Addressing Groundwater Goals of the Missouri Regional Planning Area, Phase II: First Year Progress Report

Kansas Water Office Contract #18-117

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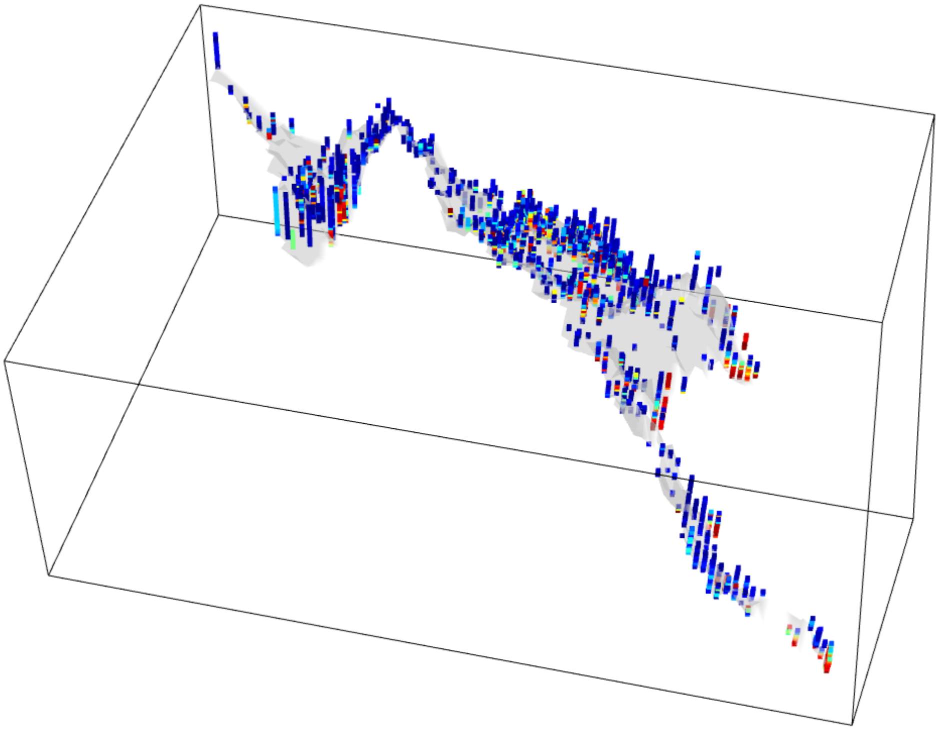

Kansas Geological Survey Open-File Report 2019-3
May 2019

GEOHYDROLOGY

KANSAS GEOLOGICAL SURVEY
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1. Introduction

This report documents the work carried out during the first year of Addressing Groundwater Goals of the Missouri Regional Planning Area: Phase II, a five-year project funded by the Kansas Water Office (KWO Contract #18-117). As stated in the project's Scope of Work, "The objective of this work is to establish a groundwater-level and groundwater-quality monitoring network in the Missouri Regional Planning Area (MRPA) and interpret the results from the acquired data to provide improved estimates of safe yield and establish a groundwater quality baseline." Project tasks listed in the Scope of Work document are as follows:

Water Quantity

1. Assess the accuracy and robustness of bedrock elevation and unconsolidated material maps generated in Phase I using a variety of interpolation methods.
2. Identify exact locations of some existing wells, specifically those in areas where multiple wells with the same nominal (Public Land Survey System [PLSS]) location provide conflicting bedrock depth estimates.
3. Identify locations of existing wells to equip with pressure transducers and locations for drilling new monitoring wells.
4. Drill new monitoring wells in areas with limited existing wells to better understand groundwater availability and movement throughout the MRPA.
5. Begin interpretation of groundwater-level surface and aquifer storage and safe yield.

Water Quality

1. Interpret information reported in Phase I as it relates to chemical characteristics and provide potential explanations for concentration trends.
2. Select groundwater sample collection sites and collect initial samples, with collaboration from Missouri Regional Advisory Committee members.
3. Analyze collected groundwater samples for selected chemical constituents.
4. Interpret analytical data and plan for future sampling.

Information Dissemination

1. Put information collected in Phase I as well as Phase II into a user-friendly format and make available to stakeholders, researchers, and other interest groups.

All of these except Quantity Task 4 were addressed to at least some extent during year 1. The headings for each of the following sections will identify the tasks addressed in each section.

2. Location and Sampling of Existing Monitoring Wells (Quantity Task 3, Quality Task 2)

The first sites selected for groundwater-level measurement and sampling were 10 U.S. Geological Survey (USGS) monitoring wells in the MRPA that the USGS sampled in 2011 (fig. 1); the Phase I report (Batlle-Aguilar et al., 2017) includes information about these wells along with the nitrate concentration (see table 2 in the Phase I report). Four of the wells are in Nemaha County, four are in Brown County, and two are in Doniphan County. All 10 of the wells were interpreted by the USGS to be in the glacial drift aquifer. After selection of locations, the USGS had these wells drilled to depths just below the water table to sample the upper part of the water-bearing sediment.

The ownership of these wells has since been transferred to the KGS. On August 8, 2018, KGS employees attempted to locate, measure water levels in, and sample groundwater from these 10 wells. Nine of the wells were located, and water level measurements were taken at eight of these locations. One of the wells was located on private property and could not be sampled at the time. Landowner permission has since been received, and this well will be measured and sampled in the next round of sampling. Of the eight wells measured and sampled, one well did not have adequate water to collect a sample for analysis and two had very slow infiltration into the wellbore. Well logs for these two wells indicate that the screens are located in clay and silt and thus are not sufficiently connected to aquifer material. Groundwater samples will not be collected from these wells in subsequent monitoring trips. Table 1 provides water-level measurement and sampling information for the 10 wells. The location and elevation information obtained during the KGS visit was slightly different for most of the wells from that in the Water Well Completion Records (WWC5) Database well logs filed by the USGS in 2011; Appendix table A1 contains additional information for these wells, including the WWC5 and the current KGS location and elevation information, the WWC5 screened interval, along with the well depth and water levels measured by the KGS on August 8, 2018. Appendix table A2 describes the lithologic character of the material encountered during drilling of the wells as listed in the WWC5 records.

The next round of monitoring and sampling will occur this spring and will include monitoring and sampling five additional wells owned by the City of Hiawatha.

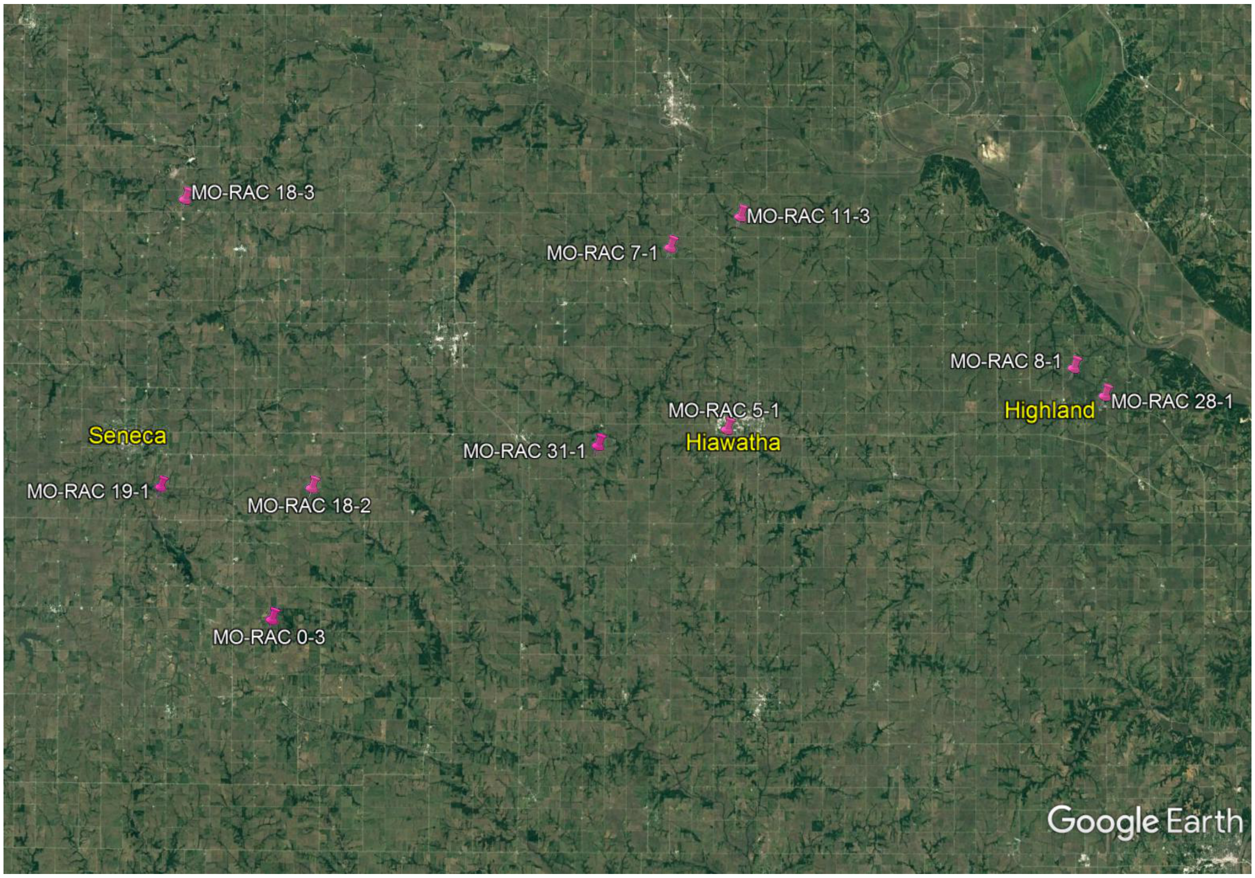


Figure 1: Locations of 10 existing monitoring wells previously monitored by the USGS.

Table 1: Water-level measurements and groundwater sampling information from August 8, 2018. WV = Well Volume.

	Depth to Bottom of Well (ft)	**Depth to Water (ft)**	**Water Sampling Notes**
MO-RAC 0-3	71.45	18.48	Purged ~ 7 gallons (1.5 WV) took 2x500 mL samples @9:30 a.m. Slow recovery.
MO-RAC 18-2	26.18	13.43	Purged ~ 5 gallons (1.5 WV) took 2x500 mL samples @10:25 a.m. Decent recovery.
MO-RAC 19-1	36.80	23.81	Purged ~ 3.3 gallons (1 WV) took 2x500 mL samples@11:20 a.m. Slow recovery.
MO-RAC 18-3	**-**	-	Can't ID which of the 6 wells at this location belong to USGS. None look similar to those we've seen or have a lock.
MO-RAC 7-1	24.58	14.43	Purged ~ 4 gallons (1.5 WV) took 2x500 mL samples @12:45 p.m. Great recovery.
MO-RAC 11-3	26.29	18.45	Purged ~ 3 gallons (1.5 WV) took 2x500 mL samples @1:10 p.m. Decent recovery.
MO-RAC 31-1	37.44	31.64	Purged ~ 1.5 gallons (1 WV) took no samples as there was no recovery @1:45 p.m.
MO-RAC 5-1	**-**	**-**	Found the well on private property. No measurements, no samples.
MO-RAC 8-1	40.68	12.60	Purged ~ 10.5 gallons (1.5 WV) took 2x500 mL samples @3:10 p.m. Decent recovery.
MO-RAC 28-1	46.01	36.81	Purged ~ 4 gallons (1.5 WV) took 2x500 mL samples @3:40 p.m. Decent recovery.

3. Bedrock Elevations and Well Locations (Quantity Tasks 1 and 2)

This section describes development of a revised bedrock elevation map for the MRPA and the related task of improving the accuracy of the location information for some wells in cases in which multiple wells with the same nominal location exhibited strongly conflicting bedrock elevations. In addition, it discusses the assessment of wells or test holes that did not seem to reach bedrock, according to the corresponding drillers' logs, but whose final depth is below the estimated bedrock elevation at that location. The bedrock elevation is relevant to the overall goal of estimating safe yield in the MRPA because, for the most part, one expects the most water-productive materials in the subsurface to be the coarser sediments above bedrock. However, some wells in the MRPA do produce moderate amounts of water from bedrock, particularly from zones where limestones and shales have collapsed due to gypsum dissolution, so the bedrock surface should not be viewed as an absolute lower boundary to water-productive material in this area.

The bedrock elevation estimates used in this project are derived from more than 2,000 water well drillers' logs, including logs associated with completed water wells, stored in the KGS's WWC5 database, and logs from test holes (that were not completed as wells). The bedrock depths picked from the logs are converted to elevations by subtracting the depth from the estimated land surface elevation at the well location, extracted from a LiDAR (Light Detection and Ranging) data set with a 1 meter x 1 meter lateral resolution and a vertical resolution of ~20 centimeters. Several factors contribute to uncertainty in the bedrock elevation estimates, including the following:

1. Uncertainty in the depths recorded in the drillers' logs, which is estimated to be on the order of one to two feet.

2. Ambiguity in picking the bedrock boundary in some logs. This choice is fairly clear in most logs, which reflect the expected picture of unconsolidated sediments (clays, silts, sands, and gravels) overlying limestone and shale bedrock (Denne et al., 1998). However, in some logs (perhaps around 15% of the total), unconsolidated sediments also occur below intervals described as limestone or shale, leading to uncertainty in the bedrock pick. In those cases, we have attempted to make a reasonable pick given the context.

3. Inaccuracy in the location information for the logs. The location information for about 77% of logs is derived from the Public Land Survey System (PLSS, a.k.a. "legal") coordinates listed on the drillers' reports, with the remainder obtained using GPS. The PLSS coordinates are converted to numerical values using software that assigns each borehole the latitude and longitude coordinates associated with the center of the smallest PLSS division listed (typically a quarter-quarter-quarter section, which has an area of 10 acres). This location inaccuracy, in addition to simply placing the resulting bedrock elevation data point in the wrong location, leads to errors in the land surface elevation assigned to the log and thus to errors in the computed bedrock elevation.

The bedrock depth and elevation uncertainties are most apparent in those cases in which multiple logs are assigned the same nominal location due to having the same PLSS coordinates. We have examined a number of such cases and have attempted to resolve bedrock depth conflicts exceeding 10 feet in magnitude by obtaining more accurate location estimates for some wells and/or by picking new bedrock depths after re-examining the logs. Specifically, we modified 28 bedrock depth picks and obtained more accurate location estimates for 25 logs, primarily by close examination of the areas in question using Google Maps.

It is important to realize that the bedrock data conflicts identified in these cases (multiple boreholes at the same nominal location) are simply the most obvious symptom of a more pervasive problem: The bedrock elevation estimates are uncertain everywhere. In fact, a geostatistical analysis of the data (details are beyond the scope of this report) indicates that the bedrock elevation values are too noisy to merit the kind of *exact interpolation* that was used to produce the bedrock map during Phase I of this project. Interpolation is the process of estimating data values at locations between observation locations; in this case, bedrock elevation values are interpolated from the borehole locations to a large number of locations (nodes) in a regular grid to produce the bedrock elevation map. Exact interpolation procedures will reproduce the observed data values wherever a grid node coincides with an observation location. Although this is reasonable behavior when the observations are relatively noise-free, exact interpolation produces numerous interpolation artifacts (e.g., bullseyes) when applied to noisy data. Consequently, we have chosen to use a *smoothing interpolation* algorithm to produce the revised bedrock map presented here. Smoothing interpolation, as the name implies, produces a smooth surface that closely reflects the observed data values but does not attempt to exactly reproduce them. Specifically, we use the geostatistical interpolation algorithm called kriging (Goovaerts, 1997), here implemented as a smoothing interpolator. The statistical modeling process that underlies kriging helps to identify the appropriate level of smoothing to use in the interpolation.

The initial bedrock elevation data set comprised 2,081 boreholes, including 1,130 WWC5 logs and 951 test holes. The WWC5 logs included 57 that were transcribed into the WWC5 logs table subsequent to the Phase I work. The test hole data were compiled from various reports during Phase I. Before interpolating these data to produce the revised elevation map, we performed a cross-validation analysis to identify highly anomalous bedrock elevations – those most out of keeping with bedrock elevation values in nearby boreholes. This process led to the removal of 23 outliers, leaving 2,058 boreholes (1,116 WWC5 and 942 test holes) in the final data set. However, because there are still a number of cases in which multiple boreholes share the same nominal location, the 2,058 boreholes represent only 1,775 distinct locations. The average bedrock elevation is used as the observed data value at locations representing multiple boreholes.

Figure 2 shows the interpolated (kriged) bedrock elevation map overlain by the borehole locations, and fig. 3 shows the map without the borehole locations, for clarity. The bedrock elevation has been set equal to land surface elevation in a few locations where the interpolated bedrock surface is above land surface. This happens particularly where present-day stream valleys have cut down into bedrock, creating a contrast between the generally smooth bedrock surface and the highly detailed representation of the valleys provided by the LiDAR-based surface elevation data. Not surprisingly, this bedrock elevation map is broadly similar to that presented in the final report for Phase I of this project (Batlle-Aguilar et al., 2017, fig. 11).

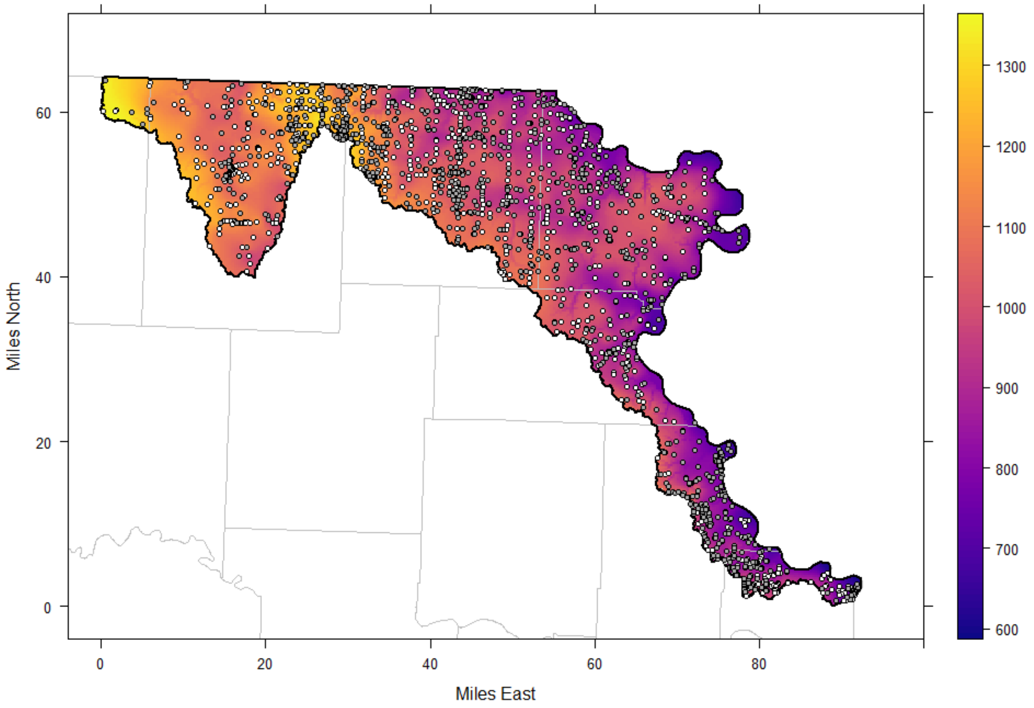


Figure 2. Interpolated bedrock elevation (feet above sea level) with locations of boreholes (white: WWC5, gray: test hole) with bedrock elevation data.

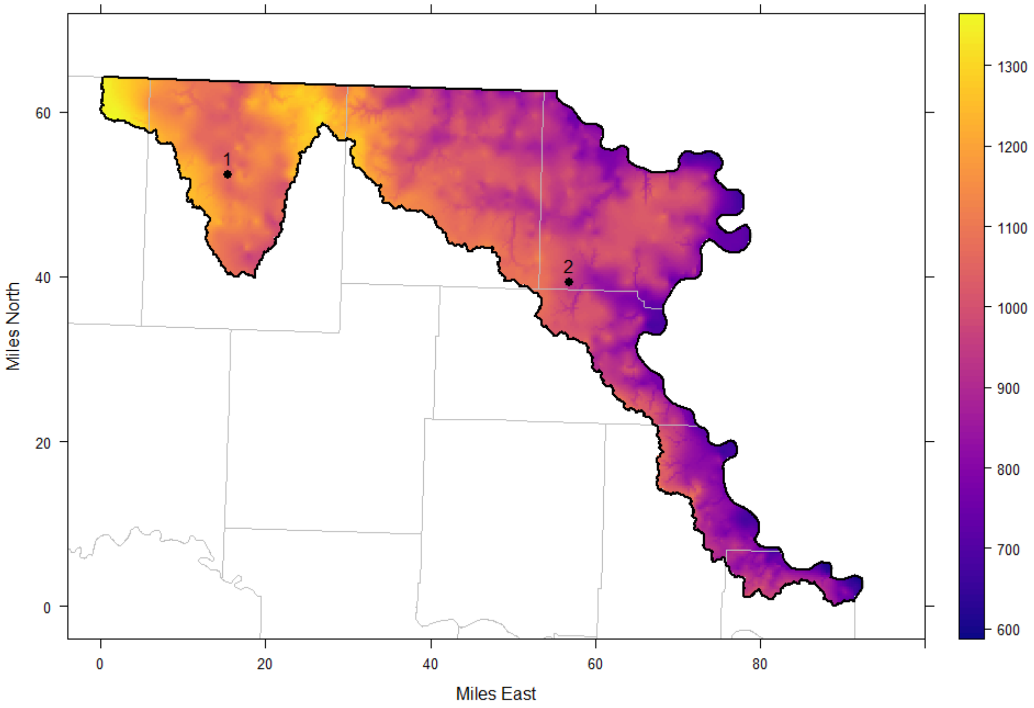


Figure 3. Interpolated bedrock elevation without borehole locations. The points labeled 1 and 2 are used in fig. 5 to illustrate how to interpret the kriging results.

It is also similar to the bedrock elevation map presented in Denne et al. (1998, Plate 1). In particular, fig. 3 agrees quite well with the Denne et al. (1998) map in terms of the placement and orientation of the paleovalleys (created by previously existing streams) in the bedrock surface.

Any interpolated map is subject to uncertainty, with the uncertainty in the interpolated value increasing with increasing distance from data points (boreholes in this case). One advantage of kriging over other interpolation techniques is that it provides a quantitative estimate of this uncertainty. Kriging is based on conceptualizing the interpolated variable (here, bedrock elevation) at any location as normally distributed with an average or expected value equal to the interpolated value at that location and a standard deviation that reflects the distances from that location to nearby data points. The resulting set of standard deviation values over the interpolation grid can also be represented as a map. Figure 4 is the standard deviation map representing the uncertainty in the interpolated bedrock elevation surface shown in figs. 2 and 3. This uncertainty is small close to boreholes and larger farther from them, so the borehole locations are readily apparent in fig. 4.

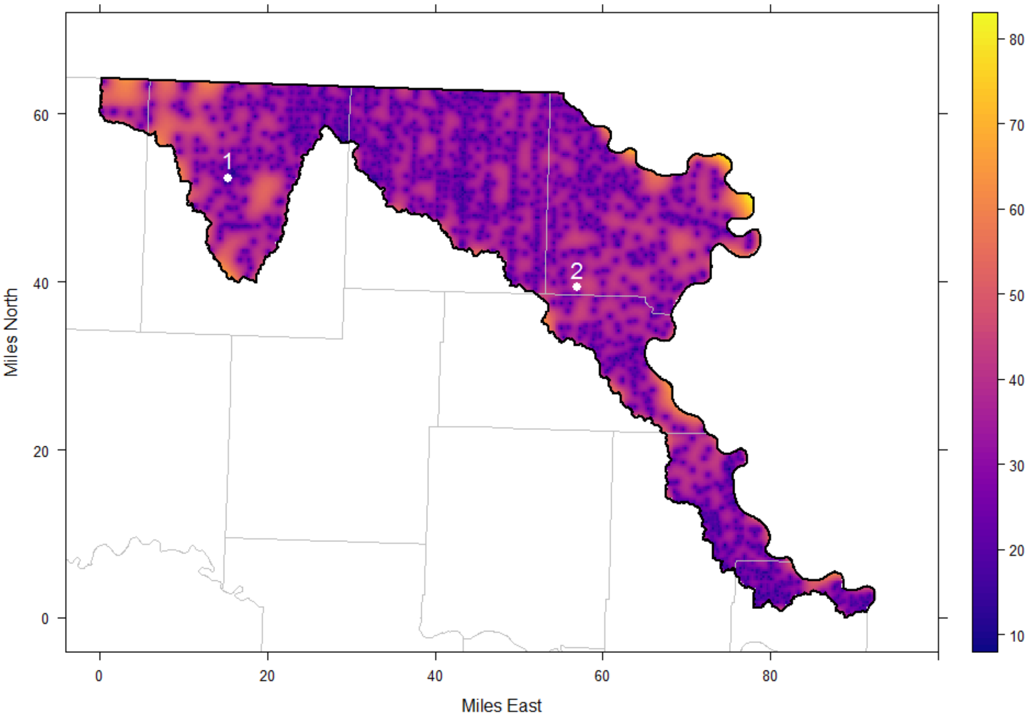


Figure 4. Map representing the uncertainty, expressed as a standard deviation in feet, in the interpolated bedrock surface shown in figs. 2 and 3. The points labeled 1 and 2 are used in fig. 5 to illustrate how to interpret the kriging results.

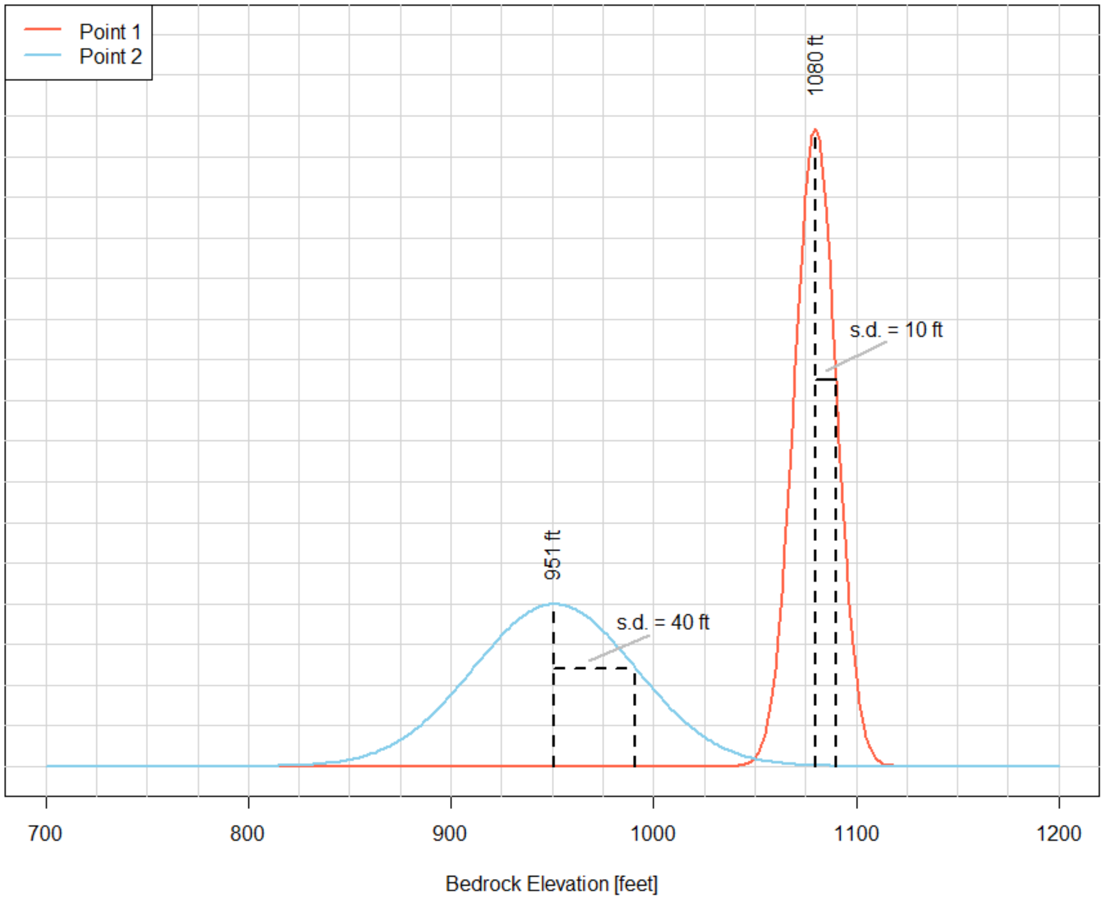


Figure 5. Interpretation of the interpolated bedrock elevation map (fig. 3) and associated standard deviation map (fig. 4) at the points labeled 1 and 2 in those maps. At each point, the bedrock elevation is represented as a random variable following a normal distribution (bell curve) with a mean value equal to the interpolated estimate (1,080 feet at point 1 and 951 feet at point 2) and a standard deviation equal to the value shown in the standard deviation map at that location (10 feet at point 1 and 40 feet at point 2).

Figure 5 illustrates the combined interpretation of the maps representing the interpolated surface and corresponding standard deviation at the points labeled 1 and 2 in figs. 3 and 4. At point 1, the interpolated bedrock elevation is 1,080 feet. Point 1 is in an area with a very high density of boreholes, so the uncertainty in the interpolated elevation at this point is relatively low; the standard deviation of the estimate is 10 feet. Thus, the estimated elevation at this point is represented as a normal distribution (the familiar bell curve) with a mean of 1,080 feet and a standard deviation of 10 feet. This means, for example, that there is a 68% chance that the true bedrock elevation at point 1 falls between 1,070 and 1,090 feet, from one standard deviation below the mean to one standard deviation above, and there is a 95% chance that the true value falls within two standard deviations of the mean, a range from 1,060 to 1,100 feet. The interpolated elevation at point 2 is 951 feet. Because this point is in a region of lower data density than point 1, the uncertainty is higher; the standard deviation in this case is 40 feet and the resulting normal distribution is notably broader than that for point 1. In this case, there is a 68% chance that the true value falls between 911 and 991 feet (one standard deviation to either side of the mean) and a 95% chance that it falls between 871 and 1,031 feet (two standard deviations).

The Phase I work identified a number of WWC5 wells that do not seem to reach bedrock, according to the logs, but whose completion depth was below the interpolated bedrock surface developed during Phase I. This is also true of the revised bedrock surface presented here. Figure 6 shows the locations of 779 WWC5 wells whose logs contain no indication of bedrock. The completion depths for 490 of these wells are above the interpolated bedrock surface, as expected, but below the bedrock surface for 289 wells. In these latter 289 wells, the differences between the interpolated bedrock elevation and completion depth range from 0.1 to 184.4 feet, with a mean of 33.5 feet and median of 20.3 feet.

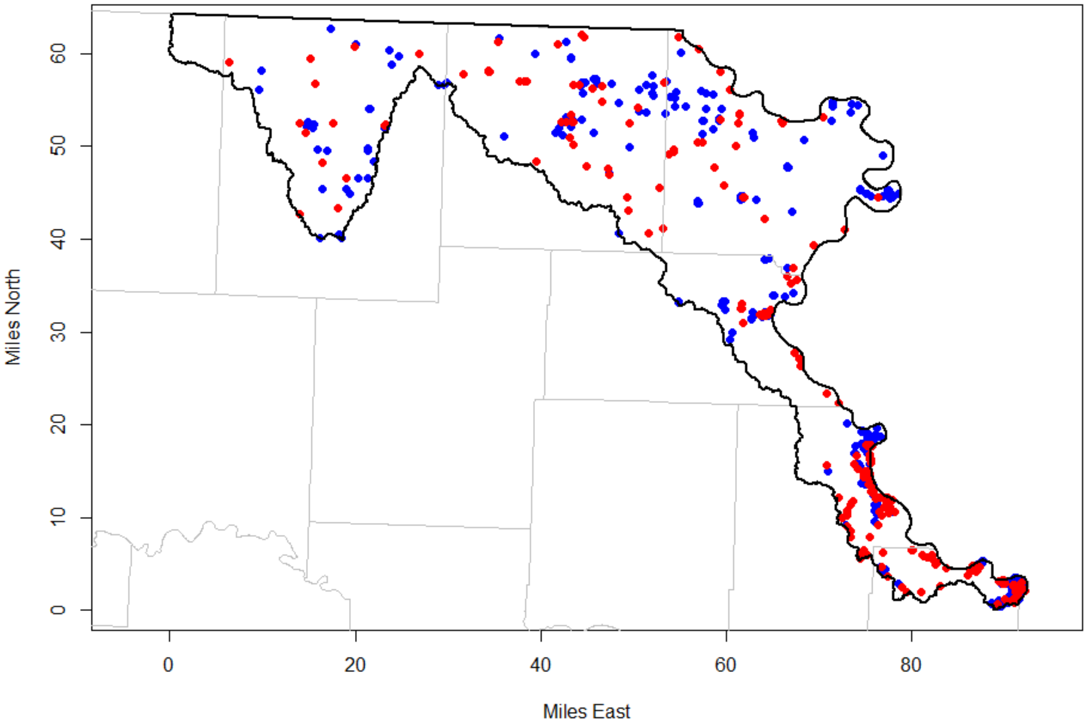


Figure 6. Locations of 779 WWC5 wells whose logs contain no indication of bedrock. The completion depths are above the interpolated bedrock surface at the well location, as expected, for 490 of these wells (blue). Completion depths are below the interpolated bedrock surface in the remaining 289 wells (red).

To attempt to address these conflicts, we have used an extension of kriging to create a number of different possible *realizations* of the bedrock surface that approximately honor the bedrock elevation values in the 2,058 boreholes in which bedrock was observed (fig. 2) but differ in detail. (The honoring of the data is approximate rather than exact because we are using the smoothing version of kriging rather than the exact version.) The realizations represent different possible renditions of the bedrock surface given the uncertainty in the interpolated values represented by the standard deviation map (fig. 4), and all realizations are equally likely given the observed data. We generated 1,000 such realizations and ranked these realizations according to the degree of conflict between bedrock elevation and completion depth in the 779 "no-bedrock" wells, aiming to identify realizations with minimal conflict. Unfortunately, the minimal-conflict realization still yielded conflicts in 227 of the no-bedrock wells, with bedrock elevations above completion elevations by an average of 30.1 feet, only a marginal improvement relative to the original interpolated surface (fig. 3). In addition, the minimum-conflict realization is only slightly different from the interpolated surface; it is 5.6 feet below the interpolated surface on average but is below the interpolated surface in only 52% of the area and above it in the remaining 48%. Since the interpolated surface represents a best estimate, in the sense of yielding the minimum expected discrepancy between estimated and actual bedrock elevations (based on the 2,058 observed bedrock elevations), a property not shared by the individual realizations, we have chosen to retain the interpolated surface as our representation of bedrock rather than using the minimum-conflict realization. As mentioned above, the "observed" bedrock elevations themselves are fairly noisy, and it would be unreasonable to expect to be able to perfectly reconcile all the available information.

Figure 7 shows the land surface elevation throughout the region, and fig. 8 shows the thickness of unconsolidated materials – the difference between land surface elevation and bedrock elevation (fig. 3). Although differing in detail from the Phase I sediment thickness map (Batlle-Aguilar et al., 2017, fig. 14), the patterns in these two maps are broadly similar.

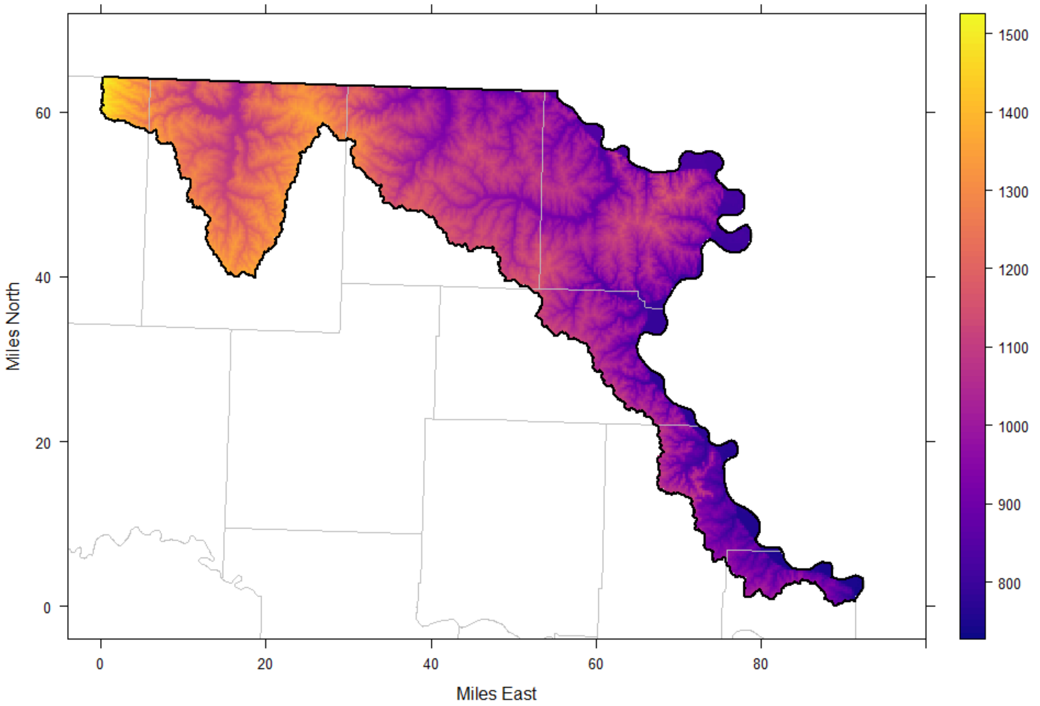


Figure 7. Land surface elevation (feet above sea level) in the MRPA.

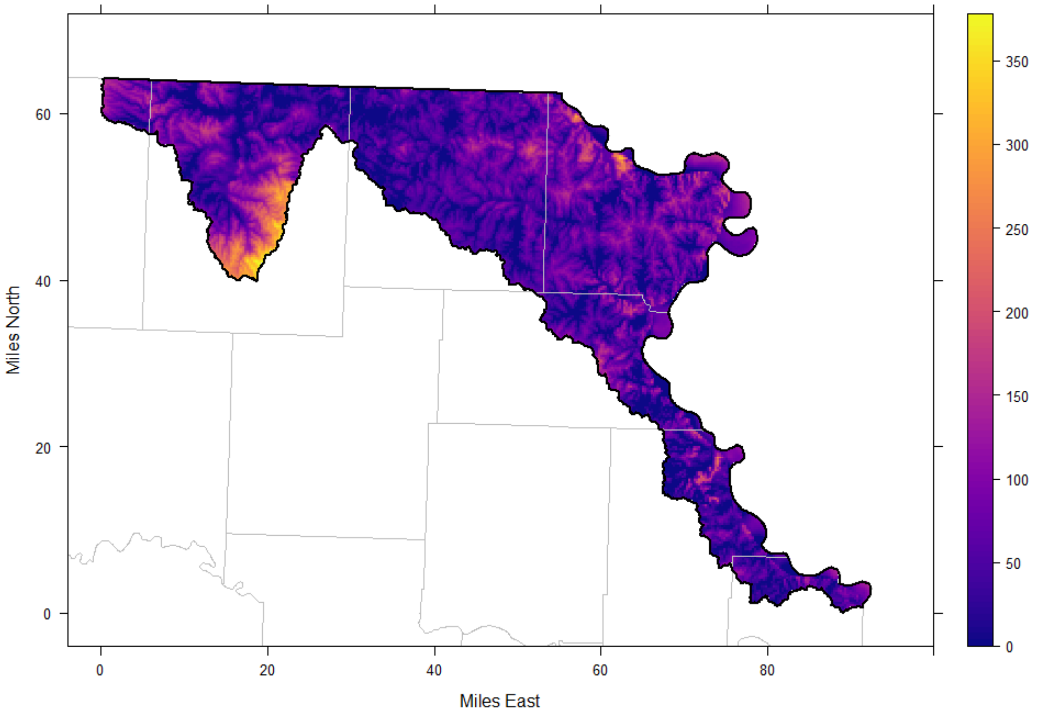


Figure 8. Thickness of unconsolidated sediments (feet) in the MRPA.

4. Distribution of Coarse Material (Quantity Tasks 1 and 5)

Phase I of this project included development of a map showing the thickness of coarse materials (sands, gravels, and sandstones) between the land surface and bedrock (Batlle-Aguilar et al., 2017, fig. 16). These materials are generally fairly permeable, meaning water will flow through them readily. Fine materials such as clay and silt are generally significantly less permeable. The distribution of permeable materials in the subsurface is a key factor controlling well yields and groundwater flow patterns. The Phase I coarse material map was produced by inspecting a number of drillers' logs (both WWC5 and test hole) and assigning a single number to each log representing the total thickness of coarse material recorded in the log. In year 1 of the Phase II work, we have worked on developing a more detailed three-dimensional (3-D) representation of the distribution of coarse materials, allowing for development of an interactive 3-D display of this information. Representing the data in 3-D also provides a means to create 2-D maps of the proportion or thickness of coarse materials between arbitrary surfaces, such as the water table at a certain time and bedrock, allowing for estimation of changes in aquifer characteristics over time. In contrast, the Phase I approach provided a single, static map, representing coarse material thickness between land surface and bedrock.

Top Depth (ft)	Bottom Depth (ft)	Description	% Coarse (assigned)
0	3	Topsoil	10
3	35	Clay, brown	0
35	38	Fine sand, coarse sand, gravel	100
38	42	Silty clay, gray	5
42	47	Sand and clay	60
47	53	Shale, gray	0

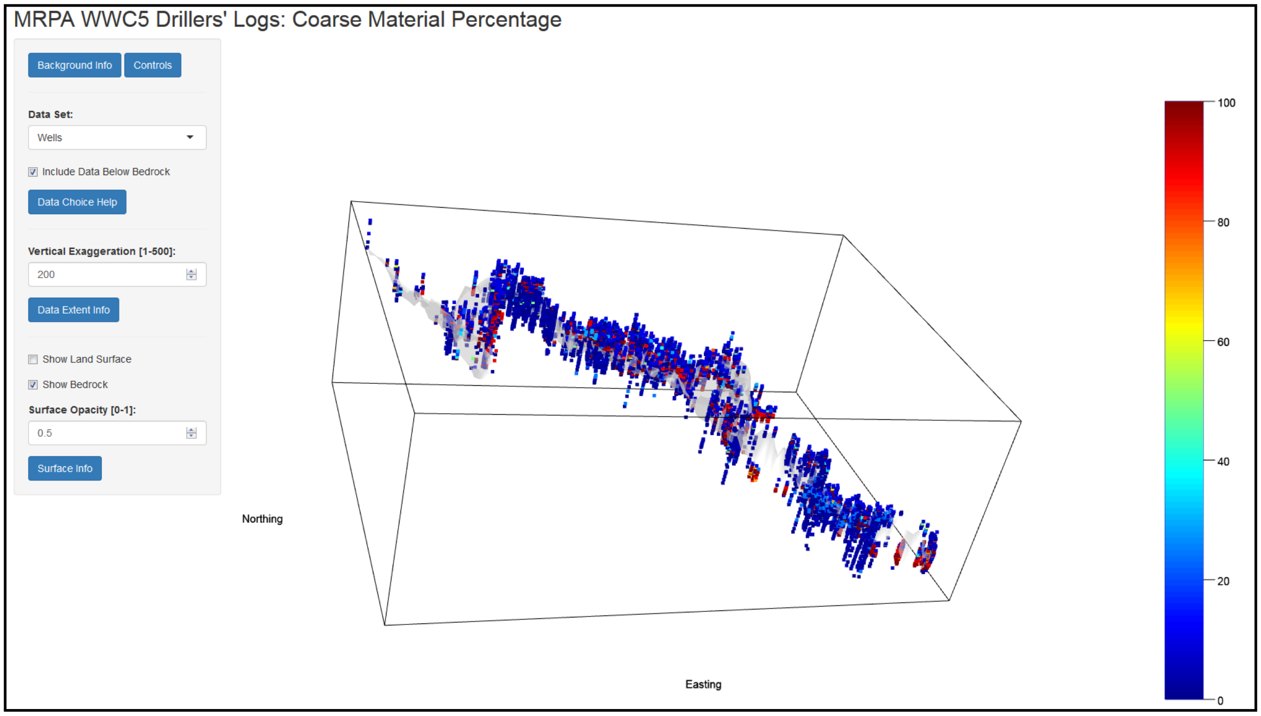
Figure 9. A typical sediment log from a drilling report. For the development of the Phase I coarse material map, this log was represented as 8 feet of coarse material (the total thickness of the two intervals highlighted in red). The current Phase II work assigns a percent coarse value to each depth interval, providing a representation of the vertical distribution of coarse material in the log.

Figure 9 illustrates the fundamental difference between the Phase I and Phase II approaches to representing the coarse material in a typical log. In Phase I, this log was represented using a single number: 8 feet of coarse material between land surface and bedrock. (The shale at the bottom of the log is bedrock.) This value, coupled with the geographic coordinates of the borehole, served as one of the data points from which the coarse material thickness map was interpolated. In the Phase II work, we have assigned a percentage coarse value to each interval in the log, providing a representation of the vertical distribution of coarse material in the borehole. The interval depth ranges are converted to elevations by subtracting them from the land surface elevation at the borehole. Adding the geographic coordinates of the boreholes to this information creates a 3-D data set representing the distribution of coarse material in the region.

Another important difference between the Phase I and Phase II approaches is that the Phase II approach represents coarseness in a gradational fashion, whereas the Phase I approach used a binary division into coarse and fine materials. For example, in the Phase I approach, silty sand was considered coarse and silt was considered fine. In Phase II, silty sand is represented as 80% coarse and silt is represented as 10% coarse.

At this point, the Phase II work uses data from approximately 2,600 WWC5 logs. The WWC5 database includes a LOGS table that contains transcriptions of the logs in the submitted drilling records. This transcription process, for logs statewide, is a continuing process. The data set presented here represents logs within the MRPA that had been transcribed into the LOGS table as of September 21, 2018. Logs transcribed since that time will be incorporated into future revisions of the data set. The Phase I work, which was based on visual inspection of logs, also employed information from test hole logs in printed reports. At present, the Phase II coarse material data set does not include test hole logs, because the processing involves "translation" of transcribed descriptions into percentage coarse values and the test hole logs have not yet been transcribed into electronic form.

The ~2,600 WWC5 logs contain descriptions of the sediments and rocks in a total of ~18,000 depth intervals. However, there are only ~5,700 unique descriptions because a number of descriptions occur multiple times. For example, "shale, gray" – the most frequently occurring description – occurs in 854 depth intervals. The second most frequently occurring description is "limestone," which represents 611 depth intervals. We have developed a table, which we refer to as the translation table, to assign a percentage coarse value to each of these unique descriptions. A script then processes the individual logs, assigning a percentage coarse value to each depth interval by matching its description to a translation table entry. At present, the translation table is incomplete; about 3,300 descriptions remain to be translated. Each of these untranslated descriptions represents only a single depth interval and they tend to be highly detailed – for example, "gray, silty sand to clayey sand with light brown sandy clay stringers, moist to wet, moderate odor, soft; fine grained sand; wet at 13 ft." Work on completing the translation table will continue as time permits. Nevertheless, the existing translation table entries account for 79% of the depth intervals in the data set, since the most frequently occurring descriptions were translated first.



MRPA WWC5 Drillers' Logs: Coarse Material Percentage

Data Set: Wells

☑ Include Data Below Bedrock

Vertical Exaggeration [1-500]: 200

☐ Show Land Surface

☑ Show Bedrock

Surface Opacity [0-1]: 0.5

Figure 10. Screen shot of interactive, rotatable display of percentage coarse data from WWC5 drillers' logs, available at https://gcb63.shinyapps.io/MRPADataExplorer. The gray surface represents bedrock. Using the web application, you can rotate the display by holding down the left mouse button and dragging and zoom using the mouse scroll wheel. You also can click on the blue buttons (e.g., "Background Info") for more information.

Figure 10 is a static screen shot of the interactive display of the percentage coarse data, which has been implemented as a Shiny web application (https://shiny.rstudio.com/). The controls on the left allow you to vary the vertical exaggeration, choose whether to include the bedrock and land surfaces and data below bedrock in the display, and select between different versions of the data to display. Initially, raw data from the logs are displayed, with the data point for each depth interval placed in the vertical center of that interval. The other options in the Data Set dropdown box allow the display of five different gridded versions of the data. The gridded data sets represent the well data averaged over 3-D grid cells, with the average percentage coarse value in each cell plotted at the center of that cell. Viewed from above, the grid cells are square, with side lengths of one-quarter, one-half, one, two, or four miles, depending on grid choice. The grid cells are 10 feet thick (vertically) in all five cases. The point of averaging over grid cells is to reduce noise and clutter in the data. The finer grids (smaller grid cells) show more of the detail in the data and coarser grids show more general trends.

Work on the assessment of the coarse material distribution continues. The following steps will be pursued in the near future:

1. Completing the translation of sediment descriptions into percentage coarse values.
2. Refining the percentage coarse representation of some materials, especially limestone and shale, which are generally fairly impermeable but can be moderately permeable when they are brecciated or fractured. Although descriptions including the terms "limestone" and "shale" already reflect this potential variation to some extent, they probably merit further review.
3. Reimplementing the interactive 3-D display in ArcGIS Online, allowing inclusion of more geographic context, better display controls, and incorporation into the existing MRPA online mapping tool (Section 8).
4. Possibly transcribing available test hole logs into electronic form to allow inclusion of this information in the percentage coarse data set.

As mentioned above, the 3-D percentage coarse data set can be used to compute the 2-D distribution of coarse materials averaged over the vertical interval between any two surfaces. For the sake of comparison with the Phase I work, we have computed the footage of coarse material between land surface and bedrock by averaging the 3-D data between these two surfaces. The resulting map (fig. 11) is broadly similar to the Phase I coarse thickness map (Batlle-Aguilar et al., 2017, fig. 16).

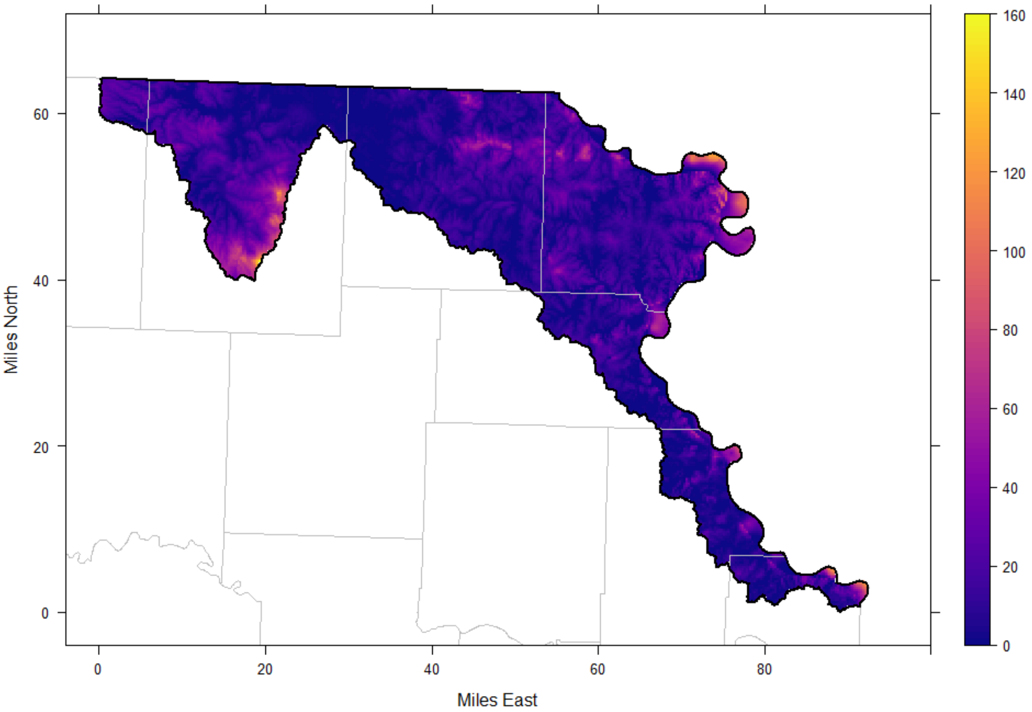


Figure 11. Net thickness of coarse material (feet) between land surface and bedrock computed from 3-D coarse percentage data.

5. Correlation of Water Use and Climate Indicators (Quantity Task 5)

To estimate safe yield for an aquifer, an estimate of the water use during droughts is valuable because these are the periods when the aquifer is stressed the most by pumping wells, especially irrigation wells, for which water withdrawals are greatest in dry years. The greater pumping during droughts, coupled with the lower recharge compared to wetter conditions, leads to lower groundwater levels.

Seasonal pumping by irrigation wells, which varies substantially from year to year in Kansas, has been shown to be mainly dependent on precipitation. Correlations between annual water use and indicators of climate that include precipitation are generally high for the High Plains aquifer (HPA) in both western and south-central Kansas (Whittemore et al., 2016, 2018). Statistically significant correlations have been found for both regional and local water use and precipitation indicators for the HPA. In addition, significant correlations exist between annual water use and average annual water-level change for the HPA; these relationships have been used to estimate safe yield as well as the reduction in pumping needed to stabilize groundwater levels where the levels are declining (Butler et al., 2016; 2018).

The methods used for examining the relationships between water use and climatic indicators for the HPA were applied in a reconnaissance mode to the MRPA to determine whether they would be applicable for assessing and estimating water use during varying climate, especially droughts. Unlike the generally regional nature of the HPA, the aquifers supplying water in the MRPA are much more localized. Thus, initial investigations needed to be focused on local areas or individual wells. In addition, the development of irrigation wells across the MRPA has been much more recent than in the HPA. Although municipal groundwater use has generally not changed substantially during the last two decades, irrigation water use has appreciably increased in the last decade, especially in Brown and Doniphan counties (fig. 12).

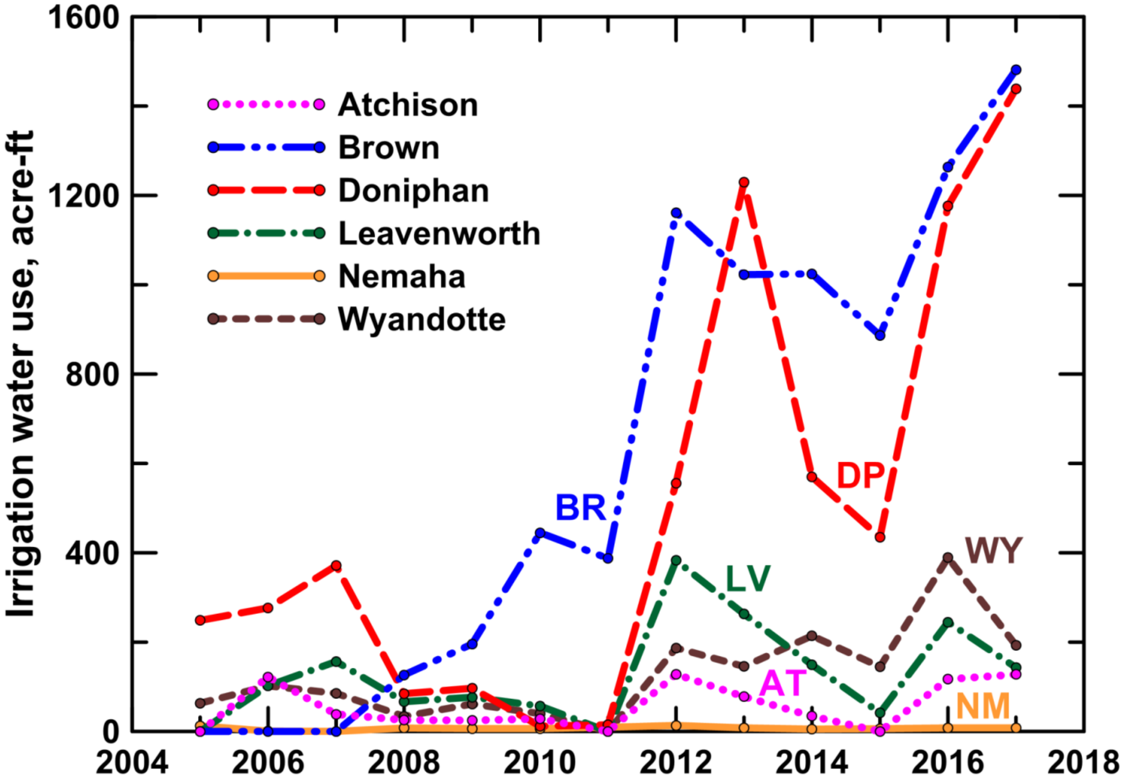


Figure 12. Irrigation water use for county areas within the Missouri Regional Planning Area. Data are from the Water Information Management and Analysis System (WIMAS) of the Kansas Department of Agriculture, Division of Water Resources, and the Kansas Geological Survey.

Measures of precipitation are available in different forms for Kansas: actual precipitation, a climatic index based on precipitation (Standardized Precipitation Index [SPI]), and climatic indices incorporating precipitation as well as other factors such as temperature and humidity (for example, the Palmer Drought Severity Index [PDSI]). These data are readily available online from the National Climatic Data Center in monthly format for the climatic divisions of Kansas (fig. 13). The MRPA is in climatic division 3 of Kansas. As indicated by the gray boundary in the northeast corner of fig. 13, the MRPA is a minor portion of climatic division 3. Thus, climatic data for division 3 may not always be as representative of climatic conditions in the MRPA as data for the MRPA area only. Precipitation values for areas smaller than the climatic divisions can be extracted from gridded coverages of radar precipitation available since 2005 from the National Weather Service (https://water.weather.gov/precip/); these data were processed using geographic information system (GIS) and statistical computer programs for areas around irrigation wells in the MRPA. Spatial averages of the radar precipitation data were computed for the nine points in the data grid (representing a 27-square-mile area) centered on the locations of irrigation wells.

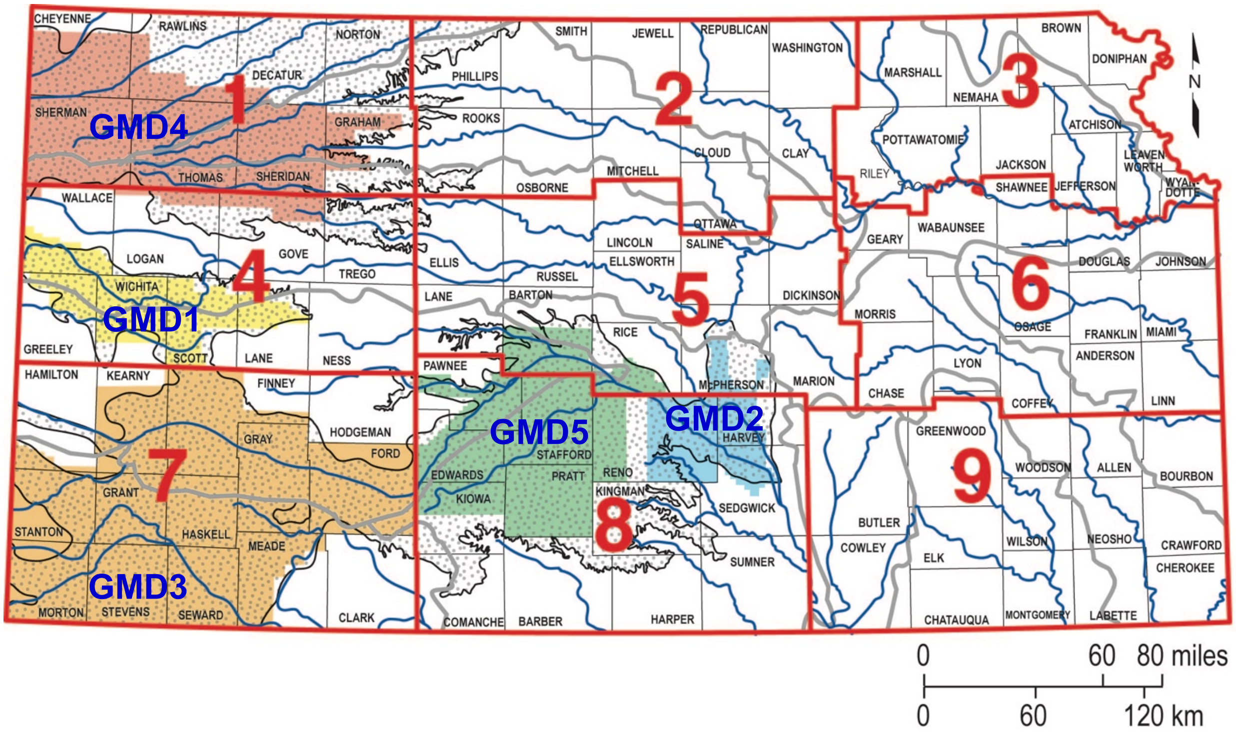


Figure 13. Climatic divisions of Kansas (red boundaries and numbers), High Plains aquifer extent (stippled area), groundwater management districts (blue labeled areas with color shading), and basins of Kansas (gray boundaries).

The SPI, PDSI, and radar precipitation values were used for a preliminary investigation of relationships with groundwater use (for example, the relationship between these indicators of climatic conditions and the amount of water pumped from irrigation wells in the MRPA). First, water use records for irrigation wells in the MRPA were examined using the Water Information Management and Analysis System (WIMAS) of the Kansas Department of Agriculture, Division of Water Resources, and the Kansas Geological Survey (KGS) (http://hercules.kgs.ku.edu/geohydro/wimas/index.cfm). Requirements for use of an irrigation well record in examining climatic indicator and water use relationships were a recent record (up to the last year of reported water use – 2017), a long enough record of annual water use to provide sufficient annual values for statistical analysis, and a consistent water use record for the period (use every year or at least use every year of normal to dry climate). Water use records for the analysis were selected for four example wells that are located in three counties (Brown, Doniphan, and Nemaha counties) of the MRPA and in three different types of aquifer systems (glacial drift, bedrock, and Missouri River alluvial aquifers).

Water use was plotted versus SPI, PDSI, and radar precipitation for each of the four wells and a linear regression was computed for the values using the program Grapher. Monthly values of radar precipitation around each well were summed for periods of different length and used in the plots to find the coefficient of determination (R^2) with the highest value for the linear regressions. The R^2 value represents the proportion of the variance in the water use explained by the variation in the climatic indicator. The monthly radar precipitation sums giving optimum R^2 values ranged from May–October for two of the four wells to June–October and June–November for the other two wells. The May–October period was then used for SPI (six-month SPI ending in October) and PDSI (mean of the six monthly values for May–October).

Table 2 lists the location, aquifer geology, water use period, and R^2 values for the optimum correlations of water use with radar precipitation, SPI, and PDSI for the four irrigation wells. Figures 14–17 show the plots for water use versus radar precipitation for each of the individual wells. In general, the R^2 values are greater for correlation of water use and radar precipitation than for SPI or PDSI (except for SPI for the Nemaha County well). The linear regressions for water use and radar precipitation are statistically significant for all four of the irrigation well records. The highest correlation was found for the well in the glacial drift aquifer (the water supply is actually obtained from eight relatively small wells tied together). The wells in the bedrock are in a zone of shale or limestone and shale in which the porosity and permeability appear, based on the well logs (available at http://www.kgs.ku.edu/Magellan/WaterWell/index.html), to be mainly the result of dissolution of gypsum; incongruent dissolution of gypsum in such bedrock can lead to calcium carbonate cementation of fragments of the shale or limestone that break upon partial collapse of the open cavities formed in the subsurface bedrock. The record for the Missouri River alluvial aquifer well extends back to 1991; only the period for which radar precipitation data are available was used in the correlation.

Table 2. Summary of correlations between water use and indicators of climatic conditions for four irrigation wells in the Missouri Regional Planning Area. Note that the statistical significance depends not only on the R^2 value but also the number of observations (period of record).

				Radar Precipitation		Standardized Precipitation Index, Division 3, May–Oct	Palmer Drought Severity Index, Division 3, May–Oct Mean
County	Well Location	Geology	Period	Month sum	R^2	R^2	R^2
Brown	1S-15E-12	Glacial drift	2009–2017	May–Oct	0.79**	0.41	0.33
Brown	1S-15E-35	Bedrock	2008–2017	Jun–Oct	0.52*	0.25	0.41*
Doniphan	1S-19E- 25	Missouri R alluvium	2005–2017	Jun–Nov	0.72**	0.32*	0.46*
Nemaha	2S-14E-01	Bedrock	2008–2017	May–Oct	0.55*	0.71**	0.44*

*Significant at the $P < 0.05$ level. **Significant at the $P < 0.01$ level.

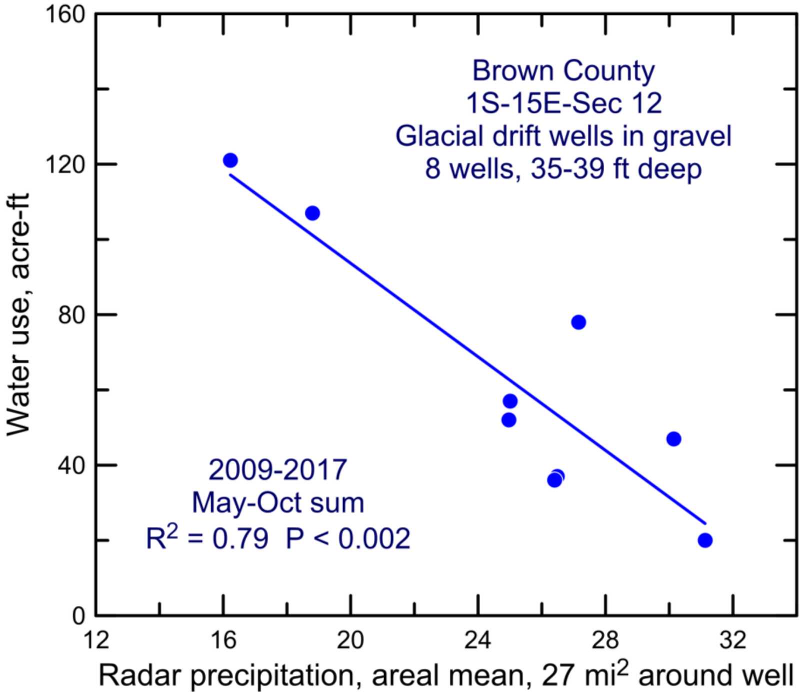


Figure 14. Water use versus spatial average of a 27-square-mile block of radar precipitation around an irrigation well in the glacial drift aquifer in Brown County.

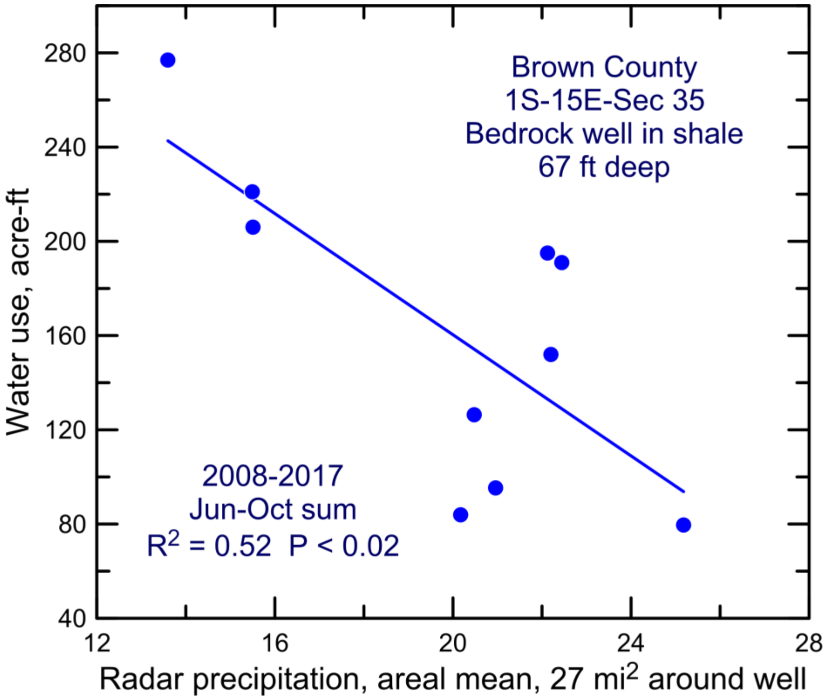


Figure 15. Water use versus spatial average of a 27-square-mile block of radar precipitation around an irrigation well in shale in Brown County. The permeability in this case is most likely the result of dissolution of gypsum in the shale.

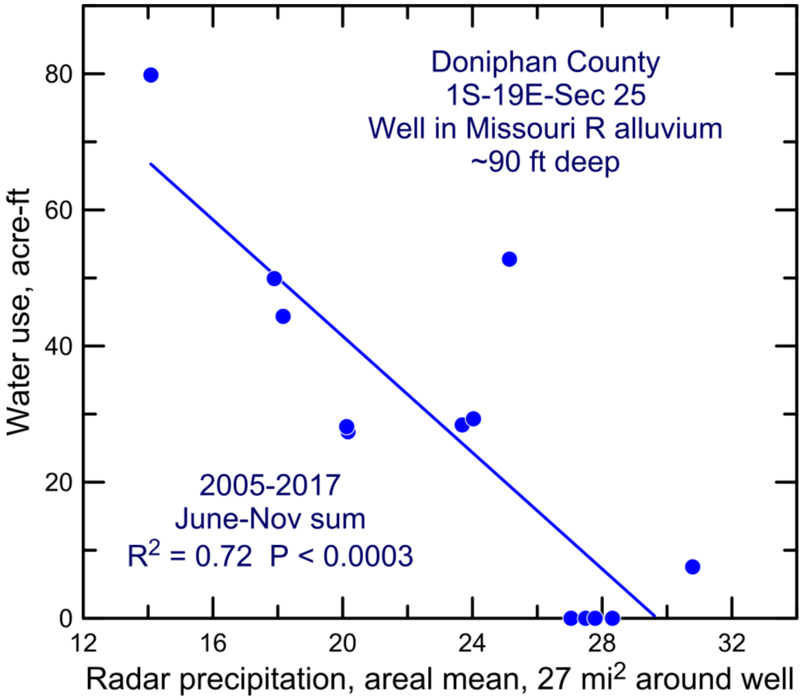


Figure 16. Water use versus spatial average of a 27-square-mile block of radar precipitation around an irrigation well in the Missouri River alluvial aquifer in Doniphan County.

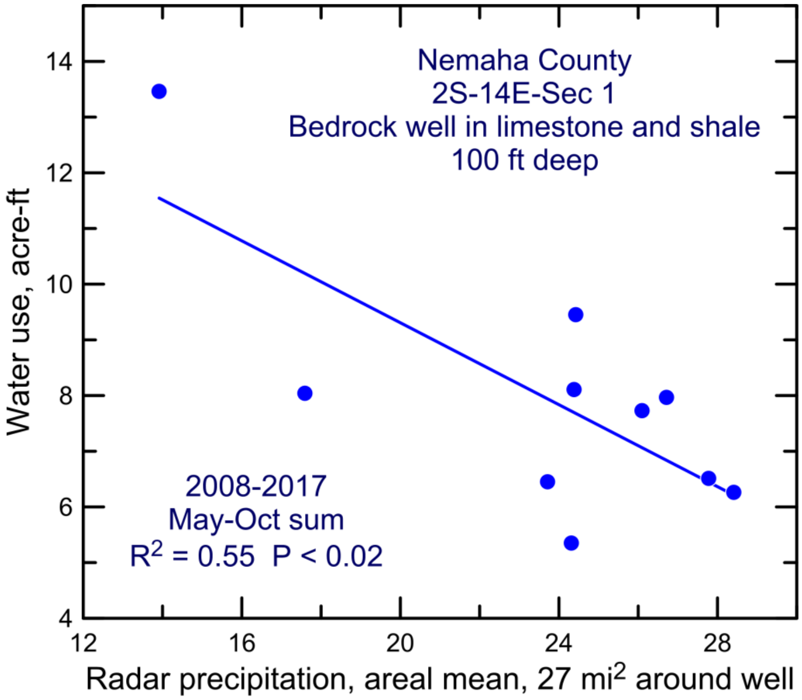


Figure 17. Water use versus spatial average of a 27-square-mile block of radar precipitation around an irrigation (substantial lawn and garden) well in shale in Nemaha County. The permeability in this case is most likely the result of dissolution of gypsum in the limestone and/or shale.

The results show that statistically significant correlations exist for irrigation wells in different aquifer types and in different counties of the MRPA. For extension to larger areas in the MRPA than individual well locations, a different method is needed to determine correlations because many of the irrigation wells have shorter annual records than the four wells described above, which is expected to lead to statistically insignificant correlations due to the availability of only a few annual observations. These short data records reflect the recent increase in irrigation water use in the MRPA (fig. 12); many irrigation wells in the area are relatively new.

Therefore, a new approach (not yet used in the KGS studies of the HPA) was applied to the four irrigation wells in the MRPA; this approach involved dividing the annual water use by the water right allocation of the irrigation wells. The water right allocation used was the most recent indicated in the WIMAS database; although the water rights may not always be the perfected amount, the values are not expected to change enough in future years to significantly affect the results. The new approach gives a percentage of the water right allocation used each year by the wells. The percentage values obtained for each well for a particular year were averaged, and the averages for all the years were plotted versus the SPI and PDSI values for climatic division 3 and versus the averages for the radar precipitation sums for May–October for each year during 2008–2017 for each well. (2008 was the earliest year of record used for three of the four wells; the record for the other well started in 2009.) Table 3 summarizes the results of this approach, and fig. 18 shows the results for radar precipitation.

Table 3. Correlations between the ratio of average annual water use/water right allocations and the average of the annual indicators of climatic conditions for four irrigation wells in the Missouri Regional Planning Area.

	Radar Precipitation for 27-Square-Mile Area Around Well		Standardized Precipitation Index, Division 3, May–Oct	Palmer Drought Severity Index, Division 3, May–Oct Mean
Period	Month sum	R^2	R^2	R^2
2008–2017	May–Oct	0.70**	0.46*	0.51*

*Significant at the $P < 0.05$ level. **Significant at the $P < 0.01$ level.

The correlations between the ratio of average annual water use/water right allocation and climate indicators are all statistically significant; the correlation with radar precipitation is substantially more significant than the correlations with SPI or PDSI. Water use for two of the years for two of the wells exceeded the water right allocation. This might not occur in the future given recent stricter regulations with penalties from the Department of Agriculture, Division of Water Resources, for water use exceeding allocation. The average water use/allocation for the four wells was approximately 100% for the drought year 2012. This suggests that the total water right allocation could be a good approximation of the total irrigation water use during substantial drought years in the MRPA. The drought in 2012 was one of the most severe during the last century in climatic division 3 in Kansas in terms of total precipitation during May–October (irrigation season drought); other years with very low precipitation during May–October were 1934 and 1937 during the 1930s drought, 1953 and 1956 during the 1950s drought, and 1976, 1988, and 1991.

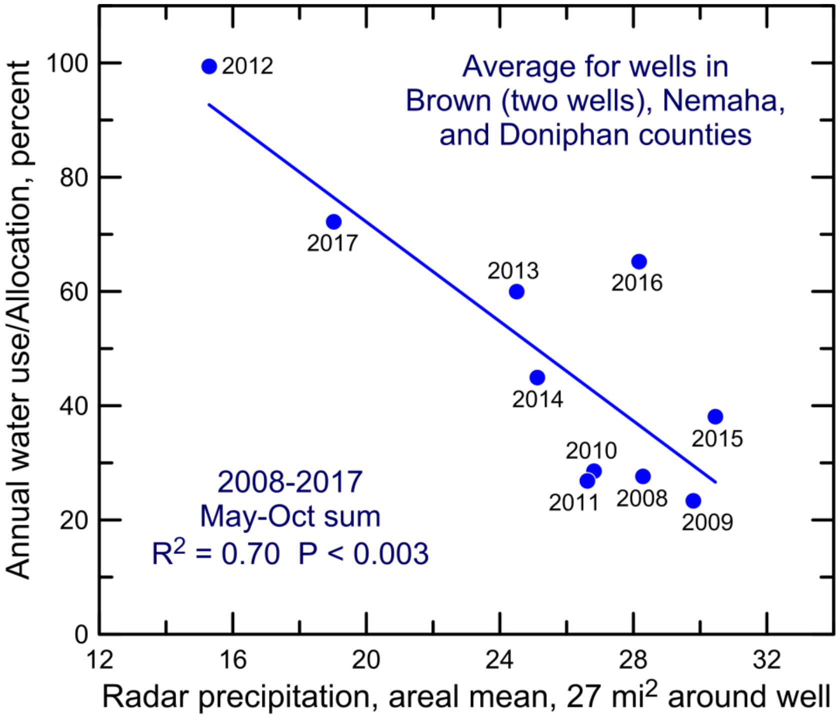


Figure 18. The average of the percentages of annual water use divided by water right allocation for each of the four irrigation wells versus the mean of the spatial averages of a 27-square-mile block of radar precipitation around each of four irrigation wells in the MRPA.

The results of this investigation indicate that an annual water use/water right allocation approach holds promise as an appropriate method for larger areas in the MRPA. The next step for year 2 in Phase II of the study is to divide the total annual water use by the total water right allocations for irrigation wells in county areas within the MRPA. A subset of correlations for which wells in the area of the Missouri River alluvial aquifer are excluded will be examined for the counties bordering the Missouri River (Doniphan, Atchison, Leavenworth, and Wyandotte counties) to determine the relationships for the upland glacial drift and bedrock aquifers.

6. Chemical Characteristics and Trends in Phase I Data (Quality Tasks 1 and 4)

Phase I of the study identified high nitrate concentrations (exceeding the maximum contaminant limit [MCL] of 10 mg/L as NO_3-N for public supplies of drinking water) in the groundwaters in many areas of the MRPA as the main water-quality issue. Most of the wells with high nitrate concentration were domestic and stock wells and most of the sampling dates were before 2000. The location of domestic and stock wells in farms and near animal waste sources and septic tanks and the older construction of wells that did not include adequate seals in the annular space around the casing (thereby allowing surface or near-surface water with nitrate contamination to directly enter the well) are expected reasons for the high nitrate in many wells. Other wells located next to or surrounded by cropland are expected to derive their high nitrate concentration from fertilizer sources.

Phase I data for groundwater quality were based on the USGS database for water quality and the former ambient groundwater quality network (which was terminated around 2001) of the Kansas Department of Health and Environment (KDHE). During Phase II, additional groundwater quality data for nitrate concentrations were obtained for well waters of public water supply systems from online KDHE web pages for Drinking Water Watch (http://dww.kdhe.state.ks.us:8080/DWW/KSindex.jsp).

During the review of public water systems for nitrate data, changes were observed in the drinking water sources for the population across the MRPA. Many rural homes began to be included within rural water districts. Thus, their drinking water sources, which may have included a domestic well with high nitrate, shifted to a public water supply system. Most of the population of the MRPA appears to now receive its supply from a public water system. Some smaller towns that may have had a well or wells that yielded water with higher nitrate concentration changed to obtaining their supply from a rural water system or a larger municipal water system with acceptable nitrate levels. The removal of public supply wells with high nitrate concentration from use would change the overall trend in nitrate concentration for actively sampled wells.

Based on the above, the decision was made for Phase II studies of existing water-quality data to focus first on public water supply systems. A review of current supply systems was conducted to determine the active systems with groundwater supply. Information about public supply systems was obtained from the KDHE Drinking Water Watch and other agency documents. Water rights data for these systems were accessed using WIMAS (http://hercules.kgs.ku.edu/geohydro/wimas/index.cfm). Additional information about the boundaries of rural water districts (some of which cross the boundary of the MRPA) was acquired from the maps web page of the Kansas Rural Water Association (https://krwa.net/ONLINE-RESOURCES/RWD-Maps). Table 4 lists the public water supply systems completely or partially within the MRPA; the list is arranged to separate those systems with groundwater supply only, a mix of groundwater and surface water supply, and surface water supply only. Table 5 summarizes the number of systems that have all groundwater, partial groundwater, and all surface water sources. Appendix table A3 provides detailed information about the supply systems, especially for those with wells.

Available data in the KDHE Drinking Water Watch for water samples from wells were examined to assess nitrate concentrations; table 6 lists nitrate levels for recent samples collected from the public water supply systems for which data were found. The NO_3-N values range from undetectable (<1 mg/L) for the Oneida well and one of the Nemaha County Rural Water District (RWD) 3 wells up to a little over the MCL of 10 mg/L for public supplies of drinking water for all four of the Hiawatha wells. In addition to the Oneida and Nemaha RWD 3 wells, seven other wells of the total 21 wells in table 6 contained less than 3 mg/L NO_3-N (the two Bern wells, one of the three Nemaha County RWD 1 wells, the remaining two of the three Nemaha County RWD 3 wells, one of the two Troy wells, and the Fort Leavenworth well). Six wells reported NO_3-N concentrations between 3 and 7 mg/L (the Public Wholesale Water Supply District 27 and White Cloud wells, the water reservoir [which is a tank combining the water from multiple wells] of Seneca, two of the three Nemaha RWD 1 wells, and one of the two Troy wells). Water from two wells contained NO_3-N between 7 and 10 mg/L (the Brown County RWD 1 and Highland wells; the level for the Highland well was close to 10 mg/L).

Figure 4 in the Phase I report (Batlle-Aguilar et al., 2017) shows historical nitrate trends for nine wells; five of the wells were part of public water supply systems. The NO_3-N concentration for Seneca Well 4 varied from less than 3 mg/L to a little over 10 mg/L during 1986–1997 compared to 3.6 mg/L for a mix of well waters in 2017–2018. The nitrate for Hiawatha Well 4 fluctuated from near 3 mg/L to a little over 10 mg/L during 1986–1997 compared to a little over 10 mg/L in 2017–2018 for the four wells listed in table 6; it is unknown at this time whether the North Clearwell or the Beckwith well is the well designated Well 4 in the Phase I report. Water samples collected from Highland Well 2 varied from somewhat over 30 mg/L to about 5 mg/L in NO_3-N content during 1986–1993, and samples from Highland Well 3 ranged from about 15 to 27 mg/L during 1961–1967 and from 4 to somewhat over 10 mg/L during 1995–2000; the nitrate concentration was close to 10 mg/L in 2017–2018. No clear pattern emerges from these data; the concentrations appear to fluctuate substantially from year to year, potentially indicating influences from precipitation variations resulting in appreciable fluctuations in recharge and from effects of differences in agricultural practices in the cropland (such as type of crop and amount of fertilizer applied) near the wells. The nitrate variations will be examined further in year 2 of Phase II studies for possible relationship to climate (wet to dry years).

Table 4. Active public water supply systems completely or partially located within the MRPA. GW = groundwater; SW = surface water. County abbreviations: AT = Atchison, BR = Brown, DP = Doniphan, LV = Leavenworth, MS = Marshall, NM = Nemaha, WY = Wyandotte.

Name	County	Portion within MRPA	System Source	Purchased Source
Systems with Groundwater Supply Only				
Brown Co RWD 1	BR	All	GW	
Brown Co RWD 2	BR	All		GW
Doniphan RWD 6	BR	All		GW
Everest	BR	Partial	GW	
Hiawatha	BR	All	GW	
PWWSD 27	BR	All	GW	
Reserve	BR	All		GW
Robinson	BR	All		GW
Willis	BR	Small		GW
Iowa Tribe of KS & NE	BR & DP	All		GW
Doniphan RWD 5	DP	All		GW
Elwood	DP	All		GW
Highland	DP	All	GW	
Troy	DP	All	GW	
Wathena	DP	All		GW
White Cloud	DP	All	GW	
Fort Leavenworth	LV	All	GW	
Leavenworth Co RWD 1C	LV	All		GW
Marshall Co RWD 3	MS	Very small	GW	
Summerfield	MS	Small	GW	
Bern	NM	All	GW	GW
Corning	NM	Small		GW
Nemaha Co RWD 3	NM	Most	GW	
Nemaha Co RWD 4	NM	Small	GW	
Nemaha Co RWD 1	NM	All	GW	
Oneida	NM	All	GW	
Seneca	NM	All	GW	
Systems with Partial Groundwater Supply				
Atchison RWD 5C (RWD 4 & 5 consolidated)	AT	Partial	GW	SW
Doniphan RWD 2 (Bendena)	DP	All		GW & SW
Lansing (Lan-Del Water District)	LV	All		SW & GW
Leavenworth (Leavenworth Water Department)	LV	All	SW & GW	
Leavenworth Co RWD 2	LV	All		GW & SW
Kansas City Board of Public Utilities	WY	Partial	GW & SW	
Systems with Surface Water Supply Only				
Atchison	AT	All	SW	
Atchison RWD 1	AT	All		SW
Atchison RWD 3	AT	All		SW
Atchison RWD 6	AT	Partial		SW
Lancaster	AT	Partial		SW
Morrill	BR	All		SW
Doniphan RWD 3	DP	All		SW
Leavenworth Co RWD 1	LV	All		SW
Leavenworth Co RWD 5	LV	Partial		SW
Leavenworth Co RWD 8	LV	Partial		SW
Sabetha	NM	Partial	SW	

Table 5. Summary of public water supply systems completely or partially within the Missouri Regional Planning Area. One of the Nemaha County systems with 100% groundwater obtains water from its own wells and purchases water from another system. The Atchison County system with a partial groundwater source obtains groundwater from its own wells and purchases surface water from another system.

County – Number of Systems	Number of Systems with Their Own Source	Number of Systems with Purchased Water
Number of Systems with 100% Groundwater – 27		
Brown – 10	4	6
Doniphan – 6	3	3
Leavenworth – 2	1	1
Marshall – 2	2	
Nemaha – 7	6	2
Number of Systems with Partial Groundwater Source – 6		
Atchison – 1	1	1
Doniphan – 1		1
Leavenworth – 3	2	1
Wyandotte – 1	1	
Number of Systems with 100% Surface Water – 11		
Atchison – 5	1	4
Brown – 1		1
Doniphan – 1		1
Leavenworth – 3		3
Nemaha – 1	1	

Table 6. Recent nitrate concentration in water samples from public water supply systems that have their own wells. The maximum contaminant level for NO_3-N in public drinking water supplies is 10 mg/L.

Public Water Supply	NO_3-N average, mg/L	Source	Years
Brown County			
Brown County Rural Water District 1	7.6	Wells 1–6 pump house	2017–2018
Hiawatha	10.1	Well 6	2017–2018
	10.6	North Clearwell	2017–2018
	11.5	Beckwith Well	2010–2011
	11.2	Well 3	2002–2003
Public Wholesale Water Supply District 27	5.3	Well water entry point	2018
Nemaha County			
Bern	1.2	Well 4	2017–2018
	1.8	Wells 5 & 6	2017–2018
Nemaha County Rural Water District 1	1.4	Wells 3 & 4	2017–2018
	3.7	Well 5	2017–2018
	4.6	Wells 6 & 7	2017–2018
Nemaha County Rural Water District 3	<0.1	Wells 2 & 3	2017–2018
	0.26	Wells 4 & 5	2017–2018
	0.3	Wells 6, 7, 8	2017–2018
Oneida	<0.1	Well	2017–2018
Seneca	3.6	Reservoir (of well water)	2017–2018
Doniphan County			
Highland	9.8	Well 4	2017–2018
Troy	6.4	Well 3 water plant	2017–2018
	0.40	Wells 6 & 7 water plant	2017–2018
White Cloud	5.5	Pump house	2017–2018
Leavenworth County			
Fort Leavenworth	0.23	Water plant lab tap	2017–2018

7. Sample Analyses Completed by the Kansas Geological Survey (Quality Tasks 3 and 4)

The KGS analyzed the samples that it collected in August 2018 for specific conductance and silica, cation, and anion concentrations and summed the concentrations of the measured dissolved constituents to obtain the total dissolved solids (TDS) concentration. Tables 7 and 8 list the KGS analytical results along with the analytical data of the USGS for samples they collected in August 2011. In general, the chemical type of the groundwaters is calcium-bicarbonate to calcium, magnesium-bicarbonate, except for well site 11-3 for which the USGS sample was calcium, sodium-bicarbonate and the KGS sample was sodium, calcium-bicarbonate, chloride in type.

The nitrate concentrations for samples from wells at five of the seven sites sampled by the KGS in 2018 exceeded the MCL for public supplies of drinking water (purple shaded numbers in nitrate column in table 8). The nitrate level for samples collected by the USGS in 2011 from two of these sites also exceeded the MCL. The 2018 nitrate concentration increased from 2011 at three of the well sites and decreased at two of the sites.

The specific conductance and sodium, chloride, and TDS concentrations increased substantially in the water collected from the well at site 11-3 from 2011 to 2018. The higher TDS means that the ionic strength of the groundwater also increased, which led to increasing the solubility of calcite in the sediments; this caused the calcium concentration to increase by a small amount and the bicarbonate by a greater proportion for the KGS sample compared to the USGS sample. The suspected source of the sodium and chloride concentration increases was identified based on a bromide/chloride ratio versus chloride concentration plot with mixing zones (fig. 19). Both of the points for the 2011 and 2018 samples from the well at site 11-3 fall within the zone of mixing of very fresh groundwater with subsurface formation brine and not within the mixing of very fresh groundwater with rock-salt dissolution saltwater. The point for the 2018 sample lies farther out into this mixing zone. No oil fields are in the area of this site. Thus, the source of the saline water that increased the sodium and chloride at this location is expected to be shallow saline water in the bedrock underlying the glacial drift.

The potential reason for the increase in the amount of subsurface saline water from the bedrock mixing with the fresh groundwater in the glacial drift aquifer at site 11-3 is a substantially smaller amount of rainfall recharge during 2018 than in 2011. Climatic indices indicate that the period in 2018 before the KGS sampling at this site was a drought in contrast to generally normal conditions in 2011. This is also reflected by the appreciably greater depth to groundwater in August 2018 than in August 2011 (table 9). All of the other sites for which the USGS reported water-level measurements also had substantially lower water levels in 2018 than 2011. Less recharge also might have been the reason for the increases in nitrate concentration observed from 2011 to 2018 for three of the well sites.

Although the chloride concentration for both the 2011 and 2018 samples collected from the well at site 28-1 are not high, they are appreciably higher than for five of the other wells. The points for the waters from this well fall within the zone of mixing of very fresh groundwater with rock-salt dissolution brine. No natural source of rock-salt dissolution saltwater exists in the study area. The well is located next to the west-east paved road that connects the city of Highland to Highway 7 to the east. This road is most likely treated during snow and ice conditions in the winter. Thus, the source of the increase in chloride concentration at this location is interpreted as dissolution of road salt.

Table 7. Comparison of chemical data for analyses of samples collected by the USGS in 2011 and the KGS in 2018 from monitoring wells installed by the USGS in the MRPA: specific conductance, pH, and silica and cation concentrations. The concentration mg/L is essentially equivalent to a ppm for freshwater. The light red shading of sodium (Na) for site 11-3 indicates a large concentration increase from 2011 to 2018. County abbreviations: AT = Atchison, BR = Brown, NM = Nemaha.

Site	Location	County	Depth well, ft	Date	Lab	SpC µS/cm	pH field	SiO2 mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Sr mg/L
8-1	02S-19E-14BDCD	AT	38	8/24/2011	USGS	546	7.2	20.1	65.1	21.0	14.2	2.48	
				8/8/2018	KGS	604		14.8	68.7	26.2	13.5	2.20	0.26
28-1	02S-19E-24DACC	AT	43	8/24/2011	USGS	861	7.2	20.4	93.2	41.9	10.3	3.70	
				8/8/2018	KGS	937		15.0	105.0	49.8	11.9	3.73	0.37
7-1	01S-16E-15DCDD	BR	69	8/16/2011	USGS	487	7.4	21.2	75.1	8.42	12.9	0.54	
				8/8/2018	KGS	516		15.2	67.5	8.37	11.9	0.58	0.26
11-3	01S-17E-08CBB	BR	23.5	8/16/2011	USGS	715	7.3	13.8	65.0	17.4	51.1	1.29	
				8/8/2018	KGS	1,330		7.28	68.8	21.0	165.0	2.47	0.74
0-3	04S-13E-15ABBB	NM	69	8/23/2011	USGS	677	7.2	31.0	70.2	30.2	26.7	3.39	
				8/8/2018	KGS	605		24.3	45.0	34.3	28.5	3.10	0.48
18-2	03S-13E-13BAAB	NM	23	8/25/2011	USGS	885	7.7	28.6	102	29.3	27.8	0.90	
				8/8/2018	KGS	824		20.9	95.2	29.4	29.3	1.01	0.49
19-1	03S-12E-11CDDD	NM	34	8/10/2011	USGS	755	7.3	30.7	77.4	25.9	33.8	2.09	
				8/8/2018	KGS	782		24.7	45.9	31.0	38.9	1.87	0.34

Table 8. Comparison of chemical data for analyses of samples collected by the USGS in 2011 and the KGS in 2018 from monitoring wells installed by the USGS in the MRPA: anion and total dissolved solids concentrations. The total dissolved solids (TDS) concentration was calculated as the sum of the dissolved constituents, with bicarbonate (HCO_3) multiplied by 0.4917 to represent the TDS that would be produced if the sample were evaporated to dryness for a TDS measurement. The light red shading of chloride (Cl) and TDS for site 11-3 indicates a large concentration increase from 2011 to 2018. The light purple shading indicates that the nitrate concentration exceeds the maximum contaminant level for public supplies of drinking water. County abbreviations: AT = Atchison, BR = Brown, NM = Nemaha.

Site	Location	County	Date	Lab	HCO3 mg/L	Cl mg/L	SO4 mg/L	NO3-N mg/L	F mg/L	Br mg/L	TDS sum mg/L
8-1	02S-19E-14BDCD	AT	8/24/2011	USGS	278	6.79	21.9	8.51	0.36	0.022	327
			8/8/2018	KGS	269	8.74	31.7	13.7	0.307	0.026	359
28-1	02S-19E-24DACC	AT	8/24/2011	USGS	393	71.6	17.8	4.52	0.56	0.070	474
			8/8/2018	KGS	397	62.9	24.3	13.4	0.507	0.060	528
7-1	01S-16E-15DCDD	BR	8/16/2011	USGS	206	1.17	15.8	17.4	0.32	0.032	314
			8/8/2018	KGS	230	1.56	13.8	16.0	0.312	0.027	303
11-3	01S-17E-08CBB	BR	8/16/2011	USGS	271	29.0	76.6	2.51	0.50	0.168	400
			8/8/2018	KGS	365	208	64.1	1.52	0.69	0.790	725
0-3	04S-13E-15ABBB	NM	8/23/2011	USGS	393	12.4	12.6	4.31	1.03	0.059	401
			8/8/2018	KGS	343	11.4	13.2	4.32	0.971	0.048	349
18-2	03S-13E-13BAAB	NM	8/25/2011	USGS	317	1.76	43.7	45.8	0.58	0.052	595
			8/8/2018	KGS	308	8.89	38.2	33.1	0.60	0.025	522
19-1	03S-12E-11CDDD	NM	8/10/2011	USGS	432	2.42	30.3	9.57	0.48	0.057	459
			8/8/2018	KGS	431	3.32	26.8	10.8	0.445	0.059	433

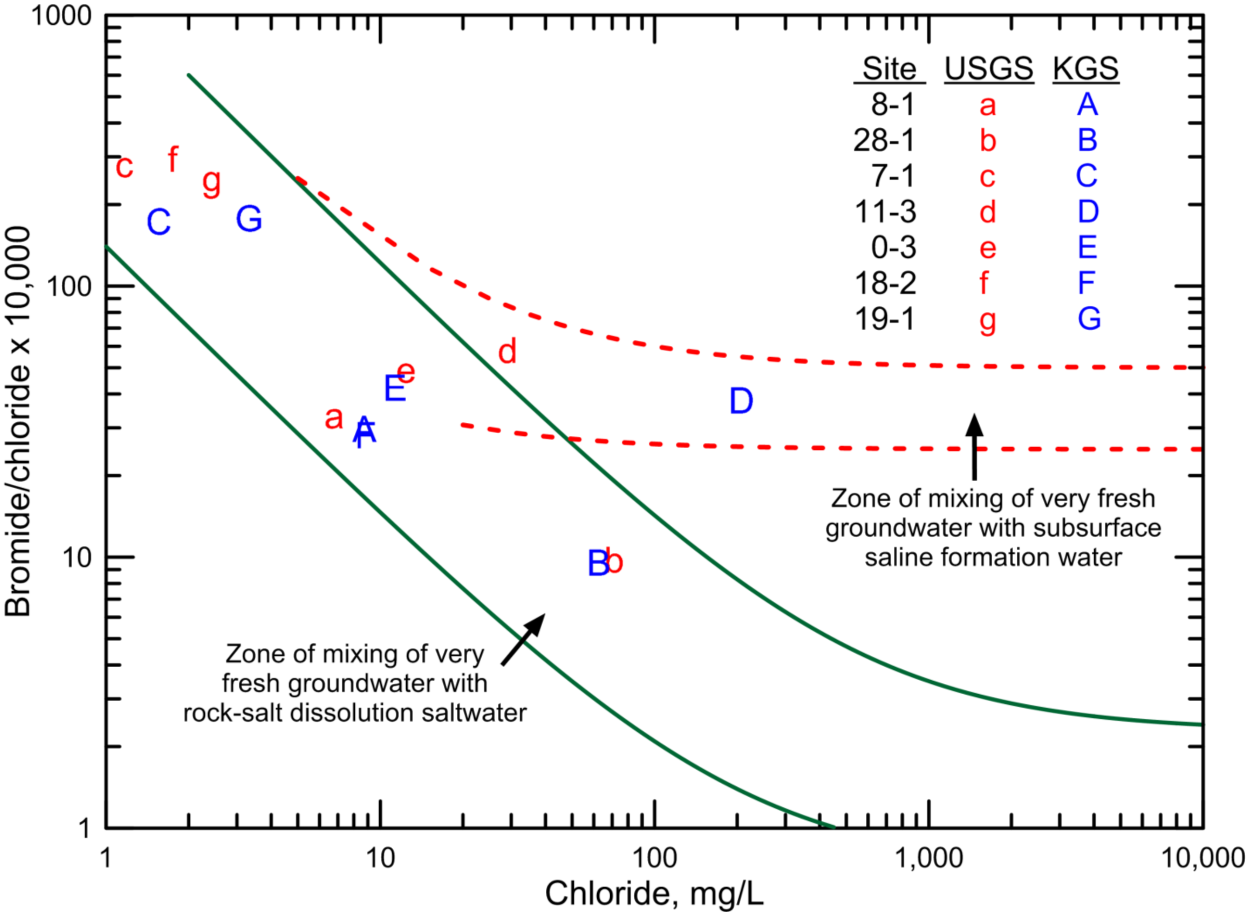


Figure 19. Bromide/chloride mass ratio versus chloride concentration for water samples collected by the USGS in 2011 and by the KGS in 2018 from USGS monitoring wells in the MRPA. The solid and dashed lines are for the mixing of end member waters that bracket the range in bromide/chloride ratios at selected chloride concentrations. The upper and lower mixing lines for mixing between two different types of water define a mixing zone. See table 8 for the chloride and bromide data used in this plot.

Table 9. Depth to water measurements for the seven USGS wells sampled by the KGS in August 2018. No water-level depth is available for well site 8-1 in the USGS database.

Site	Location	Depth to water in August 2011	Depth to water in August 2018
8-1	2S 19E 14BDCD	N/A	12.60
28-1	2S 19E 24DACC	30.31	36.81
7-1	1S 16E 15DCDD	8.92	14.43
11-3	1S 17E 08CBB	12.58	18.45
0-3	4S 13E 15ABBB	11.60	18.48
18-2	3S 13E 13BAAB	7.34	13.43
19-1	03S 12E 11CDDD	18.75	23.81

8. Online Resources (Dissemination Task 1)

Information dissemination tasks during year 1 of Phase II included establishment of a project web page (http://www.kgs.ku.edu/Hydro/Missouri/index.html), development of the MRPA online mapping tool ("Online Mapping Tool" link on project web page), and development of the 3-D display of coarse material distribution (https://gcb63.shinyapps.io/MRPADataExplorer) described in Section 4. These resources will continue to be updated as the project progresses. Tasks to be addressed in the near future include updating the Online Mapping Tool to include the revised bedrock elevation, sediment thickness, and coarse material thickness maps presented in this report and reimplementation of the 3-D data viewer in ArcGIS Online for improved display and closer integration with the Online Mapping Tool.

9. Project Status

Recapping, the list of tasks for Phase II is as follows:

Water Quantity

1. Assess the accuracy and robustness of bedrock elevation and unconsolidated material maps generated in Phase I using a variety of interpolation methods.
2. Identify exact locations of some existing wells, specifically those in areas where multiple wells with the same nominal (PLSS) location provide conflicting bedrock depth estimates.
3. Identify locations of existing wells to equip with pressure transducers and locations for drilling new monitoring wells.
4. Drill new monitoring wells in areas with limited existing wells to better understand groundwater availability and movement throughout the MRPA.
5. Begin interpretation of groundwater-level surface and aquifer storage and safe yield.

Water Quality

1. Interpret information reported in Phase I as it relates to chemical characteristics and provide potential explanations for concentration trends.
2. Select groundwater sample collection sites and collect initial samples, with collaboration from Missouri RAC members.
3. Analyze collected groundwater samples for selected chemical constituents.
4. Interpret analytical data and plan for future sampling.

Information Dissemination

1. Put information collected in Phase I as well as Phase II into a user-friendly format and make available to stakeholders, researchers, and other interest groups.

Figure 20 shows the proposed timeline for addressing these tasks over the five project years. The project is on schedule. Tasks to be addressed in year 2 include (but are not limited to) installing groundwater-level monitoring equipment in existing wells; collecting and analyzing samples from those wells, the Hiawatha city wells, and possibly other municipal wells; determining sites for new monitoring wells (to be drilled in year 3); further assessing the historical water-level data compiled during Phase I; and searching for other water-level data sources.

Task	Year 1	Year 2	Year 3	Year 4	Year 5
Water Quantity 1	▨				
Water Quantity 2	▨				
Water Quantity 3		▨	▨	▨	▨
Water Quantity 4			▨	▨	▨
Water Quantity 5	▨	▨	▨	▨	▨
Water Quality 1	▨				
Water Quality 2	▨	▨	▨	▨	▨
Water Quality 3	▨	▨	▨	▨	▨
Water Quality 4		▨	▨	▨	▨
Info. Dissemination	▨	▨	▨	▨	▨

Figure 20. Project timeline.

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APPENDIX TABLES

Table A1. Location, elevation, screened interval, well depth, and depth to water for USGS monitoring wells in the MRPA. KGS location and elevation, well depth, and depth to water were obtained during the KGS visit to the site on August 8, 2018.

WWC5 ID	Well ID	WWC5 T-R-S	WWC5 latitude	WWC5 longitude	WWC5 elevation, ft	KGS T-R-S	KGS latitude	KGS longitude	KGS elevation, ft	Screened interval, ft	Depth to bottom of well, ft	Depth to water, ft
438084	MO-RAC 0-3	4S 13E 15ABBB	39.82737	95.94862	1338	4S 13E 15ABBB	39.71099	95.94631	1,343	58.5–68.5	71.450	18.481
438476	MO-RAC 18-2	3S 13E 13BAAA	39.79785	95.91258	1297	3S 13E 13BAAB	39.79778	95.91272	1,305	13.0–23.0	26.181	13.432
438474	MO-RAC 19-1	3S 12E 11CDDD	39.79835	96.04260	1216	3S 12E 11CDDD	39.79833	96.04254	1,231	24–34	36.795	23.809
438471	MO-RAC 18-3	1S 12E 01CDDD	39.98748	96.02413	1323	Not Visited				8.5–18.5		
438460	MO-RAC 7-1	1S 16E 15DCDC	39.95747	95.60852	1056	1S 16E 15DCDD	39.95744	95.60615	1,077	13.5–23.5	24.580	14.426
438462	MO-RAC 11-3	1S 17E 08CBBC	39.97795	95.54598	940	1S 17E 08CBB	39.97791	95.54584	940	13.5–23.5	26.286	18.448
438463	MO-RAC 31-1	2S 16E 31DCCC	39.82682	95.66745	1135	2S 16E 31DCCC	39.82679	95.66746	1,147	25–35	37.444	31.637
438465	MO-RAC 5-1	2S 17E 31BADD	39.83782	95.55685	1122	Not Visited				33.0–43.0		
438469	MO-RAC 8-1	2S 19E 14BDCD	39.87877	95.25837	1085	2S 19E 14BDCD	39.87861	95.25874	1,000	28.0–38.0	40.682	12.598
438470	MO-RAC 28-1	2S 19E 24DCDC	39.86023	95.23212	1015	2S 19E 24DACC	39.86021	95.23206	1,020	33–43	46.014	36.811

Table A2. Lithologic information for intervals in the WWC5 log of the USGS monitoring wells.

WWC5 ID	Well ID	Log interval 1, ft	Lithology	Log interval 2, ft	Lithology	Log interval 3, ft	Lithology	Log interval 4, ft	Lithology	Log interval 5, ft	Lithology	Log interval 6, ft	Lithology
438084	MO-RAC 0-3	0–1	Top Soil	1–58	Brown Silty Clay	58–69	Sandy Clay						
438476	MO-RAC 18-2	0–4	Black Clay	4–13	Brown Clay	13–23	Sandy Clay w/ Sm Gravel						
438474	MO-RAC 19-1	0–29	Yellow Clay w/ Pea Sized Gravel	29–34	Sandy Yellow Clay								
438471	MO-RAC 18-3	0–10	Black Clay	10–16	Brown Sandy Clay	16–18.5	Gray/Blue Clay						
438460	MO-RAC 7-1	0–1	Black Clay	1–12	Brown Clay	12–13	Gravel	13–23.5	Sand & Gravel				
438462	MO-RAC 11-3	0–3	Top Soil	3–18	Silty Clay	18–20	Gravel	20–23.5	Gray Clay				
438463	MO-RAC 31-1	0–2	Top Soil	2–10	Brown Clay	10–16	Lt Tan Clay w/ Gravel	16–26	Green Sandy Dry Clay	26–32	Sand & Gravel	32–35	Blue Clay
438465	MO-RAC 5-1	0–27	Brown Clay	24–37	Yellow Clay	37–43	Sandy Brown Clay w/ Gravel						
438469	MO-RAC 8-1	0–30	Brown Silty Clay	30–32	Lt Brown Clay	32–38	Sand w/ Small Gravel						
438470	MO-RAC 28-1	0–38	Sandy Brown Clay	36–43	Sands with Some Clay								

Table A3. Information about public water supply (PWS) systems completely or partially within the MRPA, including well information for groundwater supplies. Shaded rows separate information about different supply systems. Multiple well depths reflect different values reported for different years in the WIMAS records. GW = groundwater; SW = surface water. County abbreviations: AT = Atchison, BR = Brown, DP = Doniphan, LV = Leavenworth, MS = Marshall, NM = Nemaha, WY = Wyandotte. Well feet N and W indicate location based on distance from southeast corner of section. WWC5 ID indicates the record number in the water well log database. PD is point of diversion. GW UDI of SW refers to groundwater under the influence of surface water. CC is cross connection.

Supply system name	Co.	Portion within MRPA	Diversion point (well) location	Well feet N	Well feet W	Well name	Water right nos.	Water use history years	Well depth feet	WWC5 ID	Current supply	PWS Wells
						Active PWS with Groundwater						
Atchison RWD 5C (RWD 4 & 5 consolidated)	AT	partial									60% SW purchased from Atchison; 40% RWD GW; Emergency from Valley Falls	Wells 1–3; 8 test wells
Bern	NM										50% city GW; 50% GW purchased from Nemaha Co RWD 1	Wells 4, 5, 6; Wells 1, 2, 3 plugged; One test well
Brown Co RWD 1	BR										99% RWD GW; 1% emergency GW purchase from Hiawatha; Sells to Reserve	Wells 1–6
	BR		02S-15E-27CAB	2,310	3,620	Well #2	18707	Use 1981–1995, 2015–2016	155			
	BR		02S-15E-27BDD	2,770	2,970	Well #4	18707	Use 1981–2016	144 155 153			
	BR		02S-15E-27CBA	2,310	4,225	Well #1	18707	Use 1981–1995, 2015–2016	144			
	BR		02S-15E-27CAA	2,310	3,130	Well #3	18707	Use 1981–1995, 2015–2016	155 144 143			
	BR		02S-15E-27CAA	2,310	2,710	Well #5	18707	Use 1981–1995, 2015–2016	133			
	BR		02S-15E-27CAA	1,585	2,710	Well #6	18707	Use 1981–1995, 2015–2016	132 143 144			

Table A3. Information about public water supply systems completely or partially within the MRPA (continued).

Supply system name	Co.	Portion within MRPA	Diversion point (well) location	Well feet N	Well feet W	Well name	Water right nos.	Water use history years	Well depth feet	WWC5	Current supply	PWS Wells
Brown Co RWD 2	BR										100% purchased GW from Public Wholesale Water Supply District 27; Also purchases emergency water from Hiawatha; Sells water to Robinson and Powhattan	11 test wells
	BR		02S-17E-03DAA	2,440	70	Batt 1 of 2	47392	No use 2011–2016	168			
	BR		02S-17E-03DAA	2,240	70	Batt 1 of 2	47392	No use 2011–2016	171			
	BR		02S-18E-10B	3,960	3,960		48807	Dismissed 2014				
	BR		01S-18E-35CCC	100	5,180		48903	Dismissed 2017				
	BR		02S-18E-11ACC	3,090	2,570		48522	Dismissed 2017				
Corning	NM	small									100% GW purchased from NM Co RWD 3	
Doniphan RWD 2 (Bendena)	DP										50% GW purchased; 50% SW purchased; Sources are DP Co RWD 5; Atchison Co RWD 5C	Well 1 emergency
Doniphan RWD 5	DP										100% GW purchased from Elwood, Wathena (abandoned); Troy (emergency); Sells to DP Co RWD 2	
Doniphan RWD 6	BR										Purchases GW from Public Wholesale Water Supply District 27; Emergency water from Highland	Proposed wells 1 & 2 abandoned; 2 test wells
	BR		02S-19E-07BAD	4,080	2,770	Batt 1 of 2	47958	Dismissed 2016			North well, PD active, use of water not active	
	BR		02S-19E-07BDA	3,880	2,770	Batt 1 of 2	47958	Dismissed 2016			South well, PD active, use of water not active	
Elwood	DP										100% GW purchased from American Water Co, St. Joseph, MO; Sells water to Wathena, DP Co RWDs 2 & 5	

Table A3. Information about public water supply systems completely or partially within the MRPA (continued).

Supply system name	Co.	Portion within MRPA	Diversion point (well) location	Well feet N	Well feet W	Well name	Water right nos.	Water use history years	Well depth feet	WWC5	Current supply	PWS Wells
Everest	BR	partial									100% city GW; (any water purchased from BR Co RWD 2?)	Wells 1, 2; one test well
Fort Leavenworth	LV										100% system GW; Emergency water from LV Water Dept.	Wells 5–9
Hiawatha	BR										100% city GW; sells to Brown Co RWD 1 and Reserve	Wells 1, 2, 5, 6 (Pfister) active, North Clearwell; well 3 abandoned, well 4 emergency; 5 test wells
	BR		02S-17E-05AB	4,620	1,650	Evans	483	Use 1981–2016	96			
	BR		01S-17E-32CDC	150	3,790	Hansbury	483	No use 2008–2016				
	BR		02S-17E-05ADA	3,847	590		41140	Use 1994–2016	108	4112	Well completed 1994	
	BR		02S-17E-01BCB	3,817	5,267		47857	Use 2012	119			
	BR		02S-18E-04CCC	69	5,277		47858	No use 2012–2014	103	444834 485127	Well completed 2011, plugged 2014	
	BR		02S-18E-06D	1,320	1,320		48960	Dismissed 2014				
	BR		02S-18E-05C	3,960	3,960		49040	Dismissed 2014				
	BR		02S-18E-10B	3,960	3,960		48843	Dismissed 2014				
Highland	DP										100% city GW	Wells 4 & 5; Well 2 plugged; Well 3 emergency
Iowa Tribe of KS & NE	BR & DP										100% GW; Will be also be supplied by PWWSD 27	Wells 01N, 02S, 06

Table A3. Information about public water supply systems completely or partially within the MRPA (continued).

Supply system name	Co.	Portion within MRPA	Diversion point (well) location	Well feet N	Well feet W	Well name	Water right nos.	Water use history years	Well depth feet	WWC5	Current supply	PWS Wells
Kansas City Board of Public Utilities	WY	partial									50% SW, 50% GW UDI of SW, Kansas City BPU; Emergency water from Water Dist 1 and SW intake	Wells 1 & 2 horizontal collector wells in MO R alluvium
Lansing (Lan-Del Water District)	LV										67% purchased SW; 33% purchased GW UDI of SW; sources LV Water Dept and KC BPU	
Leavenworth (Leavenworth Water Department)	LV										63% SW, 37% GW UDI of SW, Leavenworth Water Dept.	Wells 3, 3A, 4, 5A, 6–9, 12; Wells 1, 2, 2A abandoned; Wells 10 & 11 proposed
Leavenworth Co RWD 1C	LV	partial									100% purchased GW UDI SW from KC BPU and Leavenworth Water Dept.	Wells 4, 5–8 plugged; Well 3 nonPWS
Leavenworth Co RWD 2	LV										50% purchased GW, 50% purchased SW, from LV Water Dept	
Marshall Co RWD 3	MS	very small									100% RWD GW	Wells 2–6; Well 1 plugged
Nemaha Co RWD 1	NM										100% RWD GW; Sells to Bern; Purchases emergency water from Bern	Wells 3–8; Wells 1 & 2 abandoned; 6 test wells
Nemaha Co RWD 3	NM	most									100% RWD GW; CC water from Seneca; Emergency water from MS Co RWD 3; Sells to Axtell, Corning, Centralia	Wells 2–8; 3 test wells

Table A3. Information about public water supply systems completely or partially within the MRPA (continued).

Supply system name	Co.	Portion within MRPA	Diversion point (well) location	Well feet N	Well feet W	Well name	Water right nos.	Water use history years	Well depth feet	WWC5	Current supply	PWS Wells
Nemaha Co RWD 4	NM	small									100% RWD GW; Sells to Goff	Wells 1–4; 2 test wells
Oneida	NM										100% city GW; Purchases emergency water from NM Co RWDs 1 & 3	Well 1
Reserve	BR										100% purchased GW from BR Co RWD 1	Well 1 abandoned
	BR		01S-17E-07CBC				BR 2	1960–1966, 1978, 1981–1995	30 45 37 40 44	460838	New well 2012, 36.5 ft deep	
Robinson	BR										Purchases 100% GW from BR Co RWD 2; part of Public Wholesale Water Supply District 27	Wells 3, 8 abandoned; wells 5, 6 nonPWS; well 7 emergency
	BR		02S-18E-28BBC	4,500	5,150	Well 7	31290 35647	Created at migration of well 7	60	4141	Completed 1977	
	BR		02S-18E-28BB	4,530	4,660	Well 8	35647	Use 1982–2013	53	4156	Completed 1982	
Seneca	NM										100% city GW; Sells water to NM RWD 3, Axtell, Corning, Centralia	Wells 3–9; Well 1 emergency; 2 test wells
Summerfield	MS	small									100% city GW	Wells 5–7, Well 1 emergency, Well 4 abandoned
Troy	DP										100% city GW	Wells 3, 6, 7; Wells 1 & 2 abandoned; Well 5 plugged

Table A3. Information about public water supply systems completely or partially within the MRPA (continued).

Supply system name	Co.	Portion within MRPA	Diversion point (well) location	Well feet N	Well feet W	Well name	Water right nos.	Water use history years	Well depth feet	WWC5	Current supply	PWS Wells
Wathena	DP										100% GW purchased from Elwood; Water from MO American St Joseph abandoned	
White Cloud	DP										100% city GW	Wells 3 & 4
Willis	BR	small									Town is on MRPA border; 100% GW purchased from City of Holton (from BR Co RWD 2?)	
PWWSD 27	BR										100% WSD GW; Sells to Brown Co RWD 2, Robinson, Powhattan, Doniphan Co RWD 6	Wells 1, 2, 3
Other Towns within RWD or PWWSD with Groundwater												
Denton	DP										Within DP Co RWD 3	
Fairview	BR										Water from BR Co RWD 1	
Hamlin	BR										Within BR Co RWD 1	
Severance	DP										Within DP Co RWD 3	
Active Public Water Supply Systems with All Surface Water												
Atchison	AT										100% city SW; sells to AT Co RWDs 1, 3, 5C, 6, Nortonville, Lancaster, DP Co RWDs 2 & 3	
Atchison RWD 1	AT										100% SW purchased from Atchison; Emergency from AT Co RWD 6	

Table A3. Information about public water supply systems completely or partially within the MRPA (continued).

Supply system name	Co.	Portion within MRPA	Diversion point (well) location	Well feet N	Well feet W	Well name	Water right nos.	Water use history years	Well depth feet	WWC5	Current supply	PWS Wells
Atchison RWD 3	AT										100% SW purchased from Atchison	
Atchison RWD 6	AT	partial									100% SW purchased from Atchison; Emergency from AT Co RWD 1	
Doniphan RWD 3	DP										100% SW purchased from Atchison Co RWD 5	Wells 2–4 emergency
Lancaster	AT	partial									100% SW purchased from AT Co RWD 5C	
Leavenworth Co RWD 1	LV										100% SW purchased from LV Water Dept	
Leavenworth Co RWD 5	LV	partial									100% SW purchased from LV Water Dept	2 test wells
Leavenworth Co RWD 8	LV	partial									100% SW purchased from LV Water Dept through consecutive connection	
Morrill	BR										100% SW purchased from City of Sabetha, Pony Creek Reservoir; Emergency water from BR Co RWD 1	
Sabetha	NM	partial									100% surface water from Pony Creek Reservoir	
						Inactive Public Water Supply Systems						
Doniphan RWD 1 (Leona; within DP Co RWD 6)	DP										Inactive status; 100% GW purchased from BR Co RWD 2 non-PWS	Well 1 non-PWS
Atchison RWD 2		partial									Inactive status; 100% SW purchased from Atchison abandoned	

Table A3. Information about public water supply systems completely or partially within the MRPA (continued).

Supply system name	Co.	Portion within MRPA	Diversion point (well) location	Well feet N	Well feet W	Well name	Water right nos.	Water use history years	Well depth feet	WWC5	Current supply	PWS Wells
Nemaha Co RWD 2 (within NM Co RWD 3 just W of Seneca)	NM	partial									Inactive status; 100% GW purchased from Seneca and emergency water from NM Co RWD 3	
Sycamore Springs Resort, 3126 Bittersweet Rd, Sabetha (~4 mi NNE of Sabetha)											Inactive status; 100% resort GW; Developed in 1886, ceased operation in 2018 by owners, no satisfactory buyers	Well 2