of those samples with uranium concentration exceeding the MCL.

Aquifer from which wells pump water	Number of wells sampled	Number of wells with uranium greater than the MCL of 30 µg/L	Percent of wells with uranium greater than the MCL of 30 µg/L
High Plains aquifer	220	30	14
Alluvial aquifer	4	1	25
Dakota aquifer	18	0	0
Dakota and/or alluvial aquifer	4	1	25
All aquifers	246	32	13

Kansas Geological Survey Upper Arkansas River Mineralization Study

The voluntary sampling program of the KDHE was followed by an investigation by the KGS for the Kansas Water Office on the current conditions and controls on the distribution of the chemical parameters of concern (primarily uranium) in the groundwater in the upper Arkansas River corridor. Samples were collected during 2020–2022 by Southwest Kansas Groundwater

Management District No. 3 in cooperation with the KGS from public supply, domestic, irrigation, and stock wells and by the KGS from observation wells. Laboratories of the KDHE and the KGS determined concentrations of different inorganic constituents in the samples; the KDHE measured the uranium concentration. The current investigation is ongoing but will be completed this fall; additional samples have been collected that the KDHE is analyzing for uranium and several additional samples will be collected to complete the sampling program.

The higher percentage of wells with uranium concentration exceeding the MCL in the KGS study compared to the KDHE voluntary sampling program is due to the focus of the sampling in the KGS study; sampling locations were chosen to fill spatial gaps in areas where uranium is elevated based on prior sampling. The following table lists the number of samples collected from different types of wells and the percentage of those samples with uranium concentration exceeding the MCL. The two public water supply wells with uranium greater than the MCL are part of a wellfield that delivers water to a facility treating the water before human consumption.

Type of well sampled	Number of wells sampled	Number of wells with uranium greater than the MCL of 30 µg/L	Percent of wells with uranium greater than the MCL of 30 µg/L
Public water supply	18	2	11
Domestic	50	25	50
Irrigation	20	14	70
Stock	5	3	60
Observation	11	6	55
All well types	104	50	48

(Note: This table has been updated to reflect additional wells sampled since the report was prepared for the Kansas Department of Emergency Management.)