# Diminishing Depth to Water in Cambrian-Ordovician Arbuckle Group Disposal Wells in Kansas

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## ABSTRACT

Industrial and municipal wastewater and oilfield brines have been disposed of into the Cambrian-Ordovician Arbuckle Group for decades in Kansas and nearby states in the midcontinent United States. The industrial and municipal wastewater disposal wells (designated Class I disposal wells) are regulated by the Kansas Department of Health and Environment. The oilfield brines are disposed of in Class II disposal wells, which are regulated by the Kansas Corporation Commission. Annual testing of formation pressure and static fluid levels in Class I wells compose a body of data that is useful in monitoring movement of water and fill-up of Arbuckle disposal zones. In western Kansas, the depth to water in wells penetrating the Arbuckle can be several hundred to more than a thousand feet (305 m) below ground surface, but in parts of southern and southeastern Kansas, the depth to water locally can be less than 100 ft (31 m). Furthermore, most Class I wells indicate Arbuckle fluid levels in central and south-central Kansas are rising ~10 ft (~3 m) annually, suggesting that at current disposal rates, the Arbuckle may lose its capacity to accept wastewater under gravity flow in parts of the state in the next few decades, principally south-central and southeastern Kansas along the Oklahoma state line. At present in parts of six Kansas counties along the Oklahoma state line, low-density (~1.0 g/cc or slightly greater density) wastewater in a wellbore does not have a sufficient hydrostatic head by gravity alone to force its way into the more dense resident Arbuckle formation water.

In general, Arbuckle formation water flows west to east in Kansas. Arbuckle disposal wells in Kansas collectively dispose of ~800,000,000 barrels (~127,000,000 m$^3$) of wastewater per year, although some of this is recycled from Arbuckle oil production. Declines in oil price since mid-2014 have resulted in less oilfield disposal in the Arbuckle since 2015. The number of Class I wells recording annual fluid rises have also declined since 2015, as has the median of their annual change in static fluid level, but overall, more Class I wells are still recording fluid rises. There is a poor correlation between changes in fluid levels in Class I wells and the volume of fluid disposed in them annually, thereby indicating that more regional characteristics may control water movement in the Arbuckle. More monitoring wells are needed to better understand the movement of water in the deep subsurface and to anticipate any potential problems that may occur with reduced disposal capacity and possible migration of fluids through unplugged or improperly plugged older wells.

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## INTRODUCTION

The Cambrian-Ordovician Arbuckle Group (identified as "Arbuckle" henceforth) has been used for decades for wastewater disposal by industrial, municipal, and oilfield facilities in Kansas and adjacent states in the U.S. midcontinent. This geologic formation closely overlies the Precambrian basement over much of the midcontinent, separated from the basement by granite wash or sandstones and shales of the underlying Cambrian Lamotte (Reagan) Sandstone. Locally, and particularly on the Central Kansas uplift, no shale or Lamotte (Reagan) Sandstone separates the Arbuckle from the underlying basement (Goebel, 1968). Pressure changes, and possibly even disposal brine, can thus migrate into the basement as it disperses away from any well emptying wastewater into the Arbuckle. Increases in disposal volumes since 2011 (Ansari et al., 2019) have been correlated with concomitant increases in earthquakes in northern Oklahoma and southern Kansas (Peterie, Miller, Intfen et al., 2018; Peterie, Miller, Buchanan et al., 2018; Pollyea et al., 2018).

An ancillary issue to the increase in earthquakes — but one of serious concern having potentially significant ramifications — is an indication that the Arbuckle in some areas may be reaching a limit to the amount of water that can be injected into it solely by the force of gravity. Annual monitoring of water levels in some Arbuckle disposal wells (Ansari et al., 2019) indicates that these water levels are rising in parts of Kansas, and at present rates of rise the Arbuckle may locally cease to take water by gravity alone. This potential concern — where depth to water is diminishing and what means are available to better understand it — is the subject of this paper.

The Cambrian-Ordovician Arbuckle Group is a cherty dolomite stratigraphic sequence covering much of Kansas and the central United States. On the flanks of the Ozark uplift, the Arbuckle is a source of potable water (Macfarlane and Hathaway, 1987; Jorgensen et al., 1993, 1996; Carr et al., 2005). In deeper basinal areas, it is a petroleum reservoir and a saline aquifer into which industrial waste and oilfield brines are disposed (Carr et al., 1986). Carr et al. (2005) suggest that this unit can be used for future subsurface storage of $CO_2$, thereby helping to reduce greenhouse gas emissions into the atmosphere. The Arbuckle is thin to absent on the Nemaha uplift and Central Kansas uplift in northeastern and central Kansas, respectively, but it thickens to as much as 1,200 ft (365 m) to the south and southeast at the Oklahoma and Missouri state lines (Merriam, 1963; Franseen et al., 2004).

The best porosity and permeability in the Arbuckle is generally near its top, because weathering and erosion related to unconformities truncating the upper part of the unit commonly augment earlier-formed systems of porosity (Merriam, 1963; Cansler and Carr, 2001). Sedimentologic and diagenetic studies cite porosities of 20% or higher in some areas (Conley, 1980; Ramondetta, 1990; Byrnes et al., 1999; Franseen et al., 2004). The dense and brittle dolomite of the unit can be prone to fracturing, which can improve its permeability locally (Cansler and Carr, 2001; Franseen et al., 2004). Conversely, porosity systems in the unit also can be stratigraphically and laterally isolated (i.e., "cockpit terrane" of Cansler and Carr, 2001) due to karstic features such as sinkholes and solution fissures.

## DISPOSAL WELLS — THE SEPARATE WORLDS OF CLASS I AND CLASS II

Two types of disposal wells — Class I and Class II — are relevant to understanding habitat and movement of disposal and ambient formation water in the Arbuckle (table 1). Both classes are subject to different regulations by separate government authorities. The 1976 Resource Conservation and Recovery Act and the 1974 Safe Drinking Water Act, and subsequent legislative amendments, define and mandate regulation of Class I and II disposal wells. These regulations were passed into law as the Underground Injection Control (UIC) Program to protect underground sources of drinking water from pollution (see U.S. Environmental Protection Agency, 2016). The U.S. Environmental Protection Agency (EPA) is charged with the regulatory oversight of these two types of disposal wells.

The state of Kansas has exercised its option of requesting primacy on both Class I and II disposal wells in the state. "Primacy" allows the state government regulatory authority for permitting, inspecting, record-keeping, and reporting on these well classes. Class I disposal wells are supervised and administered under the Kansas Department of Health and Environment (KDHE), whereas Class II disposal wells are overseen by the Kansas Corporation Commission (KCC).

**Table 1. Class I and II disposal wells — two sets of rules and characteristics that apply to two classes of disposal wells.**

| CLASS I DISPOSAL WELLS | CLASS II DISPOSAL WELLS |
|---|---|
| Regulated by KDHE | Regulated by KCC |
| Gravity feed of effluent | Pressurized injection allowed |
| SFL, downhole pressure tested annually, with mechanical integrity testing | Mechanical integrity tested every 5 years |
| Injection volume continually recorded & reported monthly | Injection volume recorded by various means; reported yearly |
| Mostly industrial/municipal wastewater | Mostly oilfield water |
| Injected water can be nearly fresh to dense | Injected water is mostly dense & saline |
| 50 active wells in Kansas; 49 dispose into Arbuckle | ~5,000 SWD wells in Kansas; ~2,725 dispose into Arbuckle |
| Entire Arbuckle usually accessed | Mostly upper Arbuckle accessed |
| Individual well disposal volume can be prolific | Collective well disposal volume is prolific |
| Annual collective disposal volume is nearly constant | Annual collective disposal volume varies with energy price |
| 2010–2018 Arbuckle disposal volume = ~85,000,000 bbls/yr | 2010–2018 Arbuckle disposal volume = ~715,000,000 bbls/yr |
| Represents 10.9% of all water sent into the Arbuckle | Represents 89.1% of all water sent into the Arbuckle |
| 99.9% of all Class I disposal water goes into Arbuckle | 80.5% of all Class II disposal water goes into Arbuckle |

Class I disposal wells send hazardous and non-hazardous wastes into deep geologic formations. Wells that dispose of hazardous waste are subject to more stringent permitting, siting, construction, reporting, and plugging requirements than Class I wells that dispose of non-hazardous waste.

Class II wells are used to inject brine associated with oil and gas production. The establishment of this class of wells was a compromise to the energy industry for exemption from the rigorous supervision applied to Class I wells, thus allowing a modicum of versatility for these companies to dispose of oilfield brines (W. Bryson, Kansas Geological Survey, personal communication, 2006). Brine derived from the subsurface is essentially returned to the subsurface in Class II disposal wells but perhaps into a geologic horizon different from the one in which it originated.

Operational rules governing a Class I well in Kansas mandate that its disposal water enter the disposal zone largely by means of gravity (M. Cochran, KDHE, personal communication, 2016). No pumping or pressurization is currently allowed. According to R. Hoffman at the KCC (personal communication, 2019), Class II wells can be pumped and pressured up to 75% of the hydrofracturing pressure of the disposal formation. However, he stated that such pump pressure on Arbuckle Class II disposal wells is generally not needed because the unit has sufficiently high porosity and permeability to take virtually all practically necessary volumes and rates of disposal water by gravity alone. Arbuckle saltwater disposal wells can be permitted with 250–500 pounds per square inch (psi) (1,724–3,447 kilopascals [kPa]) if pressure is needed, but the 75% guideline is commonly just used for enhanced oil recovery wells. Fracture gradients for the Arbuckle can vary, but Fazelalavi (2015), in an analysis of hydrofracturing at the Wellington Field in Sumner County, Kansas, determined that the Arbuckle at a depth of 5,025 ft (1,532 m) at this locality had a fracture gradient of ~0.58 psi/ft (13.13 kPa/m).

There are presently 50 active Class I disposal wells in Kansas. All of these wells (except one that disposes into Pennsylvanian lower Shawnee Group strata) send effluent water into the Arbuckle Group. Energy-related industries (i.e., underground storage, pipeline compressor stations, natural-gas processing plants, refineries) compose the majority of the Class I wells (26), and industrial plants (chemical, ethanol, and fertilizer) account for 11 wells. Salt-solution mining and food-processing plants use four and three wells, respectively. The remaining wells are licensed for coal-fired electrical power plants (two wells), salt-brine underground cavern stabilization (one well), landfill effluent disposal (one well), and groundwater remediation and treatment (two wells).

Water disposed of into the Arbuckle by Class I wells ranges from storm drainage and nearly freshwater to toxic chemical-industrial wastewater. Municipal sewage plants cannot take these types of effluent in any significant volume. Subsurface disposal is thus determined to be the best remediation option. Density of the disposed water in Kansas Class I wells ranges from ~0.99 g/cc, thereby implying the effluent is a mixture of lighter organic compounds and nearly freshwater, to ~1.21 g/cc, indicating a heavy brine containing ~300,000 parts per million total dissolved solids (ppm TDS).

The City of Hutchinson #1 and #2 wells exemplify how Class I disposal wells are integral in processes of groundwater remediation and treatment. Contaminated shallow groundwater is pumped from the Quaternary-age Equus beds underlying the city. The contamination is a result of surface leakage that occurred decades ago — a combination of cleaning solvents sourced from airport maintenance facilities and city businesses, natural brines derived from Permian evaporites, and oil infiltrated from open-air storage ponds (Zerr, 2009). Part of the contaminated water is treated in a reverse-osmosis/evaporation processing facility and the resulting purified water is then added to the municipal water supply. The remaining concentrated effluent is disposed of into the Arbuckle using two Class I disposal wells (Zerr, 2009).

The two City of Hutchinson Class I wells dispose of large volumes of fluid. According to KDHE records, they accounted for 176,955,684 barrels (bbls) (28,133,706 m$^3$) disposed of into the Arbuckle in a 10-year period from 2009 through 2018. This volume is equivalent to an average rate of 24,227 bbls (3,852 m$^3$) of water per day per well. These two disposal wells are effectively the largest point source of Class I disposal water entering the Arbuckle in Kansas. The effluent is slightly saline, with fluid densities ranging from 1.006 to 1.008 g/cc (averaged from annual tests from 2005 through 2018). Chemical testing of effluent water from City of Hutchinson #1 in 2017 registered 1,780 ppm TDS (Wilkerson, 2017).

By legal mandate, each facility with one or more Class I wells must test at least one of their wells annually for fluid pressure (usually by a gauge set at or near the top of the Arbuckle) and static fluid level (SFL). Determination of the chemical and physical characteristics (e.g., pH, chloride content, dissolved solids content, specific gravity, viscosity) of their effluent waters are also mandated. The testing usually includes measuring pressures several times down the borehole in a fall-off test (see Earlougher, 1977, p. 77–85). Inferred formation pressure (P*) is determined from the pressure measurements and the times and depths they are taken, as the water column in the well eventually equilibrates to formation pressure. The equilibration process can be relatively long compared to the day or two allowed for well testing; thus, a graphical engineering method called a Horner Plot (Horner, 1951) is generally used to project the interim pressures to a final fully equilibrated formation pressure. Drill-stem tests (DSTs) also use Horner Plot analysis by monitoring pressure buildup during shut-in times to infer P* (Earlougher, 1977, p. 93–96).

Class I disposal wells are subject to mechanical integrity testing (MIT) annually so that any tube or casing leakage can be detected and remedied. Class I well MITs are overseen by the KDHE and are usually performed by a consultant contracted by the Class I facility. Class II disposal wells are subject to MITs every five years. Tests are supervised by the KCC and also are usually performed by contractors (R. Hoffman, KCC, personal communication, 2017).

The Oil and Gas Wells Database maintained by the Kansas Geological Survey (2018a) lists 44,164 wells that have been used to inject water into the subsurface. Of these wells, approximately 16,600 are now permitted for use. There are two kinds of Class II wells: enhanced oil recovery (EOR) and salt-water disposal (SWD) wells, with present-day EOR and SWD wells numbering 11,600 and 5,000, respectively.

EOR wells are those wells in which formation water, co-produced with oil or gas, is used in oilfield water floods. EOR wells are usually positioned on the perimeter of an oil field, as the principal function of the injected water is to entrain and carry oil from an injection well to a production well. EOR production water can be cycled through the field several times; hence, such water-flood operations also can be called “cycling floods.” If production water is not reused in cycling or perimeter floods, this water must be permanently eliminated from the production zone using Class II SWD wells. Although all but one of the 50 Class I disposal wells in Kansas use the Arbuckle, Class II wells dispose of their water into several separate stratigraphic zones, ranging in age from Ordovician to Cretaceous. Of the approximately 5,000 permitted Class II SWD wells currently active, approximately 3,450 wells are permitted to dispose of their water into the Arbuckle.

The distinction between Class II EOR and SWD disposal wells on the Central Kansas uplift (CKU) can be unclear. Many oil fields on the CKU produce from the Arbuckle and shallower Pennsylvanian zones. In Kansas, oil and gas production volumes are reported not by individual wells, but rather by lease; hence, relative contributions of the different producing zones and wells in the same lease are difficult to determine. Disposal water from Pennsylvanian producing zones can be sent to both Arbuckle SWD and EOR wells; therefore, considerable uncertainty is involved in knowing SWD and EOR disposal volumes. Disposal water can cycle several times from a disposal well to a production well and back to a disposal well. Disposal volumes listed may thus contain a component of recycled water. Some wells have their designation changed, functioning in their lifetime as producing, EOR, and SWD wells. The complexity of the inter- and intra-formational water movement thus constrains the authors to outline a 120-township region covering parts of 10 counties on the CKU as an area where disposal-volume summations may be suspect.

Kansas, having a history of oil production to as early as 1860 (Haworth, 1908), is characterized by production wells having a high water cut, or alternatively termed, a high water-oil ratio. In general, producing wells in newly discovered oil fields usually have low water-oil ratios, and the ratios usually increase with time. New unconventional oil fields, like those in the Mississippian Lime Play (MLP) (see Evans and Newell, 2013), however, may be characterized by high water cuts from the onset of production. This water has limited utility in EOR operations, so it is usually disposed of in SWD wells. Water-oil ratios for MLP wells in Harper County, summed from production and injection records for 2015, are ~16:1 (W. L. Watney, Kansas Geological Survey, personal communication, 2016).

## RELATIVE VOLUMES OF DISPOSAL WATER BY CLASS I AND CLASS II WELLS

Disposed water volumes for Class I wells are continuously metered and reported monthly by the well operator, whereas disposed water volumes for Class II SWD wells are required to be reported by well operators only on a yearly basis (see yearly volumetric reports for disposal wells in Kansas Geological Survey [2018a]). The sheer number of Class II wells and operators allows for some approximation of their reported disposal volumes. A few operators approximate their disposed water volumes and report identical disposal volumes every year. Some merely report pro forma the maximum allowable volume for which the well is permitted. Nevertheless, the majority of operators appear to take the rules that apply to them seriously and diligently sum monthly disposal volumes in their yearly reports (R. Hoffman, KCC, personal communication, 2016).

Class I wells in Kansas dispose of a relatively constant volume of water into the Arbuckle — ~85,000,000 bbls (13,513,920 m$^3$) per year (fig. 1). Over the length of time considered in a volumetric analysis (nine years; 2010 through 2018), the annual volume from 2,736 Class II Arbuckle wells was approximately eight times that of the Class I wells (fig. 1). Class II disposal volumes peaked in 2014, a year when oil prices were relatively high. Oil prices crashed in late 2014 (i.e., from $99.36/bbl in June 2014 to $42.18/bbl in January 2015 for Kansas crude oil [U. S. Energy Information Administration, 2019]), and accordingly, Kansas oil production peaked in 2014 and steadily dropped in subsequent years (Kansas Geological Survey, 2019). Class II Arbuckle disposal volumes, which peaked in 2015 (a year after oil prices peaked), have dropped since then but still remain significantly higher than historical injection volumes (fig. 1). Lower oil prices compel operators to cease producing both the oil and water from economically marginal wells.

Summarizing water volume disposed of into the Arbuckle on a per township basis affords an additional comparative assessment (fig. 2) and a map view (fig. 3) of the relative importance of each class of disposal well. Townships in Kansas are approximately 6 X 6 miles (12.9 X 12.9 km), or 36 sq. miles (93.2 sq. km). The greatest rate of Class I inflow into the Arbuckle from a single township is from the two City of Hutchinson disposal wells in T. 23 S., R. 05 W. As previously discussed, each of these wells disposed of an average of 24,227 bbls/day (3,852 m$^3$) over a 10-year period from 2009 through 2018. In southern Sedgwick County near Wichita, eight chemical-company Class I wells account for another single high-volume township (figs. 2 and 3).

Other townships with high volumes of water disposal into the Arbuckle in the seven years

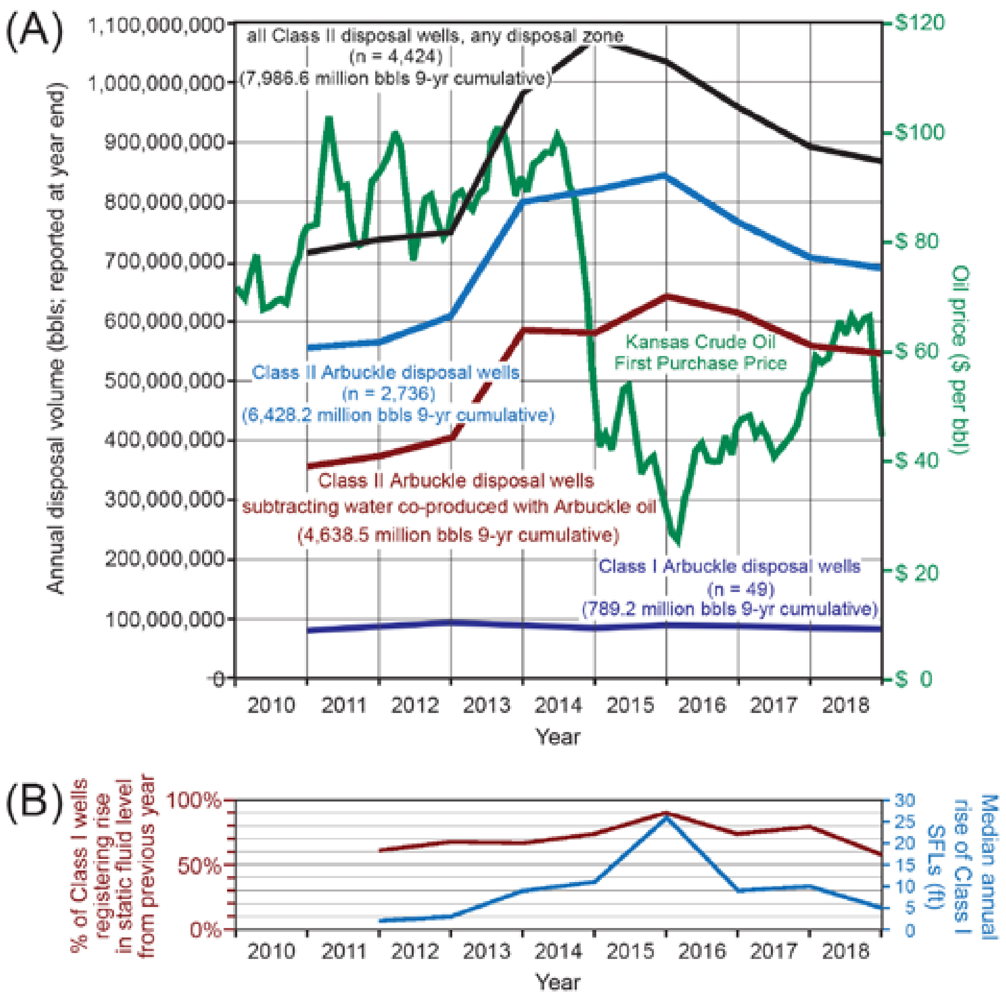
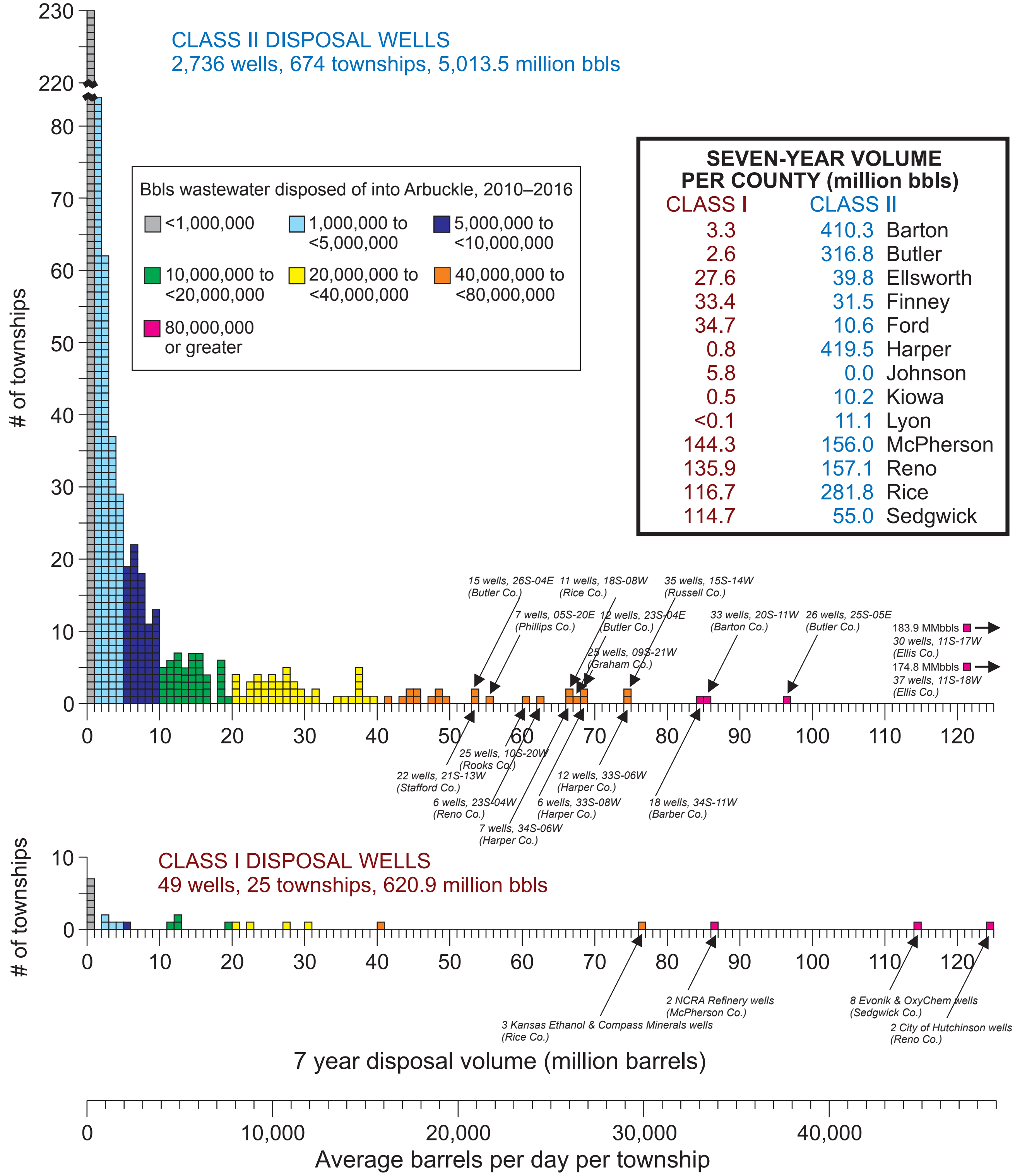


Figure 1. (A) Annual disposal volumes into the Arbuckle by Class I and II wells, respectively, over a nine-year period (2010–2018). Annual volumes are plotted on the graph at the end of each year. Kansas crude oil prices also are shown (monthly data from U. S. Energy Information Administration, 2019). Volume of water co-produced with Arbuckle oil is estimated by assuming that oil from the Arbuckle constitutes 14% of annual Kansas oil production since 1970 (personal communication, D. Adkins-Heljeson, Kansas Geological Survey, 2019), with an overall water:oil ratio of 49:1. (B) The percentage of Class I wells (n = 37 to 40 over the indicated time period) recording a rise in their static fluid level compared to the previous year, and the median annual fluid rise (compared to previous year) in Class I wells (water column normalized to freshwater density). Both measures of the change of annual levels peaked in the same year (i.e., 2015) that Class II injection volumes peaked in Arbuckle wells.

considered (shown in figs. 2 and 3) are two adjacent townships in northern Ellis County (T. 11 S., R. 16–17, W.). These townships accounted for 174.8 and 183.8 million bbls (27,790,000 and 29,220,000 m$^3$) of wastewater, respectively. Responsibility for these volumes of water are dispersed among 28 and 37 Class II wells, respectively, for these townships; thus, the daily average input per well in each township is 1,848 and 2,568 bbls (294 and 408 m$^3$), respectively. The amount of water disposed of may actually be less, as these two townships are in an area where there is likely some recycling of water between disposal wells and production wells. Nevertheless, the difference in daily water volumes per well illustrates a key difference in Class I and II wells, where Class II responsibility for disposed water volume is commonly dispersed among several wells even though the collective volume may be quite large (see table 1).

The spatial distribution of the water disposed of into the Arbuckle, with individual townships depicted as to-scale colored squares on fig. 3, shows that Class II disposal wells send large amounts of water into the Arbuckle in the southern tier of counties bordering Oklahoma, particularly Harper and Barber counties (fig. 3). Much of this water is from MLP horizontal



**SEVEN-YEAR VOLUME PER COUNTY (million bbls)**

| CLASS I | CLASS II | |
|---|---|---|
| 3.3 | 410.3 | Barton |
| 2.6 | 316.8 | Butler |
| 27.6 | 39.8 | Ellsworth |
| 33.4 | 31.5 | Finney |
| 34.7 | 10.6 | Ford |
| 0.8 | 419.5 | Harper |
| 5.8 | 0.0 | Johnson |
| 0.5 | 10.2 | Kiowa |
| <0.1 | 11.1 | Lyon |
| 144.3 | 156.0 | McPherson |
| 135.9 | 157.1 | Reno |
| 116.7 | 281.8 | Rice |
| 114.7 | 55.0 | Sedgwick |

Figure 2. Histogram of seven-year disposal volumes (2010–2016) into the Arbuckle for Class I and II wells on a per township basis. Inset table compares volumes in selected counties.

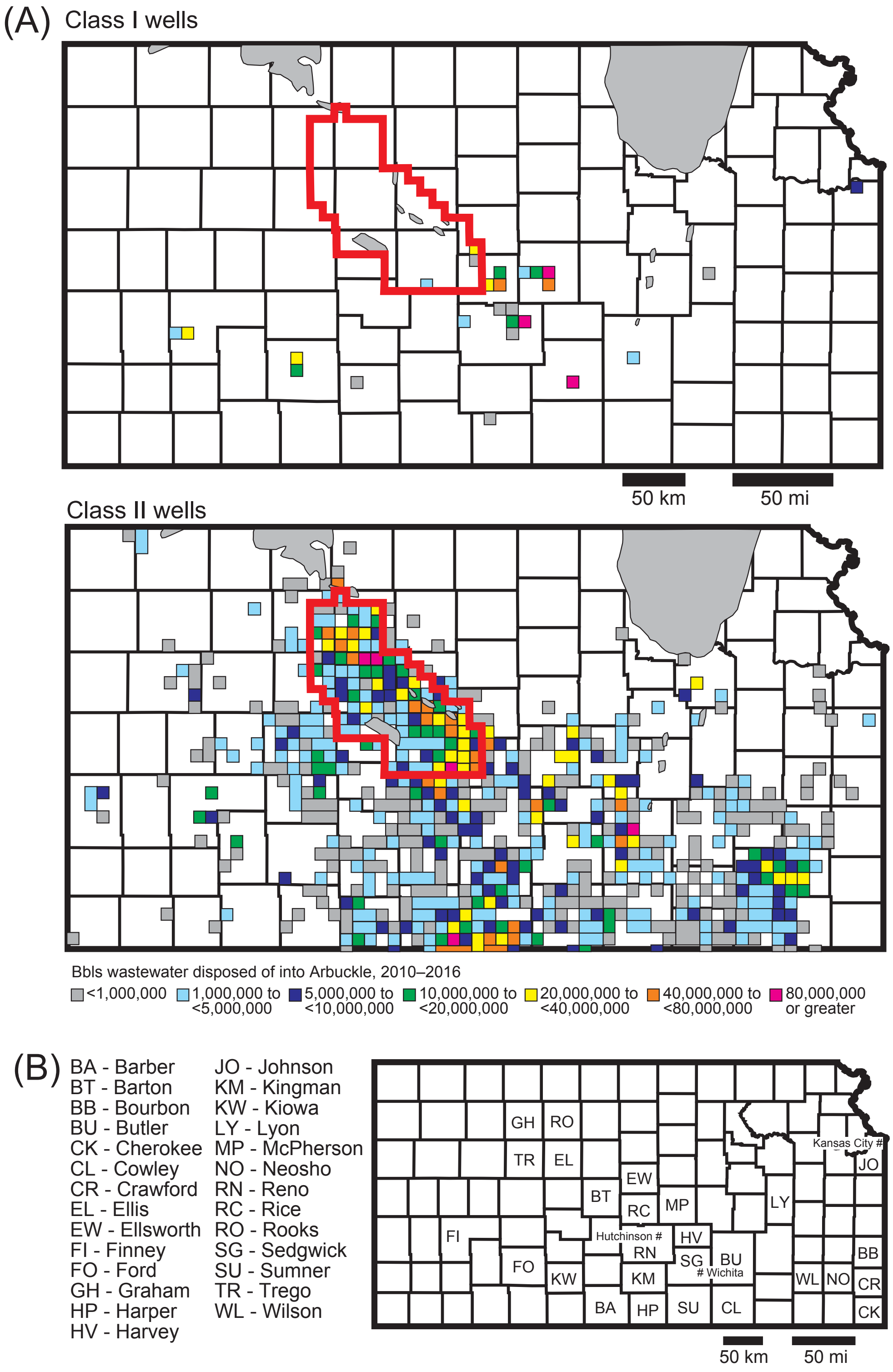


Figure 3. (A) Seven-year disposal volumes (total volume per township) into the Arbuckle (2010–2016). Maps of Kansas, color-coded on a per township basis as in fig. 2, for Class I and Class II wells. 120 townships on the CKU, where there is poor distinction between SWD and EOR wells, are outlined in red. (B) Counties with Class I wells, and other counties and cities (#) mentioned in text.

wells drilled in the last 15 years. Coalbed methane wells account for high volumes of water disposal in some townships in Neosho and Wilson counties in the Cherokee basin in southeastern Kansas. Western Butler County, in the vicinity of the prolific El Dorado and Augusta oil fields, accounts for a small but important area of Arbuckle disposal, albeit some of this disposal volume could be recycled EOR water. Class I disposal volume is significant in McPherson, Rice, and Reno counties and in isolated townships distributed across central Kansas (figs. 2 and 3).

## ARBUCKLE POTENTIOMETRIC AND HYDROSTATIC SURFACES — MATHEMATICS

When a wellbore is not being used for injection and a geologic formation in contact with the wellbore is opened to atmospheric pressure, either by perforations or open-hole completion, formation water enters and rises up the wellbore. The elevation to which the water column rises and ultimately stabilizes with time is referred to as the "static fluid level" (SFL). A related term is the "hydrostatic head," which is the length of this water column above a set reference datum. The height (or "head") of the water column is an expression of the pressure of the geologic formation to which the well is open (Dahlberg, 1982, p. 41). SFLs in Arbuckle wells typically equilibrate below the ground surface, sometimes several hundred feet, so the unit is termed "under-pressured." Equations governing behavior of an SFL and behavior of the potentiometric surface with respect to pressure and density variation are given in Dahlberg (1982, p. 41–42.)

Dahlberg (1982, p. 41) defines a potentiometric surface as "an imaginary surface, the topography of which reflects the fluid potential of the formation water from place to place within a subsurface reservoir in terms of elevation to which a column of water would rise above a reference datum within a vertical tube." A potentiometric surface is thus constructed by contouring of separate data points (in effect, SFL elevations from individual wells). A contour map of a potentiometric surface of an aquifer will ostensibly define direction of movement of the water in the aquifer, as subsurface flow will proceed from an area where the potentiometric surface is high to a nearby region where the surface is relatively low, regardless of the actual structural elevation of the aquifer in the two areas (see Dahlberg, 1982, p. 42–52).

Contouring a potentiometric-surface map is a straightforward exercise if the density of the water is relatively consistent in the region in which the potentiometric surface is being mapped. Such is the case with a freshwater aquifer, where the density of water is close to 1.0 g/cc. However, significant lateral variations of salinity in a geologic formation such as the Arbuckle complicates mapping of its potentiometric surface. Salinity depends on the quantity and types of cations and anions dissolved in the water. Increasing salinity imparts increasing density to formation water. Water in geologic formations can vary from freshwater, with a density of 1.0 g/cc, to basinal brine that has salinity several times that of seawater. Density of basinal brine can be 1.21 g/cc or more.

Mathematical corrections have to be made for valid well-to-well comparison of SFLs where there are variations in formation water salinity and density. Freshwater at a density of 1.0 g/cc is a common norm to which corrections are made (see Carr et al., 1986; Jorgensen et al., 1993, 1996).

Any corrections to a measured SFL will depend on knowledge of the SFL elevation, formation pressure, and an understanding of the density of the fluids in the formation and wellbore. The fluids in a disposal well and the surrounding geologic formation may be markedly different from each other. One of these values may not be known, but in many cases it can be mathematically determined from the other values or perhaps even approximated with knowledge of regional hydrogeology and formation-water chemistry.

A map of the salinity of the Arbuckle in Kansas (fig. 4, from Carr et al., 2005) shows that in southeastern Kansas, this unit contains freshwater, which is sourced from the Ozark uplift in southern Missouri (Macfarlane and Hathaway, 1987; Carr et al., 1986; Jorgensen et al., 1993, 1996). Over most of central and western Kansas, saline water with 10,000 to 60,000 ppm TDS dominates (fig. 4). Southward toward Oklahoma where the Anadarko basin deepens, brines can be very saline on the order of 250,000 to 300,000 ppm TDS.

Although the exact density of a basinal brine depends on the quantity and chemistry of the solutes in the water, reasonably accurate empirical correlations can be made for determining density from knowing the TDS of a formation water and

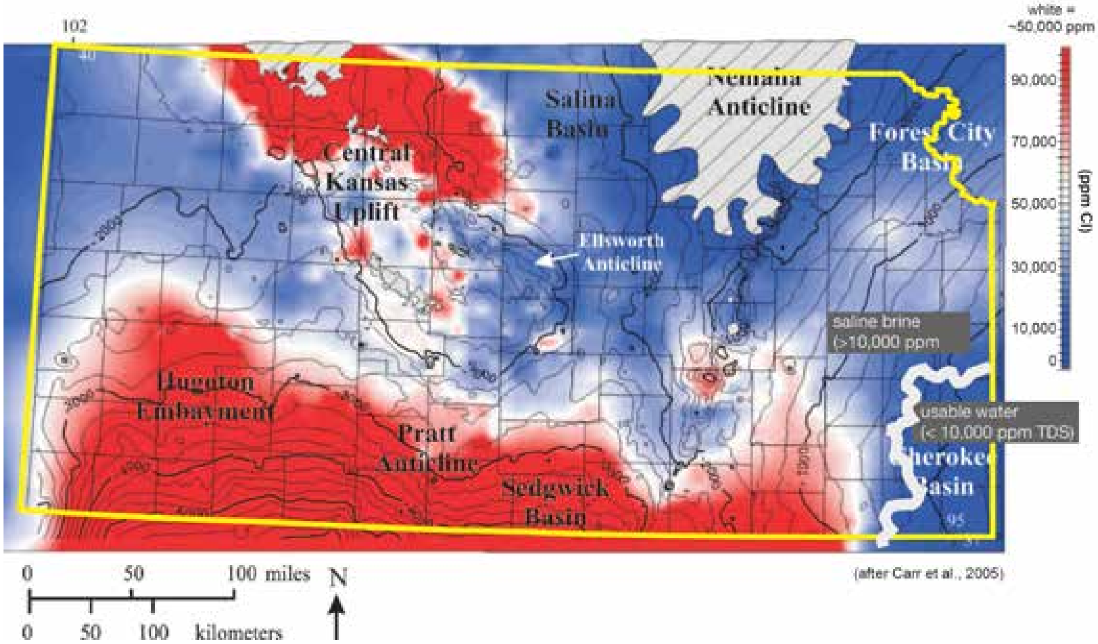


Figure 4. Salinity of Arbuckle formation water in Kansas (from Carr et al., 2005). Basinal brines are in red. White is 50,000 ppm NaCl-equivalence, whereas shades of blue have lesser salinity. The orange line indicates the limit of Arbuckle usable water (10,000 ppm TDS) in southeastern Kansas.

vice versa. An empirical relationship for correlating TDS to density specifically for Arbuckle brine can be constructed using water chemistry data available online (Kansas Geological Survey, 2018b). A regression line relating TDS in Arbuckle formation brines to density is

$$\text{brine density} = ((7 \times 10^{-7}) \times \text{TDS}) + 1.0011 \qquad (1)$$

where TDS is expressed in ppm.

This regression, graphed in fig. 5, is well constrained, with $r^2 = 0.9617$. Using the previously discussed City of Hutchinson #1 Class I disposal well, 1.004 g/cc (the density of the water in the City of Hutchinson #1 well determined from SFL and P* measurements in its 2017 annual fall-off test) corresponds to brine with ~4,150 ppm TDS calculated using the equation above. The average salinity of five water samples analyzed during the test was 1,780 ppm. This is a relatively dilute brine. A basinal brine at 250,000 ppm TDS would correspond to a density of 1.176 g/cc using this regression equation.

The City of Hutchinson #1 well also can be used to illustrate the procedure for correction (or normalization) of a measured SFL. The important measurement in determining normalized SFL in the City of Hutchinson #1 well, and other Class I wells like it, is the formation pressure (P*), which like the SFL is also measured in a typical fall-off test. In a fall-off test, water is poured down the well at a high rate to fill the well to near the surface. The flow is then stopped, and the well is left to equilibrate as the water column bleeds into the Arbuckle. Uniform radial flow is achieved in a matter of hours and as a result, the equilibration proceeds at a very precise and predictable rate. This allows for a Horner Plot determination of P*, which is the inferred "true" formation pressure.

Once the well stabilizes sufficiently so that P* and SFL can be obtained, the well is at equilibrium where the weight of the water column in the wellbore essentially exerts a pressure equal to the opposing pressure of the surrounding geologic formation, which is trying to push water into the wellbore. If the water in the wellbore is dense and highly saline, the total footage of water in the wellbore can be less than if it were freshwater. This variability of density is why the P* value is important in the normalization of SFLs. It is also important to realize that the density of the water in the wellbore in a fall-off test, however, usually does not correspond to the density of the water in the formation or even that of freshwater. In the case of the fall-off testing performed on Class I wells, the water introduced into the wellbore is usually what water is at hand at the surface. Typically, the type of water used in the test is the same as the water that is disposed of down the well.

The P* of the Arbuckle in the City of Hutchinson #1 well (surface datum 1,526 ft [465.1 m]) in 2017 was inferred from data obtained by a pressure gauge set at a depth of 4,100 ft (1,249.7 m) in the well (fig. 5). The P* was 1,659.8 psi (11,444 kPa). The SFL measured was 287 ft (87.5 m) below the surface, so its surface elevation is calculated as

1,526 ft surface elevation - 287 ft depth = 1,239 ft (377.6 m) SFL elevation, relative to sea level. (2)

The elevation, relative to sea-level datum, of the pressure gauge at a depth of 4,100 ft (1,249.7 m) is

1,526 ft surface elevation – 4,100 ft depth = -2,574 ft (-784.6 m). (3)

The length of the water column above the pressure gauge at -2,574 ft (-784.6 m) elevation is thus

1,239 ft SFL elevation – (-2,574 ft) gauge elevation = 3,813 ft (1,162.2 m). (4)

The hydraulic gradient in the wellbore calculates as follows:

1,659.8 psi/3,813 ft = 0.4353 psi/ft (9.847 kPa/m). (5)

In comparison, freshwater has a gradient of 0.4335 psi/ft (9.806 kPa/m). The density of the brine in the well can be calculated as

144 sq. in/ft$^2$ X 0.4353 psi/ft = 62.68 lbs/ft$^3$. (6)

This is the weight of 1 cubic foot of this brine. Unit conversion of this value (lbs/cubic ft) to metric (g/cc) yields a water density of 1.004 g/cc.

A back-calculation using the hydrostatic gradient for freshwater (0.4335 psi/ft) (9.806 kPa/m) yields the hypothetical length of freshwater necessary to account for a pressure of 1,659.8 psi (11,444 kPa) at the gauge depth of 4,100 ft, (1,249.7 m) where

1,659.8 psi/0.4335 psi/ft = 3,829 ft (1,167.1 m). (7)

A hypothetical distance of 3,829 ft above a 4,100 ft gauge depth calculates to an SFL (normalized to freshwater density) of 271 ft (82.6 m) below the surface, which is 16 ft (4.9 m) above the actual measured surface.

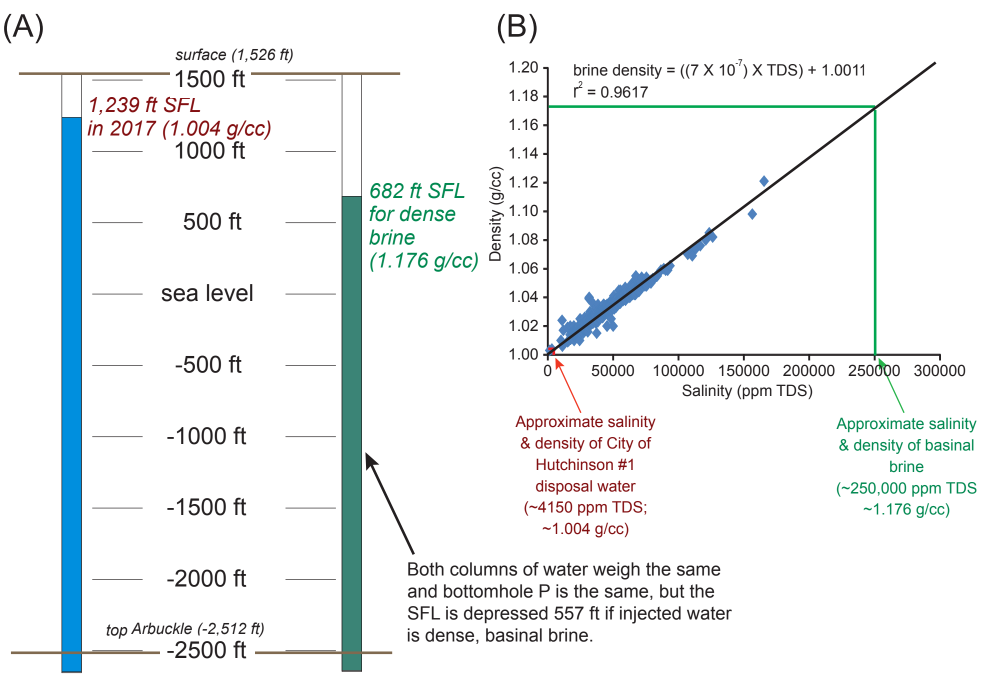
The 16 ft (4.9 m) difference between the actual and normalized SFL is small compared to the overall depth to the actual SFL in the case of the City of Hutchinson #1 well, but if the well were actually filled with dense, basinal brine, the SFL would be considerably lower. For example, a dense brine — 250,000 ppm TDS — corresponds to a density of 1.176 g/cc using the aforementioned regression equation.

The 1.176 g/cc converts to a hydrostatic gradient of 0.5098 psi/ft (11.53 kPa/m). The water column length above 4,100 ft (1,249.7 m) necessary to offset the 1,659 psi (11,444 kPa) P* is

1,659.8 psi/0.5098 psi/ft = 3,256 ft (993.0 m). (8)

The water column caused by this hypothetical dense brine would be 557 ft (169.8 m) shorter than what was actually measured (i.e., 3,813 ft [1,162.2 m] thick vs. 3,256 ft [992.4 m] thick; see fig. 5). Dense brine can thus lie very low in a wellbore compared to freshwater.

Ignoring differences in brine density when constructing a potentiometric surface can cause erroneous conclusions in determining direction and movement of formation water. For example, a cross-section showing both actual and normalized fluid levels for four Class I wells in south-central Kansas illustrates the different SFLs for the inferred actual formation water vs. that for formation water normalized to freshwater density (fig. 6). The well farthest west shows its calculated freshwater-normalized SFL to be 475 ft (144.8 m) higher than the SFL for the ambient formation brine. This is because the formation brine at that location is highly saline (~163,100 ppm TDS), and thus it will not rise very high in a wellbore. In the other wells to the northeast, the separation between the freshwater-normalized and ambient SFL surfaces is less than 100 ft (30.5 m) because the ambient brine at those localities is ~57,300 ppm or less. Note that if the SFL of the ambient brine alone was being considered, the flow-direction between the two western-most wells in the cross-section would be erroneously inferred to be flowing from northeast to southwest. Instead, normalization



Both columns of water weigh the same and bottomhole P is the same, but the SFL is depressed 557 ft if injected water is dense, basinal brine.

Figure 5. (A) Static fluid level (SFL) in the City of Hutchinson #1 well in 2017. The well is filled with dilute brine, with an SFL at 1,239 ft (377.6 m) relative to sea level. If the well were filled with dense brine, the SFL would be depressed to several hundred feet. Formation pressure (P*), which pushes the water up the wellbore, in both cases is identical (see text for discussion). (B) Total dissolved solids vs. fluid density for Arbuckle brines. Data from Kansas Geological Survey online brine database (2018b). See text for additional discussion.

of the SFL to a single standard (that of freshwater) indicates that the true flow is in the opposite direction.

A depth-to-water map (and its related hydrostatic map, where the depths to water are converted to elevations of static fluid levels relative to sea level) is different from a potentiometric-surface map because there is no mathematical conversion of the length of the water column in a well to that of freshwater. Instead, the length of the water column in a well depends on the density of the formation water. In some cases where the wellbore is filled with formation water (such as in an idle producing well with no significant oil or in a disposal well long not used), the depth to the SFL or its elevation can probably be mapped as is, without any normalization corrections. A vexing problem is that in several Class I and Class II disposal wells, the salinity of the water in the wellbore is different from that of the formation water. In such cases, a likely salinity and corresponding density for the formation water needs to be determined, and then length of the water column (i.e., the footage between the SFL and the top of the Arbuckle) has to be re-calculated as if the wellbore were filled with formation water.

Determination of brine composition in the Arbuckle carries with it some uncertainty, as the resident brine originally present in the Arbuckle has been altered by years of disposal water from other geologic formations being pumped into it. This problem may be particularly acute in areas where there has been intense oilfield development, such as on the CKU or in areas where there have been large volumes of wastewater disposed of by Class I wells or collectively from Class II wells. Injection of disposal fluid from other geologic formations changes the original composition of the brine in the Arbuckle, first in the immediate vicinity of the wellbore and then farther away with more time and increasing disposal volume. The Arbuckle, being a heavily used disposal zone, now contains a variety of water types that may abruptly change from nearly freshwater to dense basinal brine laterally, vertically, or both. Records of chemistry and volume of the wastewater put into the Arbuckle over the decades of drilling and disposal simply do not exist in any meaningful detail, nor is it clear as to which zones within the Arbuckle have taken the majority of the water from any disposal well. Mixing between porous zones is also hard to determine. In other regions of Kansas not characterized by intense oilfield development, ambient brine in the Arbuckle can be inferred to be relatively unaltered from its original composition.

With these uncertainties in mind, the Kansas Geological Survey (2018b) online brine database is composed of samples taken of oilfield water over several decades in the mid-20th century, so data from its analyses can provide an approximation of the

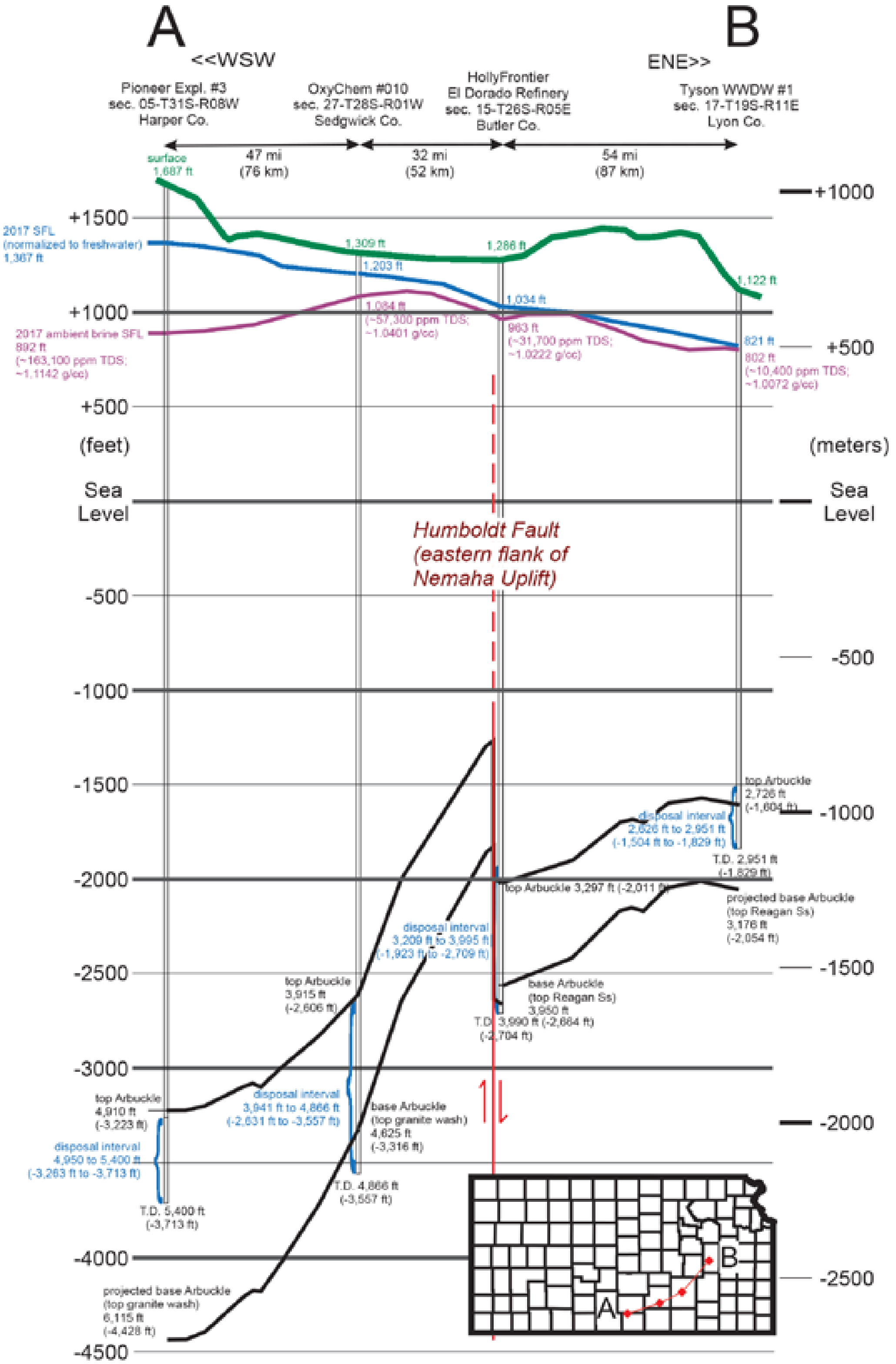


Figure 6. Structural cross-section for four Class I wells from Harper County (west) to Lyon County (east). High salinity in the Harper County well causes a greater separation between its actual SFL and its normalized SFL than in the wells farther to the east. Note that the separation decreases with decreasing salinity of the ambient water in the Arbuckle.

original chemistry and density of the ambient brine in the Arbuckle. Contouring TDS or interpolating values from several nearby localities allows for the construction of a depth-to-water map using wellbores that may have fluids different from that of the Arbuckle.

## ARBUCKLE POTENTIOMETRIC AND HYDROSTATIC SURFACES — RESULTS

A map of the elevation of the Arbuckle hydrostatic surface in Kansas (fig. 7) shows that the CKU is an area of relatively high hydrostatic head compared to surrounding regions. Fluid levels rapidly decrease to the south due to the presence of high-density basinal brines in this vicinity. Simple subtraction of this map from the surface-elevation map of the state yields a map showing the expected depth to water for wells into the Arbuckle (fig. 8). The depth to water in southeastern Kansas is within 100 ft (30.5 m) of the surface in counties along the Oklahoma state line. Over much of eastern Kansas, the depth to water is relatively shallow (less than 300 ft [91.4 m]). Conversely, the steady increase of the land surface in western Kansas west toward the Rocky Mountains allows for this region to have as much as 2,700 ft (823.0 m) depth to water along the Colorado state line.

A contour map of SFLs in the Arbuckle — where all SFL point data are normalized to freshwater density — yields a potentiometric-surface map by which direction of movement of water within the Arbuckle can be inferred (fig. 9). This map, and earlier versions (see Carr et al., 1986; Macfarlane and Hathaway, 1987; Jorgensen et al., 1993, 1996) indicate water in the Arbuckle moves northward from Oklahoma into south-central Kansas. Eastward flow into western Kansas from Colorado and general northwestward flow into southeastern Kansas from western Missouri also are indicated. Water moving down-gradient into southeastern Kansas from southwestern Missouri is due to surface recharge and downdip movement of Arbuckle water from surface exposures on the Ozark uplift (Macfarlane and Hathaway, 1987). The boundary between usable water and undrinkable brine (defined as 10,000 ppm TDS by the EPA) is a narrow interface (less than 6 mi [9.7 km] wide) that winds through five southeastern Kansas counties near the Missouri border (see fig. 4).

Most of the water in the Arbuckle in eastern Kansas will eventually flow northeastward and then exit the state in a broad region south of Kansas City (fig. 9). Salinity mapping of the Arbuckle aquifer in Missouri (Crews et al., 2010) shows a narrow (30–40

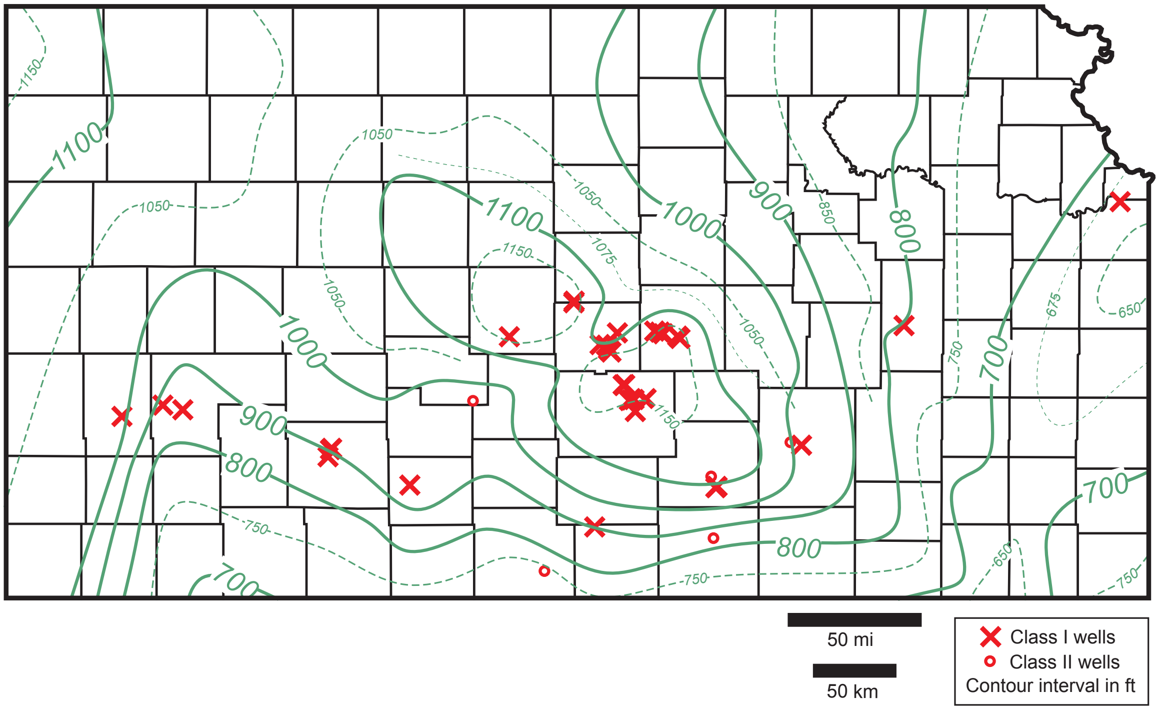


Figure 7. Elevation of SFLs for Arbuckle wells for 2017. The SFL is dependent on the density of formation fluid, which markedly varies across Kansas. This map can be used to predict the water rise in a newly drilled Arbuckle well.

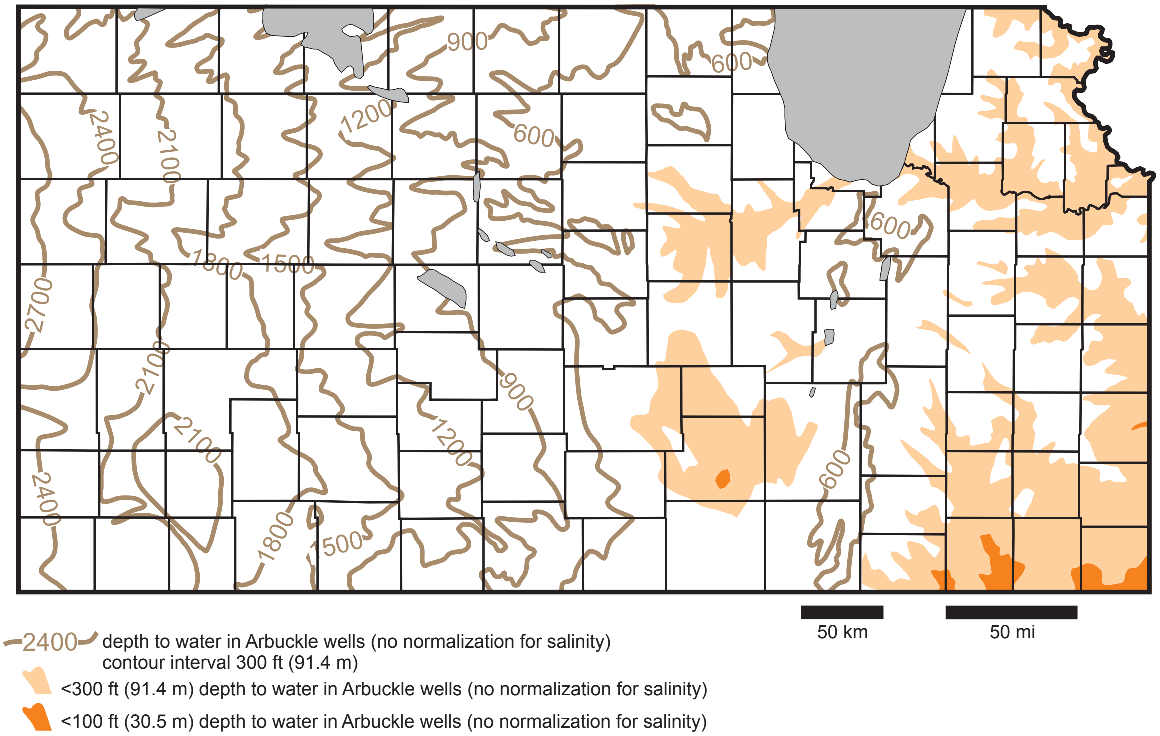


Figure 8. Depth to water in Arbuckle wells for 2017. The elevation of the SFL in Arbuckle disposal wells (fig. 7) is subtracted from the elevation map of the state to produce this map. Like fig. 7, this map does not take into account differences in salinity of the water.

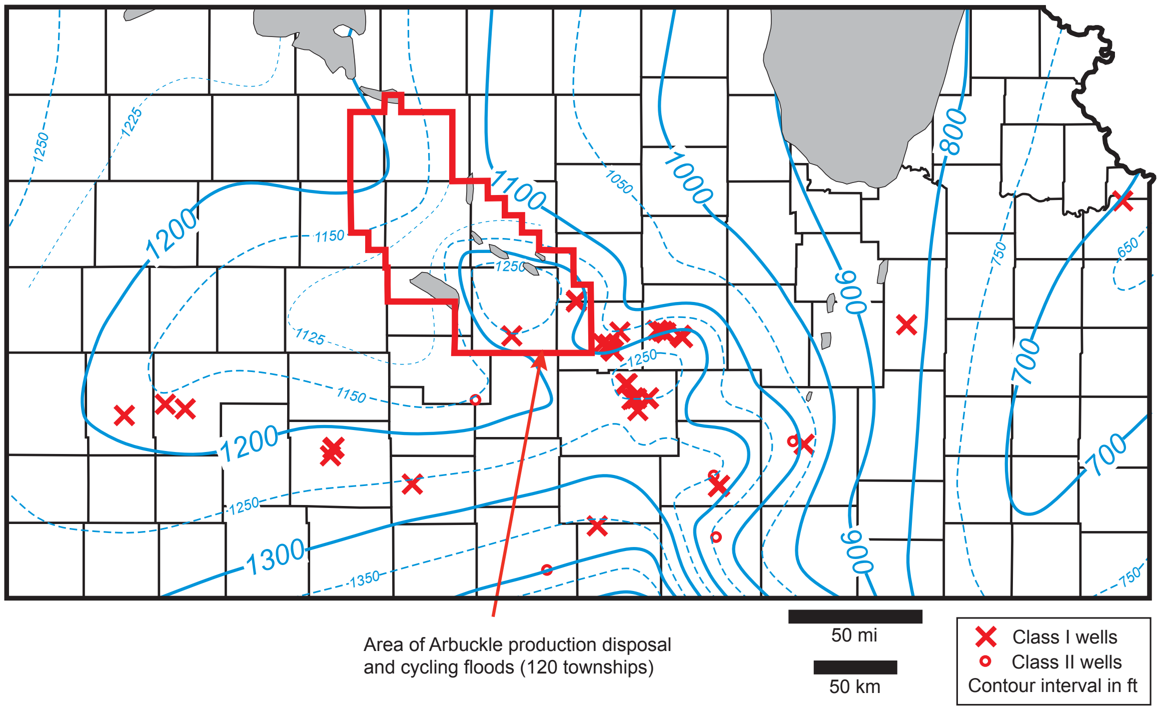


Figure 9. Arbuckle potentiometric-surface map for 2017. Normalization of the thickness of the water columns in an Arbuckle well to water with freshwater fill (i.e., a density of 1.0 g/cc) yields a map that shows direction of movement of Arbuckle formation water and relative hydrostatic head between two localities.

mi [48–64 km] wide) plume of saline water extending into Missouri from Kansas located immediately south of Kansas City. The water in the Arbuckle after it leaves Kansas flows eastward and then seeps upward into alluvium in the Missouri River valley where the Arbuckle subcrops in central Missouri on the north flank of the Ozark uplift.

Subtraction of the Arbuckle potentiometric surface (fig. 9) from a map of the surface elevation of the state yields a hybrid map (fig. 10) that highlights regions where the Arbuckle is capable of imbibing more wastewater from disposal wells and other areas where additional disposal may be problematic. Figure 10 is not a "depth-to-water" map per se, but rather it is a "freeboard" map that shows where the Arbuckle can or cannot take in low-density wastewater (i.e., wastewater with a density of ~1.0 g/cc or slightly greater) from a gravity-fed disposal well. Specifically, the light- and dark-toned blue areas in south-central Kansas along the Oklahoma state line are those areas where the elevations of the topographic map are lower, or beneath, the contours of the normalized hydrostatic map (see fig. 10).

A potentiometric surface at a higher elevation than that of ground level (i.e., the blue-toned regions in fig. 10) does not mean an Arbuckle disposal well in these areas will be artesian. Instead, any low-density wastewater that is disposed down a well in the blue-toned areas will not be able to enter the Arbuckle because there will be insufficient hydrostatic head produced by the weight of this wastewater in the wellbore. Simply put, the water in the wellbore will not be able to force its way into the formation by gravity alone. The well would fill to the top of the casing at the surface, and the water would then sit there. It could be forced into the formation by pumping, but this is not an option in Class I wells (see table 1 and prior discussion). Since Class I wells cannot be pressurized in Kansas, the permitting and drilling of a Class I disposal well in the blue-shaded areas depicted in fig. 10 would not be viable for any facility depending on that well to dispose of low-density wastewater.

The problem of wastewater not entering the Arbuckle is solved if either the hydrostatic head of the disposal well or the density of the wastewater

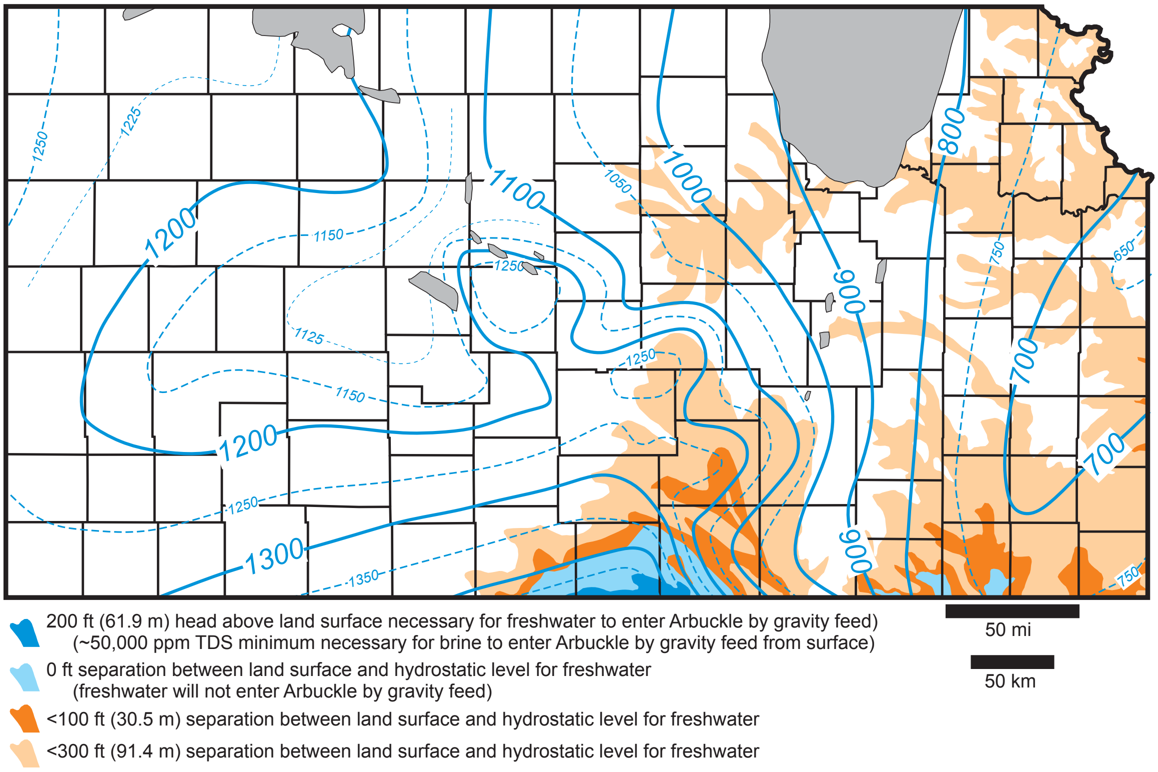


Figure 10. Arbuckle potentiometric surface compared to the land surface, for 2017. Contours are the potentiometric surface depicted in fig. 9. The blue-toned regions where the elevation of the normalized potentiometric surface exceeds the elevation of the land surface show where freshwater cannot enter the Arbuckle by gravity alone. Any wastewater will have to have a greater density to enter the Arbuckle in the blue-toned areas; specifically, in the dark blue area, a minimum density of ~1.035 g/cc is required, which corresponds to water having ~50,000 ppm TDS.

can be increased. Calculations indicate that in the most problematic areas (the dark-blue shaded regions in fig. 10), at least 200 ft (61 m) of extra hydrostatic head would be needed for low-density wastewater to enter the Arbuckle. Alternately, disposal brine with at least ~50,000 ppm TDS (~1.035 g/cc) would be just sufficiently dense to enter the Arbuckle from the surface by gravity.

A characteristic of most oilfield waters from Paleozoic reservoirs above the Arbuckle is that this wastewater is very dense saline brine, usually in excess of 100,000 ppm TDS (Newell et al., 2017). Furthermore, these oilfield brines are also usually more dense than ambient brine in the underlying Arbuckle (Newell et al., 2017). Most Class II disposal wells thus will have few problems with well overflow, because their typical high-density water causes a high pressure at depth, which will force the disposal water into the Arbuckle. Class II wells also can be subject to pressurization by pumps to aid the entry of disposal water into the Arbuckle and other disposal zones. If a Class II well that relies on the high density of its brine to enter the Arbuckle ceases disposal, hypothetically the dense brine left in the wellbore may eventually disperse into the disposal zone to be replaced by less-dense formation water, although this replacement would most likely take months to years. A rise in the SFL of the well would result. The dense brine also could displace less-dense water upward in the formation; thus, any inactive nearby well open to the Arbuckle could experience a rise in its SFL. This could present a danger if the rise were in excess of the elevation of the well head, or worse yet, if the formation water subsequently accessed casing leaks just below the surface to enter a shallow aquifer containing potable water.

## STATIC FLUID LEVEL CHANGE OVER TIME

Analysis of SFLs and P*s in Class I wells, annually reported to the KDHE, reveal that the Arbuckle may not be entirely flushing away all the fluids introduced into it. Of the 49 Class I Arbuckle wells in the state, 31 have recorded increasing bottomhole pressures (and concomitantly rising normalized SFLs) since 2006. Most of these wells with rising SFLs are in southern and central Kansas. From 2010 through 2018, normalized SFLs have risen as much as 32 ft/year (9.8 m/year), although median and average annual rises for this time period range from 9.5 to 10.5 ft (2.9 to 3.2 m) (fig. 11). Most Class I wells have recorded rises in SFL since 2010, and marked rises have occurred in central Kansas (fig. 11). Fluid rise in both eastern and western Kansas appears less than the fluid rise in central Kansas.

Rises in P* at Arbuckle level since 2011 in three Class I wells (fig. 12) located in Harper, Sedgwick, and Reno counties correspond with a general increase in the annual disposal volume from all disposal

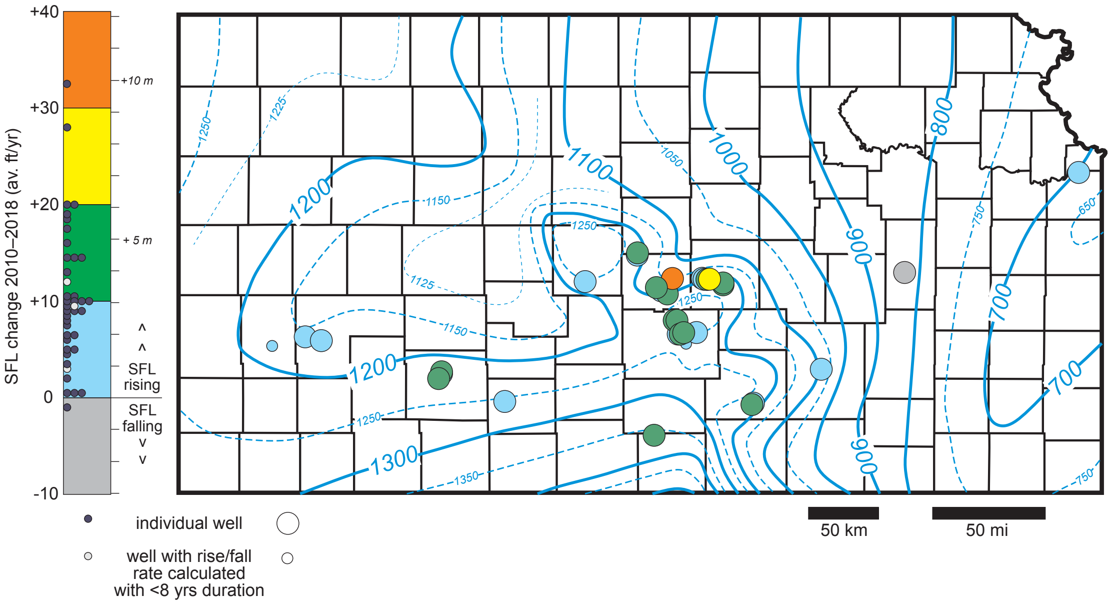


Figure 11. Changes in elevation of Class I SFLs from 2010 to 2018, presented as ft/year change over the nine-year period. Contours are from fig. 9, the map of the Arbuckle potentiometric surface.

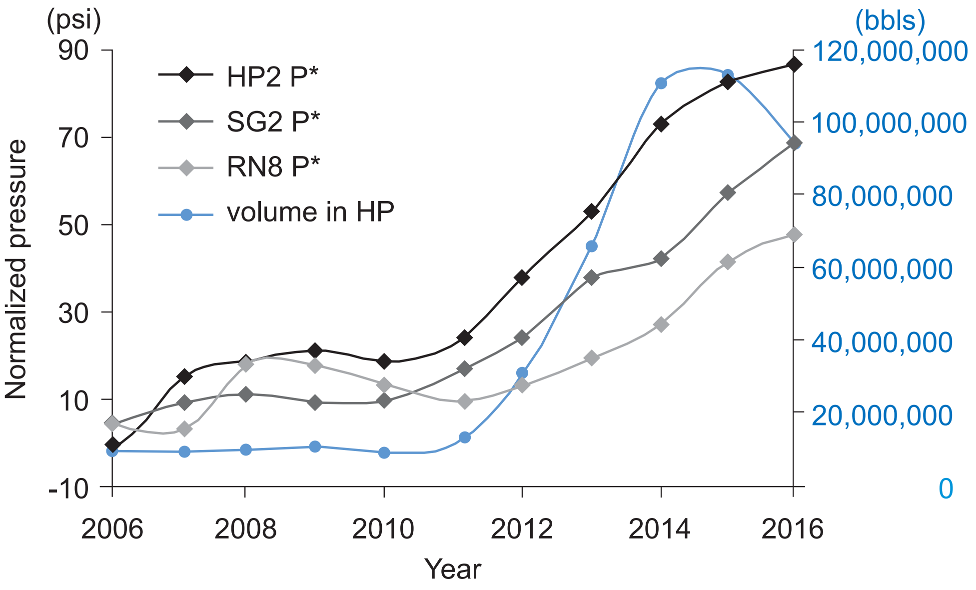


Figure 12. Normalized bottomhole pressures (P*) measured in Class I wells in Harper (HP), Sedgwick (SG), and Reno (RN) counties (shades of gray lines) relative to the combined annual injection volume of disposal wells in Harper County (blue line). Absolute pressures were normalized relative to the baseline pressure measured in each well (measured in 2002, or first reported bottomhole pressure) to facilitate comparisons between different wells. Modified from Peterie, Miller, Intfen et al. (2018).

wells (Class I and Class II) in Harper County. The increase in Arbuckle injection volume starting in 2011 (fig. 1) is significant and the current annual amount (~800 million bbls [~127 million $m^3$] for 2018 — combined volume for Class I and II disposal wells), although diminished from its maximum in 2015, still significantly exceeds all annual injection volumes recorded before 2014. Normalization of the fluid rise to the level expected if the water in the wellbore were fresh provides a better correlation to P* than simply recording the annual fluid rise, because densities of disposal water can change over time. Year-to-year changes in the salinity of the fluid used in annual well tests (which closely corresponds to density) and well-to-well differences in density of the wastewater all complicate correlation and comparison of SFLs and changes in SFLs over time unless the density of the various disposal waters is normalized to a common density (i.e., normally 1.0 g/cc).

In western Kansas where depth to the SFL in a well open to the Arbuckle can be in excess of 500 ft (152 m), an annual rise of the SFL by a few feet is unremarkable. However, in wells where current depth to water is less than 200 ft (61 m), a similar annual rise of the SFL could cause the SFL to be at the surface within a decade or two. Companies that generate wastewater that is disposed of down a Class I well must plan how to dispose of their wastewater several years in advance. In an area where SFLs are close to the surface, these companies have to either ameliorate any negative effects of their wastewater on the environment (therefore obviating the need for a disposal well) or initiate procedures to decrease their volume of wastewater, or both. A third alternative may be to increase the density of the wastewater by adding solute or mixing the wastewater with a brine more dense than the wastewater. Unfortunately, with the addition of solute or brine with higher salinity, the volume of wastewater is increased. The increase in density also may be achieved by concentrating the wastewater by evaporation or partial distillation. In any of these circumstances, a dense wastewater will depress the SFL (see arguments attendant to hypothetical changes in the SFL with fluid density for the #1 City of Hutchinson wells illustrated in fig. 5), particularly if the density of the SFL exceeds that of the resident fluid already present in the Arbuckle. The last option — the least attractive — would be to shutter the entire facility.

Understanding and predicting fluid rise (or fall) in the Arbuckle potentiometric surface is thus important from environmental and economic standpoints. A component to this understanding is examining how fluid volumes (i.e., bbls annually disposed of into the Arbuckle) and SFL changes (i.e., recorded yearly rise or fall, in ft) correspond to each other. To this aim, annual SFL changes and disposal volumes were examined in 36 Class I wells for the years 2010 through 2016. Of these 36 wells, 20 had positive correlations between annual fluid volume and annual fluid rise, but 16 had negative correlations. The $r^2$ values (i.e., coefficient of determination), which quantifies goodness-of-fit of the two data sets, are not high — ranging from 0.0003 to 0.64 and averaging 0.18.

Several factors, both geologic and dynamic, may account for the poor correspondence of SFLs and disposal volumes. Porous zones in the Arbuckle vary in length, location, and stratigraphic level. Permeability may be only loosely correlatable to porosity and can be markedly altered by fracturing, which may be hard to detect.

Annual measurements of the SFL and formation pressure do not always occur at the end of the calendar year, whereas the calendar year is the customary temporal span for summing disposal volumes. Most SFL and P* testing occurs from April through November when weather is not so extreme. Some Class I wells being tested also have Class I and Class II wells nearby (i.e., less than 1 mi [1.6 km] distant) that are actively disposing into the Arbuckle during testing. The effect of nearby active wells on the SFL of the tested well is poorly known. Mixing and movement of wastewater with resident formation brine beyond the wellbore in the Arbuckle is also poorly understood and the downhole pressure effects due to varying densities of the wastewater and resident brines are difficult to measure.

Considering data over several years duration should minimize the asynchronous measuring of fluid volumes and SFLs. To these ends, cumulative fluid rises and cumulative volumes for a longer time period of six years (2011 through 2016) are compared for 31 Class I wells (fig. 13). Wells not considered for this exercise were those wells drilled since 2011 or wells with insufficient SFL measurements. Unfortunately, as with the yearly data, there is still poor correlation between the total volume disposed of down a well during this six-year period and its total fluid rise (or fall) (fig. 13).

Fluid rise or fall recorded in an individual well over the six-year period considered may still have other extraneous influences, specifically additional wastewater pushed into the Arbuckle from nearby or far-away wells. To test whether wastewater input from other wells could influence SFL behavior in a Class I well, fluid volumes from other Class I or Class II disposal wells at set distances (i.e., within

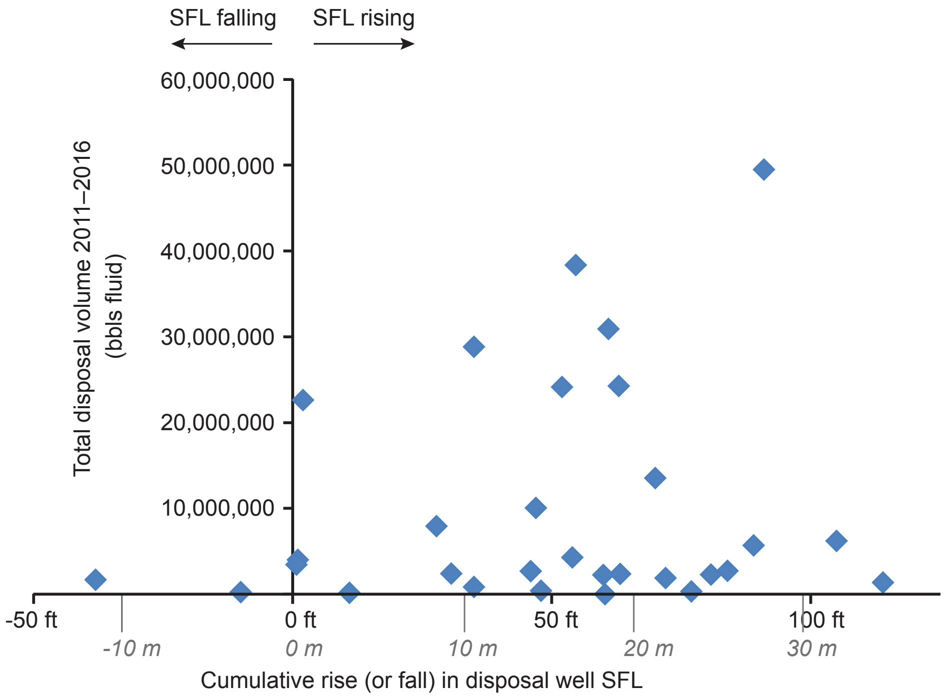


Figure 13. Total Arbuckle disposal well volumes for a six-year period (2011–2016) cross-plotted against cumulative fluid rise (or fall) for 31 Class I disposal wells from the same period.

1, 3, and 6 mi [1.6, 4.8, and 9.7 km]) were summed with that of the Class I well tested. These volumes were then compared to the six-year (2011–2016) SFL change for the Class I well tested (fig. 14). In each of these three cases, there were no discernable trends correlating SFL and disposal fluid volumes. A rather unsatisfactory conclusion is that SFLs in most Class I wells are rising, but the amount of rise cannot be readily tied to the amount of fluid disposed of down the Class I well or nearby wells up to 6 mi (9.7 km) away. We infer that the Arbuckle consists of complex porosity systems and that various disposal wells access those porosity systems to varying degrees by the amount of Arbuckle section open in their well bore. Connectivity of the porosity systems by fracturing, sedimentologic, or diagenetic pathways is possible. We interpret that the poor correlation of static fluid levels and wastewater volume is more a function of regional controls beyond just 6 miles (9.66 km) distance away from the individual Class I well. The regional control of fluid levels is also evident in the collective behavior of all the Class I wells with time (see fig. 1). Statistically, annual fluid rise in Class I wells corresponds to the total amount of wastewater put into the Arbuckle annually (peaking in 2015), as expressed by the annual median fluid rise of all Class I wells and the percentage of these wells annually recording fluid rise, both of which also peaked in 2015 (see fig. 1).

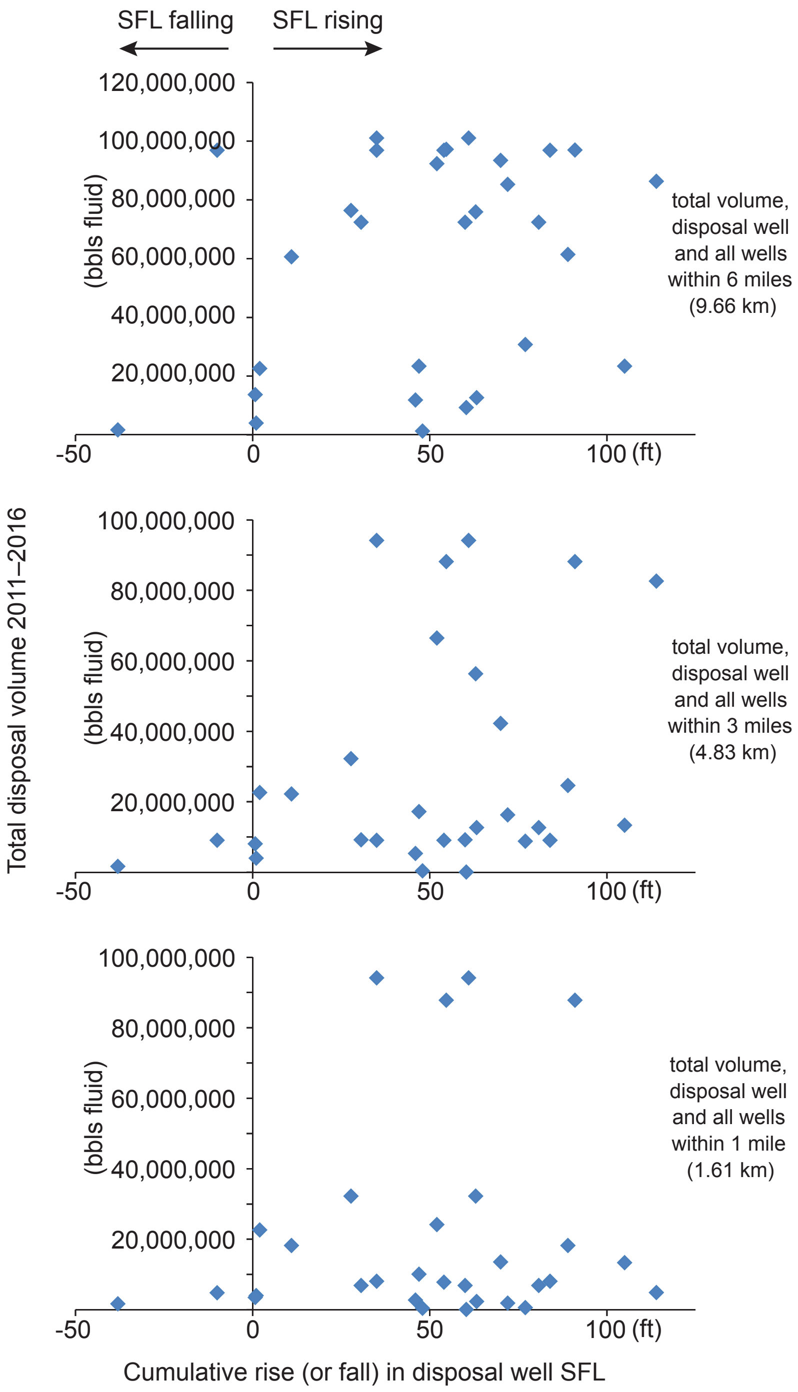


Figure 14. Comparison of the total SFL changes in Class I wells (2011–2016) with the total volume of brine disposed down the well and the sum of disposal volumes of any Class I and II wells within a 1 mi, 3 mi, and 6 mi (1.6, 4.8, and 9.7 km) radius of the Class I well. Wells depicted are the same as those in fig. 13.

Quantitative prediction of fluid rise based on disposal fluid volume is thus still speculative, but modeling fluid flow in the Arbuckle would be an essential investigative step to better understand interactions of wastewater and formation water volume, porosity, permeability, subsurface pressure, and resultant static fluid levels. Modeling is always an approximation of the behavior of the real world, but larger-scale, multi-township-scaled and multi-county-scaled models of fluid movement in the Arbuckle can supply some insight into potential problems at hand with earthquakes and fluid rise.

The rise in SFL in some Class I wells is still a cause for concern, though, particularly in those localities where there is little depth to water and taking into account the historical rate of rise of the potentiometric surface. In some cases, this implies an imminent end to the ability of the disposal well to take wastewater. A linear projection of remaining well life, as controlled by the ability of the Arbuckle to take water, can be effected by a simple cross-plot of depth to water in a well vs. the nine-year rate of fluid rise observed from 2010 to 2018. Two types of graphs can be made: a cross-plot with actual depth to fluid and fluid rise (fig. 15) and a similar graph showing those fluid footages normalized to the density of freshwater (fig. 16). The first cross-plot (fig. 15) would be of primary use to Class II operators who deal with high-density fluids and their immediate effects on the Arbuckle, whereas the second graph (fig. 16) may be more important to Class I operators, some of whom work with low-density wastewater that may eventually not have sufficient hydrostatic head to force its way into a more saline Arbuckle disposal zone.

Although some Class I wells appear to have projected disposal lives of less than 25 years, recent drops in SFLs over the last two years (see fig. 15) may portend a reversal in the progression of ever-lessening depth to water with time. When footages in the annual rate of change of the SFL and the depth to water are adjusted to that of freshwater (fig. 16), the effective life of a nearly freshwater disposal well is illustrated, even though actual water depths in such a well can be considerably deeper than the normalized depth. Differentiation of the density of the wastewater vs. that of the ambient formation fluid (see fig. 16) into those wells with wastewater more dense than formation fluid and those wells with wastewater less dense than formation fluid is thus important. Those wells with relatively dense wastewater may be afforded a few more years of life since their fluid will tend to force its way into the Arbuckle.

A caveat to the problem of estimating the remaining life of a disposal well is that the rates and capacity of water movement in the Arbuckle are still not well understood. Hopefully, the rate of rise in some at-risk wells will diminish or perhaps even reverse in the future due to the overall decrease in the volume

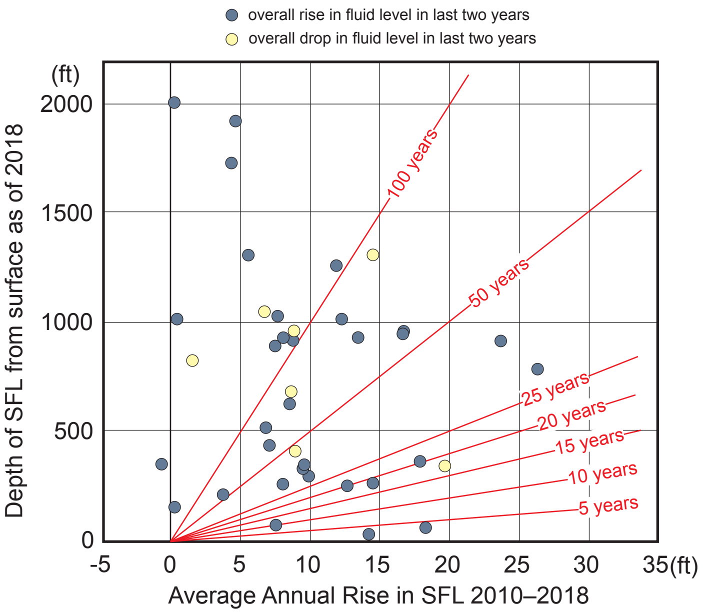


Figure 15. Remaining depth to water vs. average SFL change in Class I disposal wells (from 2010 through 2018), with a projection of remaining life of the Class I well. Depending on rates of fluid fill-up, a Class I well will have a projected life of 15 to 20 years if it has less than 300 ft (90 m) of freeboard remaining.

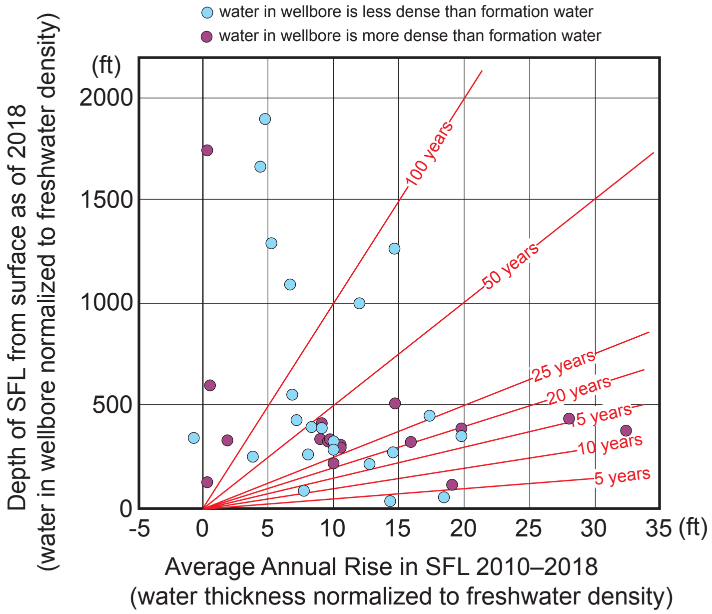


Figure 16. Remaining depth to water vs. average SFL change in Class I disposal wells (from 2010 through 2018), with a projection of remaining life of the Class I well. This graph is similar to fig. 15, except footages for the average annual change of SFL and the depth to water are normalized to that of a density of freshwater (1.0 g/cc).

of fluid disposal into the Arbuckle since 2015 (see fig. 1). The drop in Arbuckle disposal volume since 2015 and its possible future effects on SFLs may prove to be an enlightening, although unintended, experiment about fluid movement in the Arbuckle. However, SFLs may continue to rise despite diminished disposal volumes. Additional SFL and pressure data, and perhaps modeling of fluid flow, may refine our understanding of the Arbuckle potentiometric surface and how it changes with time.

Collectively, SFL changes in Class I Arbuckle disposal wells may be responding to the total volume of fluid put into the unit. The percentage of Class I wells recording year-to-year rises in their normalized SFLs and the median annual rise in SFL both peaked in 2015, the same year in which the most fluid was disposed of into the Arbuckle (fig. 1). The percentage of Class I wells recording fluid rise apparently drops with each year since 2015, even though the majority of Class I wells are still recording fluid rise as of 2018. Class II wells are mostly responsible for the large changes in Arbuckle yearly disposal fluid volumes whereas disposal volumes for Class I wells are relatively constant (fig. 1). The meticulous testing the Class I wells have to undergo may thus be detecting, as a group, regional effects of fluid disposal primarily driven by the thousands of Class II wells disposing in the unit.

## SUPPLEMENTAL DATA SOURCES FOR ARBUCKLE HYDROLOGIC MAPPING

Considering the small number and limited geographic distribution of the Class I wells, additional data are required to more fully characterize and determine what changes are occurring in Arbuckle pressure and hydrostatic gradients in Kansas, particularly in areas where the normalized or actual potentiometric surface is close to or above the land surface. Potential sources of supplementary data that can be used to construct more detailed maps of the Arbuckle potentiometric surface include 1) DSTs, 2) MITs, 3) fluid fill-up from wireline-logging runs, 4) water levels in municipal water wells, and 5) additional pressure and SFL measurements on selected Class II wells. The great number of Class II wells and their geographic spread across the state make them a potentially valuable data resource. Each of these data sources has potential applications and limitations that demand their judicious use. The following is a brief discussion of the limitations and use of each of these potential data sets.

### *Drill-Stem Tests*

DSTs are a prolific source of P*, temperature, and fluid analyses for subsurface formations. However, there are complications in applying DST data to mapping the Arbuckle potentiometric surface. Typically, an oil-industry DST focuses on a relatively thin interval of strata, approximately 5 to 50 ft (1.5 to 15 m) thick. A DST also can test a large length of open hole below where the tool is set, but these generalized tests covering thick stratigraphic intervals are not common. This less-common type of DST is what would be needed to map the Arbuckle potentiometric surface because the potentiometric surface, as it is measured in most Class I wells, is a product of several porous and permeable zones present in the entire Arbuckle. Considering that the Arbuckle can be up to 1,200 ft (365 m) thick in Kansas (Franseen et al., 2004), DST results from the very top of the unit in a heavily produced and flooded Arbuckle oil field may bear little correlation to pressures and fluids encountered deeper within the unit.

A detailed examination of Arbuckle DSTs in northwestern Kansas in four townships at the common corners of Graham, Trego, Ellis, and Rooks counties illustrates that porous zones in the Arbuckle at this locality have drastically varying P* values (fig. 17). Of 242 DSTs analyzed, 146 were tested for sufficient time to indicate that P* was nearly achieved during shut-in periods of the tests. Twenty of the DSTs had continuously recorded time/P measurements so that a Horner Plot could determine a P* value for the test. The P* values for these 146 tests ranged from 435 to 1,239 psi (2,999 to 8,543 kPa). The four-township area analyzed covers an aggregation of several closely spaced oil fields that produce from Pennsylvanian strata and the top of the Arbuckle, so the extraordinary range of P* values indicates that marked lateral and vertical pressure gradients are already established in the Arbuckle, most likely by pumping, water disposal, and waterflooding of pay zones near the top of the Arbuckle. The regional P* value of the entire Arbuckle at this locality is thus obfuscated and can only be approximated at best by these exploration- and production-oriented DSTs. DSTs taken in other regions away from active Arbuckle oil production may yield more consistent results, which could be more applicable to potentiometric-surface mapping, but further study is needed.

*Mechanical Integrity Tests*

MITs are required of every Class II disposal well in Kansas every five years (table 1). In addition to pressure testing, disposal wells in the Cherokee basin and Forest City basin typically have an SFL measurement, whereas disposal wells in western Kansas are pressurized to determine whether the pressure drops off with time (thereby indicating a possible casing leak) (R. Hoffman, KCC, personal communication, 2017). SFLs from MITs in eastern Kansas are thus readily useable for construction of depth-to-water and potentiometric-surface maps.

Data from MITs conducted for the KCC for a nine-township area (~18 X 18 mi) in southeastern Kansas (R. Hoffman, KCC, personal communication, 2017; fig. 18) show that wells disposing of water into Arbuckle and Mississippian strata have SFLs that vary in depth but appear to be generally rising with time. SFLs for Arbuckle strata are generally lower than those for Mississippian strata; hence, if a well is open to both zones, fluid from porous zones in the Mississippian would likely force its way into the Arbuckle. The depth to water for the Arbuckle in this region could be approximately 675 ft (206 m). Salinity measurements (ppm TDS) on nearby wells (from Kansas Geological Survey [2018b]) are also plotted on fig. 18. The salinity data indicate that the Arbuckle is conceivably useable in this study area, having less than 10,000 ppm TDS (i.e., the EPA maximum for usable water). A normalized potentiometric map would need this salinity data for corrections to freshwater SFLs.

*Fluid Fill-Up from Wireline-Logging Runs*

Exploration and production wells for oil and gas commonly have wireline logs run on them after the well has reached total depth. Air-drilled wells (common in eastern Kansas) usually quickly fill with formation water soon after the air compressor, which forces air through the borehole and up the well annulus during drilling, is stopped. During a wireline-logging run, fluid level is sometimes noted on well logs or can be read from a tool (such as the SP log) that is sensitive to the presence of water.

Local experience by the primary author indicates that in southeastern Kansas coalbed methane wells, Mississippian strata are the major source of wellbore fill-up rather than the thin porous zones in the Pennsylvanian strata present higher up in the well. Air-drilled wells thus may have a unique utility for constructing potentiometric-surface maps for Mississippian strata in southeastern Kansas. If a well is cased down to the Arbuckle, then any water in the wellbore and its level (if stable) could be attributable to the Arbuckle and thus also used in mapping potentiometric surfaces for that unit.

Mud-drilled wells are more problematic for this type of analysis because drilling muds, by design, are supposed to infiltrate and seal off porous zones along the side of the wellbore (Doveton, 1986, p. 27). Drilling mud is also denser than formation water, so

Figure 17. Pressure vs. date for DSTs in a four-township (~12 X 12 mi [~19.3 X 19.3 km]) area in northwestern Kansas. DST reports graphing shut-in P vs. time were used to determine whether pressure buildup in a test was nearly equilibrated to formation pressure (P*). In 20 DSTs, continuous digital readings of P and time enabled P* determination with Horner Plots. The pressure range on the vertical axis is from 1,000 to 1,250 psi, but 31 of the 146 DST P* determinations (21%) were below 1,000 psi and are thus not shown. See text for discussion.

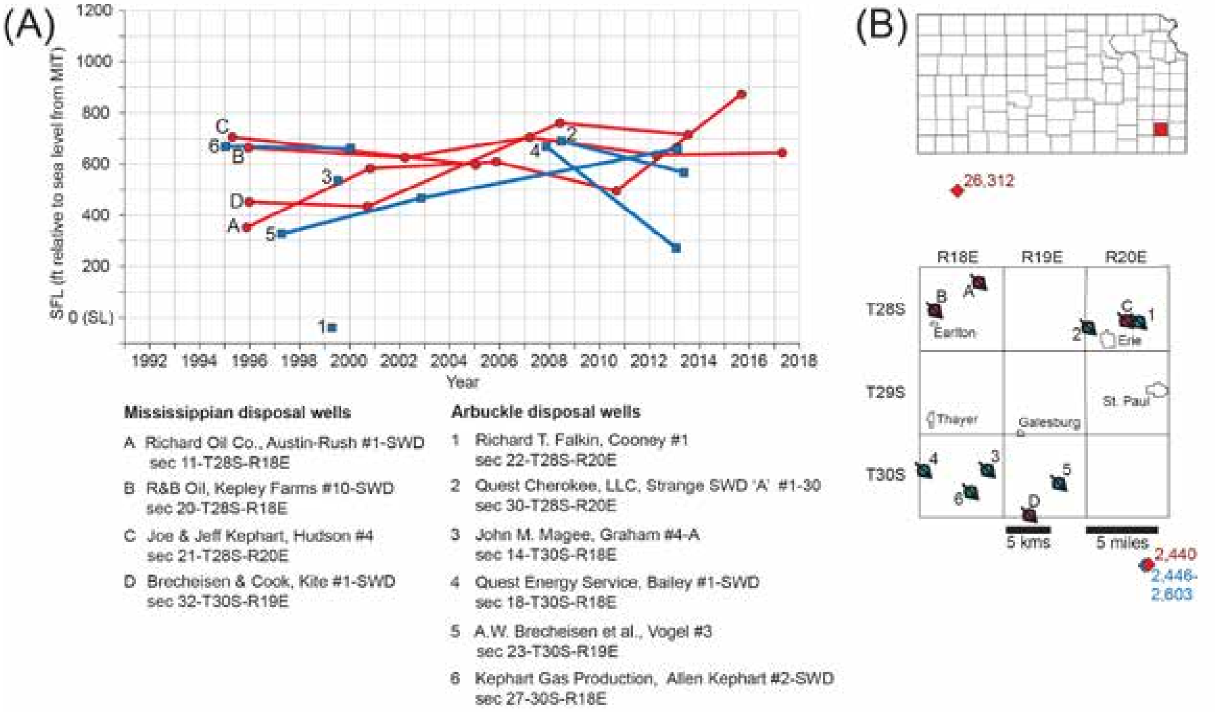


Figure 18. (A) SFLs from mechanical integrity tests (MIT) made on disposal wells in southeastern Kansas in a nine-township area in Neosho County. The KCC requires these tests every five years. Mississippian disposal wells are denoted by letters and are in red; Arbuckle disposal wells are numbered and in blue. (B) Well locations in Neosho County. Diamonds on map indicate well locations with available salinity data from the Kansas Geological Survey (2018b) online brine database. See text for discussion.

entry of formation fluid into a wellbore is inhibited by the presence of drilling mud in a wellbore.

SFLs obtained during MITs from two selected Mississippian wells and one Arbuckle well (fig. 18) compared to fluid levels obtained in logging runs in nearby coalbed methane wells (see fig. 19) show that the fluid levels obtained from the logging runs are almost consistently 100 to 300 ft (30.5 to 91.4 m) higher than the SFLs from the MITs. This brief exercise indicates that fluid levels determined during logging runs are perhaps not dependable for potentiometric-surface mapping because in an open-hole well (i.e., a well not cased), the fluid level is an eclectic expression of water entering the wellbore from all the porous and permeable zones in contact with the wellbore. This is analogous to why a DST taken in a thin zone near the top of the Arbuckle may not represent the potentiometric surface that would result if the entire Arbuckle were opened to the DST.

### *Water Levels in Municipal Water Wells*

Arbuckle formation water in the southeastern corner of Kansas is potable (see fig. 4), and some towns have wells that tap the formation for their municipal water supplies. This region is composed of Crawford, Cherokee, and Bourbon counties and parts of adjacent counties farther west and north where the Arbuckle has water with slightly higher salinities transitioning to basinal brine (fig. 4). SFLs from water wells may have merit for mapping potentiometric surfaces, although there may be a problem getting accurate measurements because the water wells probably have to be pumped more or less continually to satisfy a consistent demand for water from even a small municipality. The region in Kansas where Arbuckle water is potable is relatively small compared to the rest of the state where the Arbuckle water is a high-salinity brine (fig. 4).

### *Additional Pressure and SFL Measurements on Selected Class II Wells*

Class II wells that penetrate into the Arbuckle are widespread and numerous. These Class II wells represent an untapped source of needed data that could aid in better understanding Arbuckle water disposal and movement.

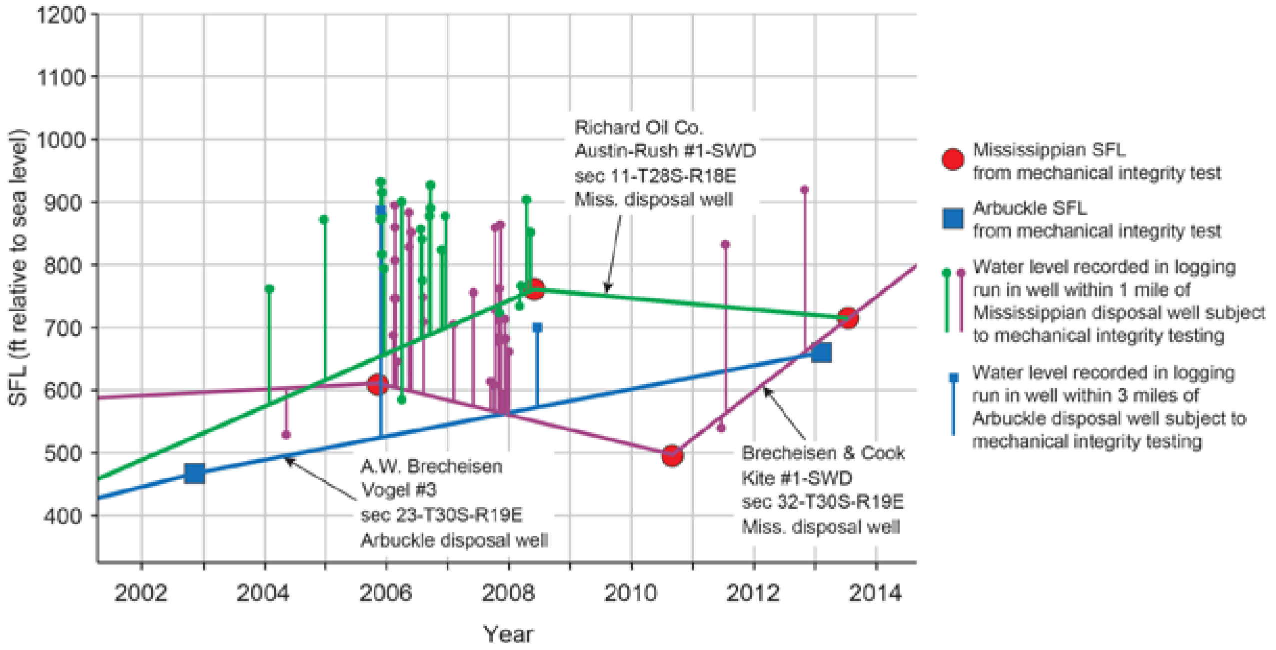


Figure 19. Comparison of fluid levels recorded in geophysical logging runs in wells within 1 mi (1.6 km) of two selected Mississippian disposal wells subject to five-year mechanical integrity tests and within 3 mi (4.8 km) of a selected Arbuckle disposal well subject to five-year mechanical integrity tests (from fig. 18).

Unfortunately, most Class II wells do not penetrate any great distance into the Arbuckle — generally having total depths only a few tens of feet into the top of the unit. Conversely, most Class I wells are open to most or all of the Arbuckle. As previously discussed in the section on DSTs, selecting wells with minimal penetration into the Arbuckle runs a danger that only individual and possibly isolated porous zones near the top of the Arbuckle will be sampled for P* and SFL. These zones may not characterize the sum and influence of all the porous zones in the Arbuckle, particularly where the unit is relatively thick off the crests of the major uplifts in the state. In effect, if only small depths of penetration are taken into account, data obtained could have a large spread in P* values, like that observed for the thin zones that were separately tested by the DSTs in the northwestern part of the state (see fig. 17).

Deeper porous zones near the bottom of the Arbuckle may influence P* and SFL in most of the Class I wells. Scheffer (2012) studied chemical stratigraphy of water from the entire Arbuckle at the Wellington Field in Sumner County, Kansas, and found that porous zones in the upper part of the Arbuckle are hydrologically separate from other porous zones near the base of the formation. Water chemistry in these lower porosity zones was remarkably uniform, possibly due to communication via fractures. The intervening middle of the Arbuckle has relatively low porosity.

Class II disposal wells with deep penetration into the Arbuckle thus stand the best chance to correlate with extant P* and SFL data obtained from Class I wells, but the number of such Class II wells that merit possible testing is considerably less than the total number of Class II wells. For example, there are 632 Class II Arbuckle disposal wells in 10 counties in south-central Kansas (i.e., Barber, Butler, Cowley, Harper, Harvey, Kingman, McPherson, Reno, Sedgwick, and Sumner). Of these wells, only 68 (11%) significantly penetrate (i.e., entirely, or within 200 ft [61 m] of the total length) the Arbuckle. Some of these 68 wells are near Class I wells, so even fewer of them would be worth testing.

Selectively testing some of these deep-penetrating Class II wells would supplement hydrologic mapping based primarily on data from Class I wells. Well testing, particularly with operating Class II wells, can be expensive, time-consuming, and potentially disruptive to oil field operations. Operational time necessary for testing may cause lost income; therefore, some oilfield operators are hesitant to commit to well testing that may interfere with the complex production infrastructure that produces, stores, and delivers their product.

Using Class II wells with deep penetration into the Arbuckle is preferable to shallow-penetrating Class II wells for the same reason that DSTs that test large lengths of Arbuckle are preferable to those testing only a few feet at the top of the unit. The potentiometric surface of the Arbuckle, as determined using data from Class I wells, is an eclectic product of many or all of the porous and permeable zones in the Arbuckle, rather than just what can be measured from one or two thin pay zones near or at the top of the unit.

Further study of permeability and pressure and fluid movement vertically within the Arbuckle is needed. Just as DSTs indicate that thin zones at the top of the Arbuckle appear to be quite variable in their P* and SFLs due to oilfield production and disposal, a logical follow-up question would be to what extent do Class II fluid disposal volumes (which are dominantly directed to the upper part of the unit) affect the entire Arbuckle? If the large amount of fluid that enters near the top of the Arbuckle does not have much influence on the potentiometric surface as defined by the Class I wells, then where is this Class II wastewater going and what is the geometry of its particular potentiometric surface?

## FUTURE IMPLICATIONS

A better picture of the Arbuckle potentiometric surface (fig. 9), through the collection of additional data (outlined in the previous section), is necessary. At present, Class I wells are the primary source for constructing this surface. These wells are relatively few in number and many are geographically concentrated in relatively small areas of central Kansas. More data are needed, particularly in regions where Class I well density is sparse.

Although we now know the approximate areas where there is limited depth to water, and where hydrostatic head for gravity feed of low-density wastewater may be insufficient for forcing entry into the Arbuckle, more accurate mapping will better define the extent of these marginal areas. Placement of new facilities dependent on new Class I disposal wells probably should not be solely reliant on generalized regional mapping.

Inasmuch as most industrial facilities must plan and construct their waste-stream processes years in advance of their need, better prediction of fluid rise (or fall) of a potentiometric surface would be directly helpful to those industries. If SFLs continue to rise, the diminished or lost capacity of the Arbuckle to take wastewater may dictate shutting down otherwise economically viable establishments, such as facilities that use Class I wells or profitable producing oil wells dependent on nearby Class II disposal wells. Shutting down a refinery or oilfield-related industrial facility due to Class I waste disposal problems would certainly have an economically deleterious effect on oil and gas fields that feed their product to that facility.

In addition to the seismicity potentially induced by rises in hydrostatic pressure, the rise of SFLs and concomitant decreasing depth to water in Arbuckle disposal wells also may have a direct and deleterious environmental impact. If the hydrostatic head of the Arbuckle exceeds that of shallower aquifers that contain potable water, then brine or toxic effluent from the Arbuckle could flow into the shallow aquifer. Although a disposal well may be operating normally with no casing integrity issues, there may be nearby abandoned and unmonitored wellbores, known or unknown, that may leak hazardous waste or saline brine into the endangered aquifer or possibly onto the ground surface in areas where fluid rise is most extreme. These are worst-case scenarios that have not been detected so far in Kansas. Nevertheless, if Arbuckle SFLs continue to rise, any chances of these scenarios occurring will also increase over time.

Considering these scenarios, it would be wise to anticipate and understand the manifold problems that could result from loss of the Arbuckle as a disposal zone rather than wait for any problems to manifest themselves. Areas where problems may occur are only now rudimentarily identified, and the best solutions to any problems that may occur are unclear, given the nascent state of our knowledge.

At present, any problems with fluid rise in Arbuckle disposal wells (i.e., loss of disposal capacity, subsurface contamination of shallow aquifers, surface spillage, etc.) are still hypothetical. However, potential loss of disposal capacity in the Arbuckle is now very real for the companies and municipalities that have to plan years in advance to construct facilities to solve their future waste-disposal operations. Do they just have to drill a new disposal well? Should they concentrate their wastewater to decrease its volume? What ideas will best ameliorate the possibility that disposal capacity of the unit will be lost, and what can be done to assure that subsurface or surface contamination will not occur?

## CONCLUSIONS

Historically, the Arbuckle has taken large amounts of disposal water at virtually any locality where a disposal well has been drilled into it. This paradigm for easy wastewater disposal, in effect, makes the Arbuckle a valuable resource despite it also being a petroleum reservoir and potable aquifer in some parts of Kansas. However, it may not remain a viable disposal zone for the foreseeable future. Some areas in south-central and southeastern Kansas are seeing the potentiometric surface of the Arbuckle approaching the topographic surface. This implies that some critical areas can be used for Arbuckle disposal for only a few more years. Industrial facilities depending on disposal wells to eliminate their wastewater may be significantly affected if their disposal wells can no longer take any wastewater and if alternatives to subsurface disposal are not economically viable. Facilities disposing of low-salinity wastewater will be particularly vulnerable to possible well fill-up. Requisite shut-downs of industrial facilities could be a worst-case scenario. Shutting down energy-related industries, such as refineries and pipelines that rely on Class I disposal wells for wastewater disposal, also could indirectly affect oilfield operators.

Most Class II disposal wells and some Class I wells, by virtue of the very dense water they move into the subsurface and their frequent well inspections, are not readily vulnerable to a scenario of surface overflow or subsurface leakage into a shallow aquifer. However, any wastewater not removed by subsurface flow down the hydrostatic gradient will increase the pressure of the Arbuckle, first in the immediate vicinity of the wellbore and then farther out with time. SFLs in nearby unused wells will commensurately rise in response to the pressure rise, and those SFLs may be relatively high if the formation water at those localities is not very dense. If that buoyant backflow of formation water makes its way into a leaky well annulus or a faulty casing and then enters a shallow aquifer that contains useable or potable water, or perhaps even spills onto the ground surface, an environmental cleanup and its attendant costs are foreseeable.

Any plans for possible storage of $CO_2$ (see Carr et al., 2005) in the Arbuckle will have to take into account those regions in the state where the unit is already approaching its capacity to hold any more disposal brine. If the Arbuckle is indeed at risk of losing its capacity for wastewater disposal in some localities, technological fixes may need to be instituted to reduce disposal volume or to purify the wastewater so disposal is not necessary. Partly evaporating dilute, low-density brine without release of hazardous chemicals into the environment can be energy-intensive and expensive, though.

At present, more data on formation pressure, static fluid levels, and fluid density are needed to obtain a more detailed picture about what happens to disposal waters that are introduced into the Arbuckle. Most Class I wells studied are concentrated in small groups, with rather large distances between groups. Additional wells, most likely selected from the hundreds of Class II wells in the state, could fill in the large data gaps and supply useful data for fluid modeling studies.

With the decrease in disposal volume into the Arbuckle since 2015, SFLs in Arbuckle disposal wells also may decline in the future in delayed correspondence with decreased oil production in the state. We could also assume that annual disposed fluid volumes will never rise again. However, we cannot omnisciently predict future SFLs or oil production or industrial disposal activities with absolute certainty. Simply put, more data and analyses are necessary to better understand and predict how the Arbuckle will behave as a disposal zone. Additional data, which would have to be obtained from selected Class II wells, can aid in better understanding the complexities of Arbuckle hydrology. Current and future water-disposal issues in the Arbuckle deserve our understanding and the input of all who use and regulate it.

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