Study to Establish a Measurement Protocol for Accurately Estimating Regional Arbuckle Properties in South-Central Kansas

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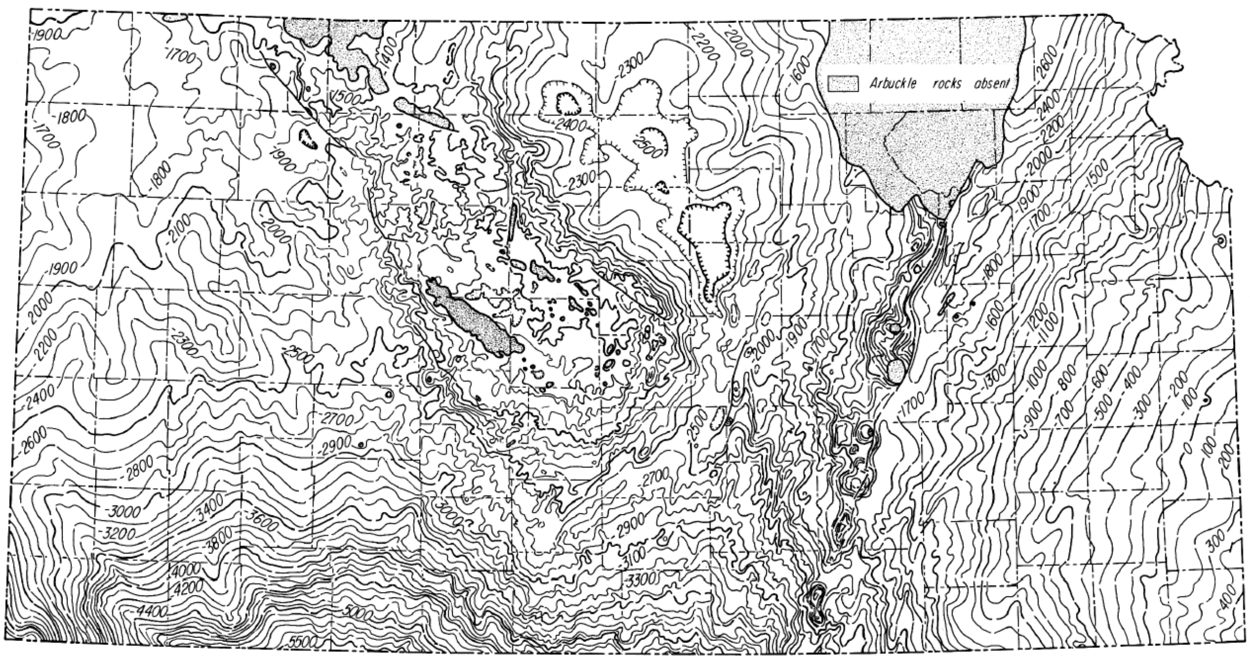

Final report to

Kansas Water Office
900 SW Jackson St., Ste. 404
Topeka, Kansas 66612

In fulfillment of KWO Contract #21-113

Kansas Geological Survey Open-File Report 2024-12

This project is funded by the State of Kansas Water Plan Fund

January 2024

Cover Figure Caption: Elevation of the top of Arbuckle contoured at 100 ft intervals (modified from Merriam, 1963).

Executive Summary

The Arbuckle Group (Arbuckle) is heavily relied upon by a range of industries and municipalities in Kansas for fluid-waste disposal, oil production, material storage, and a source of freshwater. Conserving and maintaining a sustainable capacity within the Arbuckle are critical for the energy industry and industrial/municipal facilities in Kansas that extract freshwater from or dispose of wastewater into the Arbuckle Group. The capacity of the Arbuckle to accept a range of fluid types could be exceeded in the next few decades in certain areas in Kansas and may already have been exceeded in a few isolated locations in south-central Kansas. Extrapolating changes in Arbuckle fluid levels measured in Class I wells in Reno, Butler, Sedgwick, and McPherson counties over the last decade suggests proper management of this resource necessitates routine monitoring of Arbuckle static fluid levels over a large portion of south-central Kansas. Routine monitoring of dynamic characteristics and building a temporal database with sufficient historical measurements and adequate spatial resolution is essential to well-informed management decisions and ensuring the long-term potential of the Arbuckle as a Kansas industry-wide resource. Acquiring supplemental data in a distributed network of Class II wells would provide the necessary enhanced spatial resolution of the current database primarily consisting of Class I wells.

A feasibility study was proposed to evaluate methodologies and develop a testing protocol for accurately and functionally acquiring Arbuckle fluid data on a routine basis across a spatially optimized network of Arbuckle monitoring wells. To that end, static fluid level (SFL), density, and bottomhole pressure (BHP) data were to be collected in several “average” Class II saltwater disposal (SWD) wells suitable for an annual measurement program using a specified set of reasonable measurements methods. Barriers faced to optimally completing this goal ranged from physical limitations within a normal functioning produced water disposal well to perceived risk and liability to the owners. Even with these impediments, the primary goal of the feasibility study was met and a relatable measurement protocol was established for Class II SWD wells. Supplemental tests were conducted to resolve some key methodology questions and validate extrapolations between measurement points.

As part of ongoing Kansas Geological Survey (KGS) investigations of the Arbuckle, the KGS commissioned supplemental testing in a Class I well in October 2020, directly preceding planned and required annual Class I compliance testing. The objective of this internally funded KGS study was to complement the objectives and outcomes of the feasibility study funded by the Kansas Water Office (KWO). Although the KGS sampling was intended only to piggyback onto the required Class I compliance testing and provide additional data for the larger study, data recorded were extensive enough to provide insights into the optimal design of data acquisition procedures necessary to produce data sets relatable to existing Class I databases.

Based on the results of this test, correcting pressure measurements for tidal effects is generally unnecessary because the diurnal changes are on the order of measurement uncertainty. The most accurate methods for determining BHP are static measurements or pressure transient analysis from a pressure fall off (PFO) test. Measurement projections from shallower depths, even within the open-hole portion of the well at the top of the Arbuckle, result in unacceptably large errors in the calculated freshwater-equivalent SFL due to a variable density profile in Arbuckle brine disposal wells. A possible solution to the segregation of fluids in the casing that are not representative of the formation fluid is to pump the well to vacate injected fluid within the cased portion of the borehole and allow it to fill with local Arbuckle formation fluid. This would provide a much more consistent or at least constant density profile. With a constant density profile, BHP could be accurately projected from shallow measurements, which would be useful for cost-efficient time-lapse monitoring using an inexpensive shallow transducer and data logger.

Following the completion of the KGS Class I study, measurements were collected in three Class II wells under the supervision of the Kansas Corporation Commission (KCC) in Barber,

McPherson, and Sedgwick counties, two Class II wells in McPherson and Marion counties, and one uniquely constructed Arbuckle monitoring well in Sumner County. To evaluate the accuracy of interpolation through spatially undersampled areas, updated piezometric surface maps were generated for 2021 and 2022 both with and without data from the Class II wells, primarily using Class I well measurements. Inclusion of these Class II wells results in no change in the extrapolated fluid level contours at the Barber County well and a 20 ft downward correction at the Sedgwick County well due to erroneous measurements in a nearby Class I well. These erroneous measurements were caused by interference from nearby active disposal wells during pressure falloff testing. Upward corrections of 5 and 10 ft resulted for the two Class II wells in McPherson County, whereas the Class II well in Marion County had results that were suspect and possibly attributable to shallow-borehole obstructions. (The Wellington KGS 1-28 well in Sumner County was not directly included here due to the unique construction and very limited sampling interval toward the base of the Arbuckle, but historical data from the well were used for general reference). The relative consistency of the measured SFL compared to the previously interpolated SFL suggests broad connectivity of the Arbuckle Group rather than isolated near-well responses to local injection.

Statistical analysis of change in SFL adjusted to freshwater density provided a clear indication that change in SFL in any individual well is more closely correlated to regional disposal volumes than the actual volumes recorded for each individual well. This regional connectivity within the Arbuckle is consistent with observed permeability at the geologic province size (egg carton analogy) rather than the "inverted cone of depression" model with near well (section) influences of injection volumes greatest relative to far field influences (counties). Key to this observation is the stabilizing timeframe of fluid properties in the Arbuckle. The time lag between SFL rise and fall vs. the disposal volume for most wells is probably on the order of weeks or months rather than years, with annual measurements allowing assessment of diffusion of fluid pressures well beyond the wellbore.

Between 2018 and 2021, freshwater-equivalent SFL generally increased west of and decreased east of the Midcontinent Rift System, with approximately 0 ft change along the approximate trace of the rift. As there is uncertainty interpolating between sparse Class I well data points, it is unclear whether this apparent pattern in SFL rise and fall is real and represents a pressure gradient associated with the rift and differing hydrologic properties between geologic provinces.

The annual volume of water disposed of into the Arbuckle has declined since its peak in 2015, principally due to a decrease in Class II well disposal volumes. The total annual disposal volume in the study area in 2022 is consistent with the 2011 volume (prior to development of the Mississippian limestone and rapid rise in disposal volumes near the Kansas-Oklahoma border). SFL in most Class I wells has stabilized, with only slight rises or drops relative to 2015 levels. In some localities, the actual measured SFL remains within as little as 30 ft of the ground surface. In addition to operational concerns in such wells, this observation leads to the question: at what elevation is the actual piezometric surface (i.e., the elevation to which formation fluid, rather than freshwater, would rise in an Arbuckle well)? A natural extension of the current study would be to correct for the actual salinity/density of Arbuckle formation fluid to characterize the true piezometric surface relative to not only ground surface but also shallow aquifers. This analysis would facilitate assessment of hypothetical environmental risk in the unlikely event of a casing breach in an Arbuckle well.

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1. Introduction

1.1. Background and motivation

The Arbuckle Group (Arbuckle) is heavily relied upon by a range of industries and municipalities in Kansas with significant potential for future commercial development. The Arbuckle has been the source for about 30% of all the oil produced in Kansas starting in the 19th century in eastern Kansas (Franseen et al., 2004). Earliest large oil discoveries were Augusta (1914, Butler County), El Dorado (1915, Butler County), and Fairport fields (1925, Russell County). Most Arbuckle production is currently on the Central Kansas Uplift. Natural gas storage for retail markets has found utility in Arbuckle structural traps. Additional storage capacity for natural gas is possible considering potential future infrastructure and associated needs. Communities in southeastern Kansas along the Missouri state line (Cherokee, Bourbon, and Crawford counties.) use deep wells into the Arbuckle for freshwater (Macfarlane and Hathaway, 1987; Jorgensen et al., 1993, 1996; Carr et al., 2005). Since 2000, the Arbuckle has been studied as a possible zone for CO_2 sequestration. Early studies were concentrated at sites in south-central Kansas (Sumner County), where subsequent well measurements have indicated that reservoir capacity may be limited in some areas. Current sequestration studies focus on southwestern and central Kansas, where the Arbuckle has localized reservoir capacity to assimilate supercritical CO_2.

Technologies for large-scale upgrading of oilfield brines, industrial effluent, and in-situ saline formation water to useable water are in the early stages. Wastewater minimization efforts underway have made some progress toward reducing Arbuckle disposal volumes, but more than 700,000,000 bbls are injected in the Arbuckle annually. Perhaps future technologies could overcome the formidable barriers to economically upgrading the many types of wastewater now permanently entering the Arbuckle. Well into the future it might even be possible to harvest and treat or process waste fluid currently stored in the Arbuckle for limited use (industrial or agriculture) or mining opportunities (fluid-borne critical minerals). Continued permanent disposal into the Arbuckle will be necessary at least for the near future. As technology advances deeper into the 21st century, abandoned or underutilized disposal and production wells may have the potential to be modified in some areas for a wide range of applications (e.g., geothermal). The Arbuckle is a unique and vast resource with untold potential waiting for technology to emerge to exploit that potential. Looking at the Arbuckle as a resource for centuries to come, someday it might be practical to produce low-temperature geothermal power or harvest formation fluids for extracting critical mineral resources.

Historical disposal of fluids in the Arbuckle in both Class I and Class II wells has been at sustainable to moderate filling rates. However, yearly tests of Class I Arbuckle disposal wells indicate that pressure and static fluid levels are rising more rapidly in the last decade than the prior century, particularly in south-central Kansas (Figure 1) (Newell et al., 2020). These changes are collectively correlated to large disposal volumes, which more than doubled from 2010 to 2015. Much of this waste fluid is from oil production wells along the Kansas-Oklahoma state line. Disposal volume has declined since the 2015 high but not yet returned to pre-2010 levels. Some disposal wells are recording decreasing fluid levels, but the majority of these wells are still recording rising fluid level. Rising fluid levels measured in Class I wells in Reno, Butler, Sedgwick, and McPherson counties suggest that if recent rates of fluid rise continue, Arbuckle fluids could eventually reach shallower unlithified sediments and if a migration pathway exists (or is formed through anthropogenic activities, as previously documented [e.g., Walters, 1977]), mixing of Arbuckle waters with potable water resources might be possible.

Future resource conservation and capacity of the Arbuckle is critical for industrial operations and municipal facilities in Kansas where wastewater is disposed of into the Arbuckle Group. In certain areas, the capacity of the Arbuckle to take fluid could be exceeded in the next few decades even at current reduced disposal rates. Suggestions of regional changes in static fluid levels are based on data from a sparse few Class I disposal wells that spatially under sample the aquifer. The degree of extrapolation and associated error necessary to map the likely surface of Arbuckle fluids highlights the need for more spatially dispersed sample points to confidently determine fluid level changes. An in-depth study of fluid characteristics in a large number of wells with significant penetration of the Arbuckle across an eight-county area in south-central Kansas (Sedgwick Geologic Province) would provide a much higher-resolution and accurate database for studying static and dynamic trends. Supplemental data in a distributed network of Class II wells will enhance the spatial resolution of the current database from Class I wells and reduce interpolation distances. The information obtained from such a study would be crucial for management and sustainable use of the Arbuckle while protecting this important Kansas resource for the future.

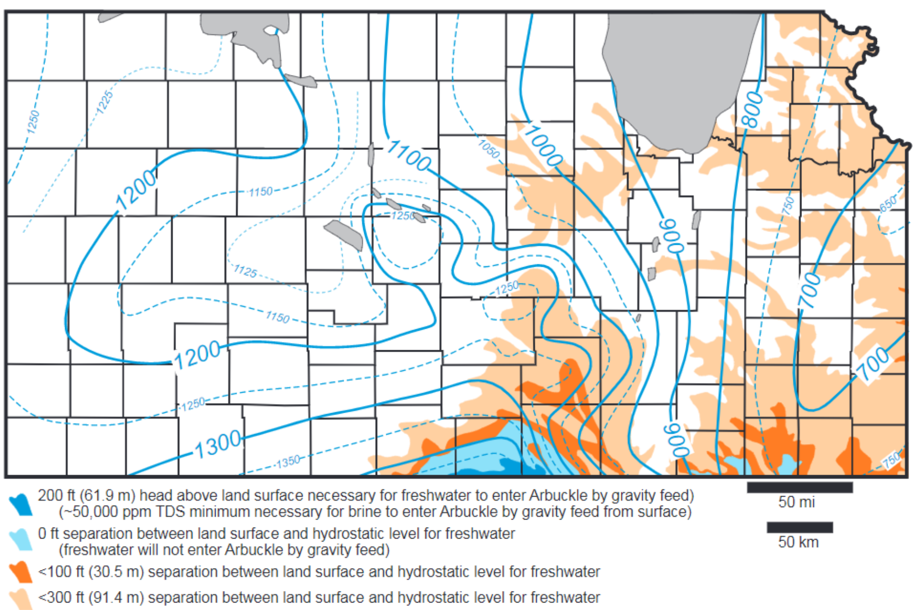

Figure 1. 2018 elevation of the Arbuckle piezometric surface (freshwater equivalent). The blue-toned regions where the elevation of the freshwater-equivalent hydrostatic level exceeds the elevation of the land surface show where freshwater cannot enter the Arbuckle by gravity alone. Projections beyond the sample points are contoured based on a regional Arbuckle piezometric surface map published by the U.S. Geological Survey (Jorgensen et al., 1993).

1.2. Feasibility study: original scope of work and barriers

In advance of a full study to investigate critical Arbuckle fluid data across an eight-county area, a preproposal/feasibility study was designed to assess measurement methodologies and establish the protocols and procedures to be used in the full study that will be the precursor for a regimented monitoring program. Data required to characterize and assess Arbuckle fluid changes are formation pressure at the bottom of the borehole (bottomhole pressure, BHP), static fluid level (SFL), and fluid density (ρ) profile. Together, these measurements describe the three variables in the hydrostatic pressure equation:

$$P = \rho g h \ , \tag{1}$$

where P is the pressure due to the overlying fluid column, g is the acceleration due to gravity (9.8 m/s^2), ρ is density, and h is the height of the fluid column (equal to the depth d where BHP is measured minus SFL). Thus, equation 1 can be rewritten:

$$\mathrm{BHP} - \mathrm{P_{atm}} = \rho g(d - \mathrm{SFL}) \ , \tag{2}$$

where $\mathrm{P_{atm}}$ is the atmospheric pressure.

A variety of methods may be used to measure or calculate the variables in this equation. At Class I facilities, formation pressure is typically determined from Horner analysis (Horner, 1951) of pressure transients recorded near the bottom of the borehole during a pressure falloff (PFO) test. This is an active test in which fluid is injected until radial flow is achieved; the well is then shut in and pressures are recorded over time (as a time series). Horner analysis uses mathematical modeling and data fitting to estimate relevant reservoir properties, including the extrapolated pressure (P*), which is equivalent to formation pressure. Pressure gradients are calculated from pressure recorded at various depths throughout the borehole during a pressure gradient survey. Pressure is linearly extrapolated using the pressure gradients of the borehole fluid and open atmosphere to determine the depth at which they intersect—the SFL. Using P* and SFL, the apparent density of the fluid column can be calculated with equation 2.

PFO tests are sophisticated approaches used by engineers to more fully characterize the reservoir and evaluate well performance. As such, these tests are more involved and expensive, require specialized analysis, and may be influenced by other factors (restricted flow, etc.). Therefore, PFO tests are not recommended for routine monitoring in a network of Arbuckle wells, but results from routine monitoring of Class II wells for this study must be compatible with the existing database predominantly obtained from PFO testing in Class I wells. The objective of the feasibility study and original scope of work was to evaluate other more cost-effective and practical methods for accurately determining BHP, SFL, and density and to establish industry standard baseline measurements in Class II wells consistent with Class I.

The Kansas Geological Survey (KGS) identified Class II wells that met the minimum criteria for the study where the borehole was open in the Arbuckle more than 200 ft to allow representative sampling of the formation and had an inner diameter greater than 1.75 in to minimize risk to the tool and the well. Many of the wells originally targeted were located across Barber, Harper, and Sumner counties and belonged to a single operator (Figure 2). The Kansas Corporation Commission (KCC) provided contact information for the operator's field staff who manage these wells. These field staff were very supportive of and interested in participating in the testing. Ultimately, insurance carried by the contractor to cover potential damage to the operator/owner's well and associated loss of income was deemed insufficient to mitigate financial risk and liability if a well was damaged during measurement.

The KGS contacted five additional operators, one for whom the KCC provided a direct contact. Three did not respond; two indicated that they had potential interest and would speak with their management but ultimately did not respond despite the KGS's multiple attempts to reengage with them. Conversations between KGS and KCC staff revealed that an additional concern of operators was potential damage to the anticorrosive lining inside the tubing; pulling that tubing is invasive and expensive and well beyond the scope of this study. Barriers related to physical limitations of wells, risk, and liability concerns of owner/operators could not be sufficiently overcome for the KGS to perform the planned feasibility study within the proposed timeline. The KGS also pursued abandoned wells under the supervision of the KCC, temporarily abandoned wells, and newly drilled wells but could not identify any abandoned or newly drilled wells that fit the criteria for and were available within the timeframe of the feasibility study.

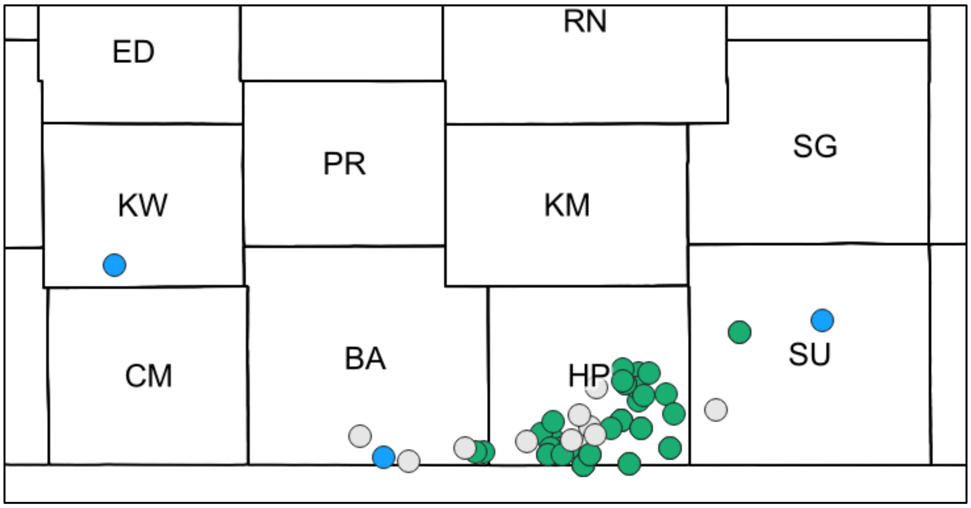

Figure 2. Wells in south-central Kansas proposed for the feasibility study. Green indicates a single owner/operator's wells, and gray and blue indicate other operators.

1.3. Amended deliverables

An independent operator with wells on the periphery of the primary area of interest offered two wells for measurement. Ultimately and consistent with the originally defined goals, three KCC-operated saltwater disposal (SWD) wells, two independently operated Class II SWD wells, and one uniquely completed stratigraphic test well were measured using a static BHP measurement and pressure gradient measurement sequence. Given the challenges in gaining permission to measure additional wells, the deliverables for this contract were amended to include analysis of data from a KGS-funded study from a Class I well, an updated map of SFL, map of change in SFL, compilation of annual Class I and Class II disposal volumes, and assessment of year-to-year SFL changes and comparison with disposal volumes. This report represents completion of the contract, with each of the deliverables provided in the following sections.

2. Class I Well Testing

2.1. Data acquisition

The KGS commissioned testing at a Class I facility in October 2020 coincident with testing required by the Kansas Department of Health and Environment (KDHE). The objective of this internal KGS study was to directly compare a few methodologies for determining BHP, SFL, and ρ to results from compliance testing in a Class I well using a PFO test and gradient survey (Appendix A). The methodologies used were similar to those proposed for the feasibility study and well KS-01-155-008 is an excellent proxy. Furthermore, the well had been inactive, with no injection for a year at the time of the test, allowing for assessment of the injectate (effluent brine) and Arbuckle formation fluid mixing and potential stratification within the fluid column. In the absence of a full suite of test data from several representative Class II wells, findings from this internal KGS study of a Class I well served to identify suitable methodologies and develop protocols to use in the future to acquire data compatible with the existing Class I well database from a designed network of Arbuckle wells.

The KGS contracted the consultant managing the compliance testing to ensure the same pressure transducer was used for both tests to obtain directly relatable pressure measurements with minimal error. Prior to the PFO test, an acoustic sounder was used to estimate SFL. A bailer was lowered to 4,460 ft (about the center of the open-hole portion of the well) to collect a fluid sample for density analysis. The pressure tool was secured at 4,170 ft below top of casing and beneath the bottom of the tubing in the open-hole portion of the well, and pressure was recorded with a 10 s sample rate for 24 hrs. The pressure tool was then secured at a depth of 4,735 ft, the gage depth for the PFO test—formation pressure at this depth is considered BHP. Static BHP was recorded, and the PFO test was performed. After the PFO test, pressure was measured at 500 ft intervals as the pressure tool was raised through the well (pressure gradient survey).

When two of the three variables in the hydrostatic equation (equation 1) are known, the third variable can be calculated using equation 2. In this internal KGS study, we used a variety of methods to directly measure or calculate all three variables (Table 1) for redundancy and quality assurance and to identify any potential sources of error or uncertainty. The following subsections provide assessments of diurnal changes recorded during 24-hr monitoring, the hydrostatic variables measured or calculated with a variety of methods, and the impact of errors on downstream calculations. Based on those findings, we recommend a protocol for acquiring relatable data in Class II wells.

Table 1. Methods used to measure or calculate ρ, SFL, and BHP.

ρ	**SFL**	**BHP (at 4735 ft)**
water sample	gradient survey	PFO - P*
gradient survey	acoustic sounder	static BHP
calculated from P @ 1000 ft, SFL	calculated from P @ 1000 ft, ρ	projected from 4710 ft
calculated from BHP, SFL		projected from 1000 ft

2.2. Diurnal changes

The objective of monitoring KS-01-155-008 was to assess any non-static variability. Because this well was inactive prior to testing, the only expected changes are diurnal associated with Earth tides. Tides induce poroelastic changes that result in diurnal pore pressure variation within a 24-hr cycle. Continuous 24-hr monitoring revealed the expected diurnal changes on the order of 0.13 psi, which is similar to the inherent uncertainty of the pressure transducer (Figure 3). Therefore, with these tools and this method, it is not necessary to correct for tidal effects to compare pressure measurements taken at different times.

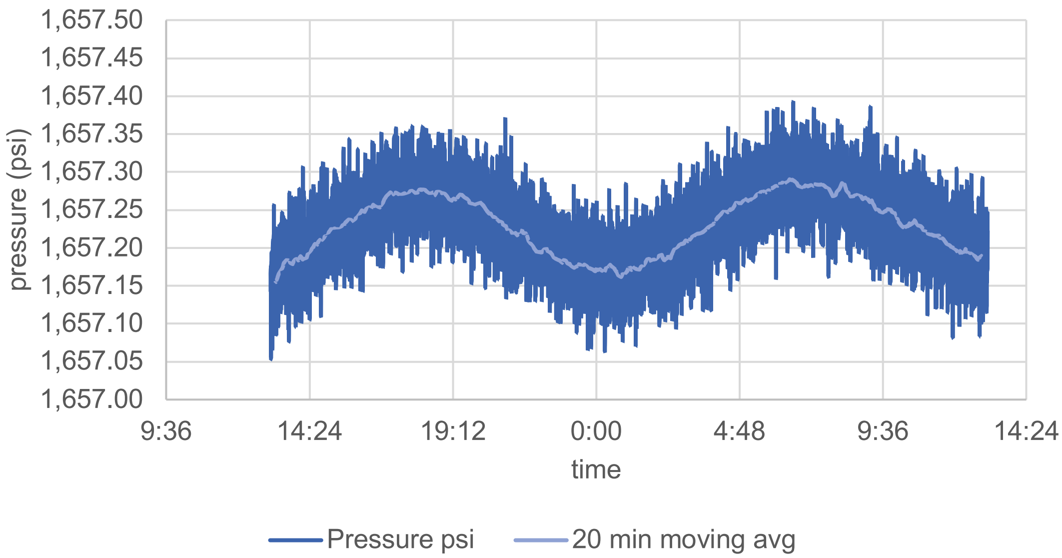

Figure 3. Pressure recorded at KS-01-155-008 during the 24-hr monitoring period.

2.3. Fluid density

Density was directly measured from a fluid sample, and the average density was calculated at 500 ft intervals in the well, a shallow interval, and over the entire fluid column (Table 2). The density of the fluid sample collected in the middle of the open-hole portion of the well prior to any other downhole measurements was 1.194 g/cc. This density was unexpectedly high for Arbuckle formation fluids (closer to freshwater density). This density can be compared to the density profile calculated for the open-hole portion of the well using measurements from the pressure gradient survey.

Taking the derivative of both sides of equation (1) with respect to depth *h* and rearranging, density becomes:

$$\rho = g\ dP/dh\ . \tag{3}$$

Therefore, the average density between two points in the well is directly proportional to the pressure gradient (the change in pressure divided by the change in depth). Results from the gradient survey (Appendix A) reveal a density inversion at depth (Figure 4). The fluid density above 4,000 ft in the cased portion of the borehole is reasonably constant and averages 1.194 g/cc. The average density from 4,000 to 4,500 ft, which is primarily open hole, drops to 1.055 g/cc. These findings suggest that the fluid in the cased portion of the borehole is primarily the injected fluid (a brine) and the density inversion indicates less-dense Arbuckle formation fluid (and/or a mixing with injected fluid) occupies the open-hole portion of the well. Although the fluid sample was collected in the middle of the open-hole portion of the well, its density was equal to the average density of the fluid in the cased portion of the borehole. Therefore, it is unlikely the sample provides an accurate representation of the density at the collection depth and was probably contaminated with the injected fluid from the cased portion of the borehole.

Average density was calculated at two locations in the well from a single pressure reading and SFL using equation 2. SFL from the gradient survey (discussed in the following subsection) was 981 ft. Using BHP, the average density of the fluid column between SFL and 4,735 ft is 1.166 g/cc. Using the pressure at 1,000 ft, the average density of the upper portion of the fluid column is 1.199 g/cc. This is consistent with a sample of fluid injected during the PFO test collected as a part of the annual compliance testing (Appendix A). The lower average density over the entire fluid column is consistent with the inversion observed in the density profile obtained from the gradient survey.

These results indicate that fluid density within the borehole is not constant. The most important implication is that the shallow fluid density cannot be extrapolated to the bottomhole depth and therefore a shallow pressure measurement alone cannot be used to accurately estimate BHP. Furthermore, a fluid sample collected at depth does not provide an accurate representation due to contamination with fluid from shallower depths. The overall density of the in-situ fluid column is best characterized using at least one measurement at depth to obtain the average density of the entire column (minimum requirement) or a gradient survey to calculate the density profile.

Table 2. Fluid density ρ measured or calculated in KS-01-155-008.

Method	ρ (g/cc)
water sample @ 4460 ft	1.194
gradient survey @ 4000-4500 ft	1.055
calculated from BHP, SFL	1.166
calculated from P @ 1000 ft, SFL	1.199

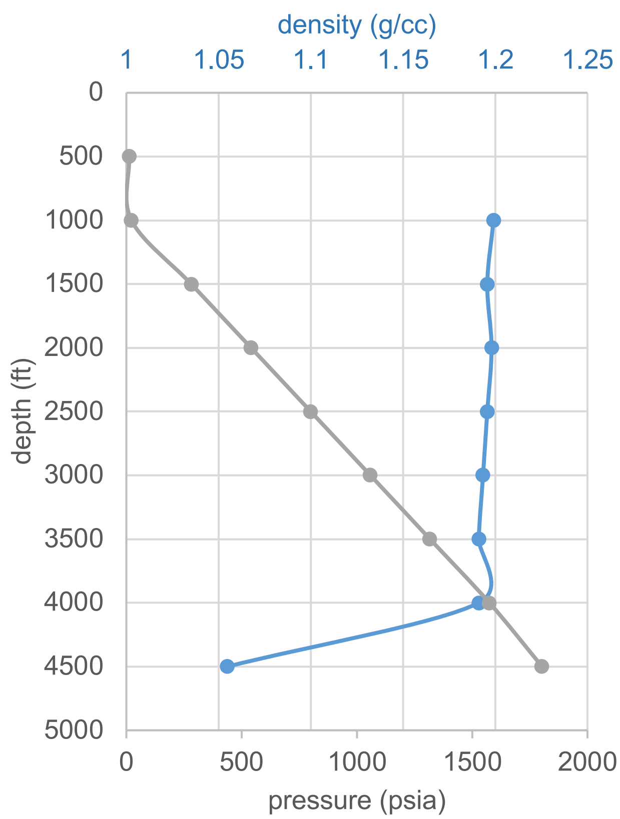

Figure 4. Pressure (gray) measured at 500 ft intervals, and average interval density (blue) calculated from the pressure gradient.

2.4. *Static fluid level*

SFL was directly calculated from the pressure gradient survey, measured using an acoustic sounder, and calculated from pressure measured at a shallow point in the fluid column (Table 3). The pressure gradient survey is used to calculate SFL for compliance testing, and SFL was determined to be 981 ft (Appendix A). For the purposes of the current study, this will be considered the benchmark. The acoustic sounder was used to record 28 readings that ranged from 843 to 1,118 ft. The average SFL was 970 ft with a standard deviation of 70 ft. Although the average SFL is only 11 ft greater than the actual SFL, the uncertainty is unacceptably large. Using equation 2, the density of the shallow borehole fluid (density of the injected fluid captured during compliance testing = 1.199 g/cc), and pressure recorded at 1,000 ft, the resulting SFL is 981 ft and is consistent with the SFL obtained from the gradient survey.

Table 3. SFL measured or calculated in KS-01-155-008.

Method	SFL (ft)	Error (%)
gradient survey	981	n/a
acoustic sounder	970	1 %
calculated from P @ 1000 ft, ρ	981	0 %

2.5. *Bottomhole pressure*

BHP was calculated from the PFO test, directly measured at the BHP depth, and projected from pressures measured at shallower depths (Table 4). Formation pressure determined using pressure transient analysis (P*) from data collected during the PFO test was 1,909.3 psia, which serves as the benchmark value for BHP. Immediately prior to the injection portion of the PFO test, a static pressure was measured at the same depth. Static BHP was 1,909.0 psia. BHP was then calculated using pressures measured at 4,170 ft (just beneath the bottom of the casing) and 1,000 ft (the shallowest pressure measurement recorded in the fluid column). Pressure was projected from these depths to 4,735 ft using equation 2, the atmospheric pressure and SFL determined from the gradient survey (12.3 psia and 981 ft, respectively), and the average fluid density between SFL and the measurement depth. The resulting BHP projected from 4,170 ft and 1,000 ft were 1,948.7 psi and 1,962.3 psi, respectively. Because pressure from 4,170 ft to the bottomhole depth spans the open-hole interval, average fluid density for this interval should provide a more accurate extrapolation. Projecting pressure from 4,170 ft using the 1.055 g/cc density from the gradient survey at 4,000–4,500 ft results in 1,915.1 psi.

The static BHP was nearly identical to P*. This suggests that a full PFO test and pressure transient analysis are unnecessary for determining formation pressure only and that static BHP measurements are accurate, relatable, and compatible with P* calculated in wells with good formation connectivity under static conditions. Projecting pressure from a shallow measurement is sometimes used as an easy, cost-effective method to estimate BHP. In this case, BHP projected from 1,000 ft was 53 psi greater than the actual BHP. The error in projected BHP is due to the variable fluid density profile in this well and the use of the shallow fluid density for the extrapolation to depth. Although the error is only 3% relative to true BHP, it should be noted that even small errors could lead to considerable differences in downstream calculations, as discussed in the following section. If pressure is projected from 4,170 ft using the interval density, projected BHP is much more accurate. However, this requires additional information or assumptions about density at or below the depth of the pressure measurement.

Table 4. BHP measured or calculated in KS-01-155-008.

Method	BHP (psia)	Error	Freshwater SFL
PFO - P* at 4735 ft	1909.3	n/a	359.2 ft
static BHP at 4735 ft	1909.0	0.3 psi (0.02%)	359.8 ft (0.2 % error)
projected from 4710 ft	1948.7	39.4 psi (2%)	268.3 ft (25 % error)
projected from 4710 ft with interval ρ	1915.4	6.2 psi (0.3%)	344.9 ft (4% error)
projected from 1000 ft	1962.3	53.1 psi (3 %)	236.7 ft (34 % error)

2.6. Freshwater-equivalent SFL correction

One of the primary objectives of the Arbuckle monitoring project is to calculate the freshwater-equivalent hydrostatic elevation—the elevation to which freshwater would rise in an Arbuckle well—in additional wells in spatially under sampled areas to refine the piezometric surface map (Figure 1). This value allows direct comparison of all Arbuckle SFL data without the very localized variability associated with different density injectate disposed of in each well adversely affecting regional comparisons. The key measurement required to accurately calculate the freshwater-equivalent SFL is BHP. Using equation 2, $\rho = 1$ g/cc, and P*, the freshwater-equivalent SFL is 359.2 ft. Freshwater-equivalent SFL calculated with the static BHP is 359.8 ft, less than 0.2 % error. Freshwater-equivalent SFL calculated with BHP projected from 4,710 ft and 1,000 ft using the average density of the overlying fluid column is 268.3 ft and 236.7 ft, respectively. Although the error in projected BHP is 3% or less, the error in resulting freshwater-equivalent SFL exceeds 25%, which is well outside the acceptable range. Freshwater-equivalent SFL calculated with BHP projected from 4,710 ft and 1,000 ft using the average density of the open-hole interval is 344.9 ft, representing a 4% error. This is much closer to the benchmark freshwater-equivalent SFL but requires additional information or assumptions about density below the measurement depth.

2.7. Summary and recommended protocol

Diurnal pressure changes related to the Earth's tides are negligible, and accounting for tidal effects appears to be unnecessary. Borehole fluid density is variable with the density profile suggesting injected fluids in the cased portion of the borehole, Arbuckle fluids in the open-hole portion, and mixing in between. Because density is a crucial variable to calculate the SFL from BHP or vice versa, it cannot be assumed to be constant and both SFL and BHP must be measured to avoid potentially large errors in the resulting freshwater-equivalent SFL. Therefore, the optimum protocol for a relatable database is a static BHP pressure reading, time-lapse pressure monitoring to assess static conditions when possible , and pressure gradient survey to calculate SFL.

3. Class II SWD Well Testing

3.1. Data acquisition and density profiles

Data were collected in five SWD wells and a stratigraphic test well (Table 5, Figure 5) following the protocol recommended in the previous section. Pressure was recorded at approximately 250 ft intervals for the pressure gradient survey. The tool was secured at the bottom of the hole for 12–24 hrs monitoring, except for Koehn #3, where an obstruction was encountered in the cased portion of the well.

Table 5. Class II Arbuckle wells measured for this study.

API Number	Well Name	County	Date
15-173-20308-0001	Lamp #1	Sedgwick	3/24/22
15-007-22577-0001	Harbaugh SWD #1	Barber	5/4/22
15-113-20946-0001	Koehn #2	McPherson	3/30/23
15-115-21470	† Koehn #3	Marion	5/30/23
15-113-21342	Canton SWD #1	McPherson	5/31/23
15-191-22590	‡ Wellington KGS #1-28	Sumner	8/25/23

† Measured within the cased portion of the well due to an obstruction encountered at 1,818.9 ft.
‡ Cased and cemented through the Arbuckle and perforated in a 20 ft section 829 ft beneath the Arbuckle top.

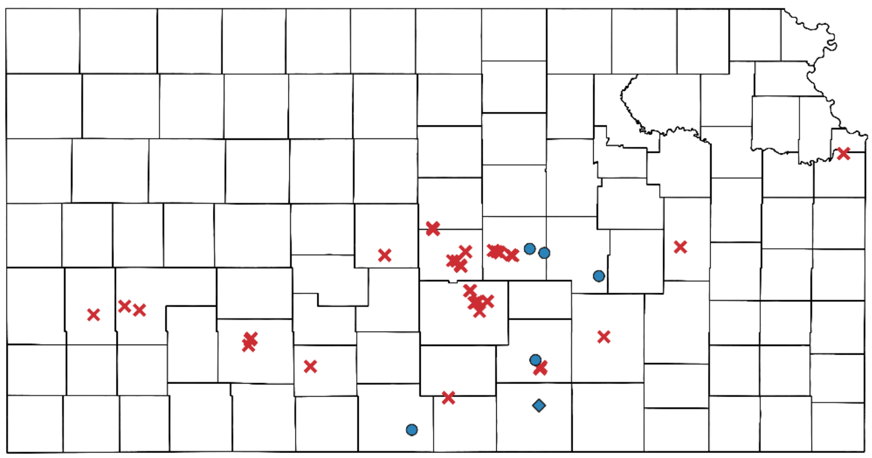

Figure 5. Class I wells (red X's) that comprise the existing Arbuckle BHP and SFL database, and Class II SWD wells (blue circles) and stratigraphic test well (blue diamond) measured for this study.

Density profiles from the pressure gradient surveys were highly variable (Figure 6). Similar to KS-01-155-008, the density within the cased portion of the borehole most likely represents the density of the injected fluid, the open-hole density represents Arbuckle fluid, with various degrees of mixing in between. The low densities in Koehn #3 are likely the result of a combination of the presence of oil (observed on cabling as it was removed from the well) and uncertainty in the final depth caused by the obstruction encountered in this well. These observations further support the need for directly measured BHP and SFL to characterize and calibrate for varying density prior to using shallow measurements to estimate BHP and avoid potentially large errors in freshwater-equivalent SFL.

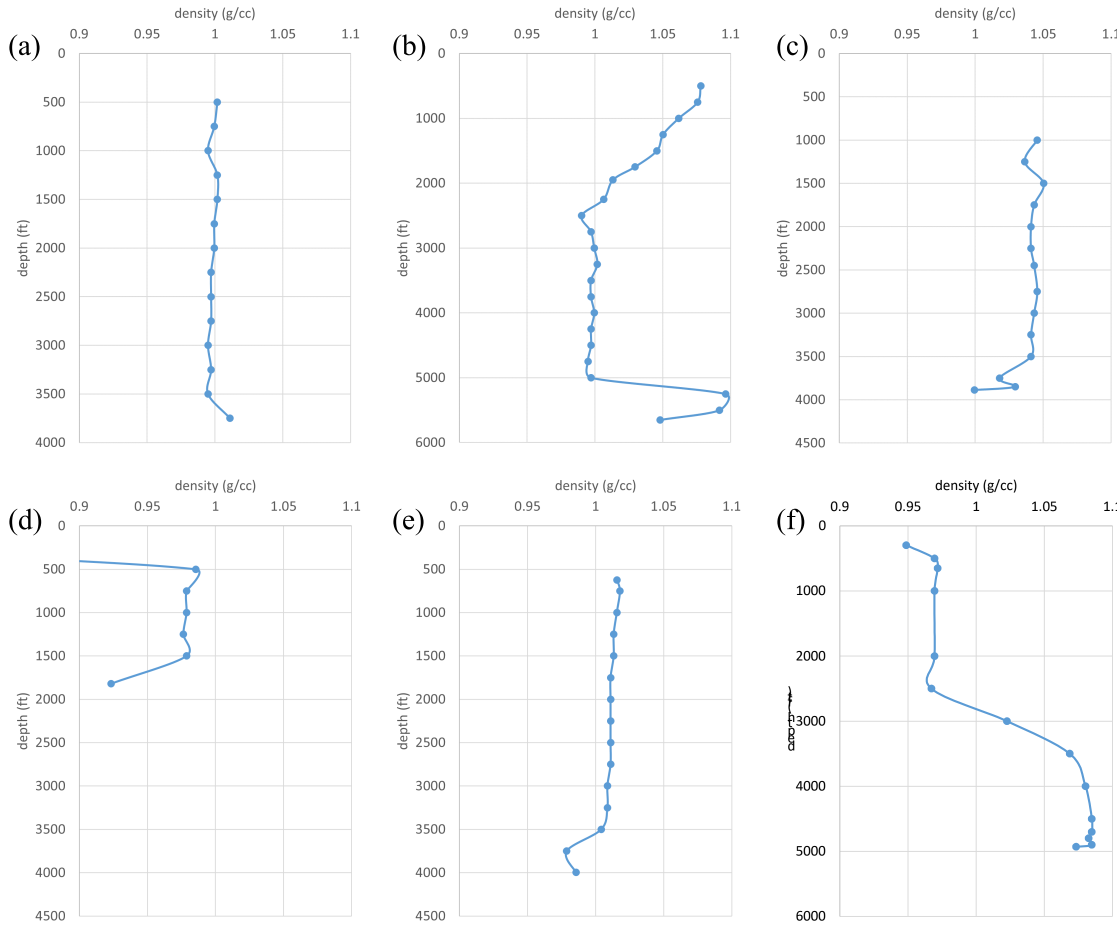

Figure 6. Density profiles from the (a) Lamp #1, (b) Harbaugh SWD #1, (c) Koehn #2, (d) Koehn #3, (e) Canton SWD #1, and (f) Wellington KGS #1-28 wells.

3.2. Measurement details and freshwater-equivalent SFL

Differing densities of the water in the Arbuckle have strong effects on the SFL. Very saline water, being denser than freshwater, will not rise as high in a wellbore as freshwater. To construct a coherent SFL map, density of the water in each measured well must be normalized to a uniform value resulting in comparable and relatable SFL. Most hydrologic studies correct for varying densities by adjusting to a freshwater density, which is 1.0000 g/cc (e.g., Jorgensen et al., 1993). A contour map of the elevation of the SFLs, with the SFL corrected to the density of freshwater, is a map of the piezometric surface of a geologic formation. Subsurface water movement, defined by a piezometric surface, flows from higher elevations to lower elevations. Freshwater-equivalent SFL was calculated as described in the previous section.

Table 6 presents data obtained for Harbaugh SWD #1 well (SE NE NW NE sec 29, T. 33 S., R. 11 W., Barber County, 1,373 ft ground elevation, 5,650.3 ft Arbuckle gage depth).

Table 6. Harbaugh SWD #1 data.

P* (psi)	SFL depth (ft below surface)	SFL (ft elev.)	Water Column (gage depth-SFL)	Pressure Gradient (psi/ft)	Water Density (gr/cc)	Elevation of SFL if water density is 1.0000
2461.7	145.7	1227.3	5504.6	0.4447	1.0257	1401

Table 7 presents data obtained for the Lamp #1 well (NW SE NE sec 07, T. 28 S., R. 01 W., Sedgwick County, 1,337 ft ground elevation, 3,750.5 ft Arbuckle gage depth).

Table 7. Lamp #1 well data.

P* (psi)	SFL depth (ft below surface)	SFL (ft elev.)	Water Column (gage depth-SFL)	Pressure Gradient (psi/ft)	Water Density (gr/cc)	Elevation of SFL if water density is 1.0000
1583.1	127.8	1209.2	3622.7	0.4331	0.9991	1238

Table 8 presents data obtained for the KGS Koehn #2 well (NE NW NW sec 23, T. 19 S., R. 02 W., McPherson County, 1,560 ft ground elevation, 3,886.1 ft Arbuckle gage depth).

Table 8. KGS Koehn #2 well.

P* (psi)	SFL depth (ft below surface)	SFL (ft elev.)	Water Column (gage depth-SFL)	Pressure Gradient (psi/ft)	Water Density (gr/cc)	Elevation of SFL if water density is 1.0000
1499.4	597.7	962.3	3288.4	0.4560	0.10518	1133

Table 9 presents data obtained for the Te-Pe Oil Canton #1 SWD well (NW NW NW NW sec 36, T. 19 S., R. 01 W., McPherson County, 1,577 ft ground elevation, 3,995.3 ft Arbuckle gage depth).

Table 9. Te-Pe Oil Canton #1 SWD well

P* (psi)	SFL depth (ft below surface)	SFL (ft elev.)	Water Column (gage depth-SFL)	Pressure Gradient (psi/ft)	Water Density (gr/cc)	Elevation of SFL if water density is 1.0000
1529.2	495.9	1081.1	3499.4	0.4370	1.0080	1109

Table 10 presents data obtained for the Te-Pe Oil Koehn #3 well (E2 W2 E2 SE sec 23, T. 19 S., R. 05 E., Marion County, 1,397 ft ground elevation, 1,824.6 ft Arbuckle gage depth).

Table 10. Te-Pe Oil Koehn #3 well.

P* (psi)	SFL depth (ft below surface)	SFL (ft elev.)	Water Column (gage depth-SFL)	Pressure Gradient (psi/ft)	Water Density (gr/cc)	Elevation of SFL if water density is 1.0000
676.4	227.6	1169.42	1597.0	0.4235	0.9770	1133

Table 11 presents data obtained from the Berexco Wellington KGS #1-28 well (SE NE NW NE sec 28, T. 31 S., R. 01 W., Sumner County, 1,257 ft ground elevation, 4,930 ft Arbuckle gage depth).

Table 11. Berexco Wellington KGS #1-28 well.

P* (psi)	SFL depth (ft below surface)	SFL (ft elev.)	Water Column (gage depth-SFL)	Pressure Gradient (psi/ft)	Water Density (gr/cc)	Elevation of SFL if water density is 1.0000
2078.84	4930	996.83	4669.83	0.4452	1.0268	1122

3.3. Accuracy of SFL projections from Class I wells

The effect of these additional Class II wells on the piezometric surface for the Arbuckle Group in Kansas are illustrated when data from these two wells are superimposed on a map of the Arbuckle piezometric surface based only on data from Class I wells (see Figure 7). The Harbaugh SWD #1 well has a SFL consistent with the contours based on Class I wells. The Lamp #1 well results in a downward correction of about 20 ft. The correction for the Lamp #1 well is due to its proximity (approximately 3 miles) to the OxyChem and Evonik Class I disposal wells. Several closely spaced disposal wells are operating at both the OxyChem and Evonik facilities. The annual Class I test for these facilities is normally performed on one of the facilities' many disposal wells that has been dormant for approximately 24 hours. It is possible well-to-well interference from nearby active disposal wells can artificially elevate the SFL of the well undergoing testing. The Lamp #1 well is likely sufficiently far from Evonik and OxyChem disposal wells to minimize any interference, resulting in measurements from that well that better characterize the regional piezometric surface.

The Koehn #2 well indicates an upward correction of about 10 ft from the Class I-based contours. The Te-Pe Oil Canton #1 well and the Koehn #3 SWD well indicate corrections of -5 ft and 115 ft, respectively. However, the 115 ft correction indicated by the Koehn #3 SWD is inordinately large compared to the contours established with the Class I wells. Furthermore, the resultant pressure gradient (0.4235 psi/ft) and water density (0.9770 g/cc) are unrealistic. An obstruction at a depth of 1,990 ft in this well precluded a deep measurement of pressure, so data for this well are ignored until this borehole obstruction can be removed and the well can be re-measured.

The Wellington KGS #1-28 well was calculated to have a freshwater-equivalent SFL of 1,122 ft elevation. Despite the limited footage of the Arbuckle open to the wellbore, the freshwater-equivalent SFL in 2023 was very close to (likely within 10 feet) the extrapolated contours at the well location in Sumner County (see Figure 7). The close correlation is encouraging but possibly only coincidental. Because of the unique construction and limited sampling interval near the base of the Arbuckle, data from this well are used for general reference but omitted from the analysis in the following sections. Future measurements would be necessary to assess whether the limited sampling interval in the Arbuckle is representative of the formation as a whole and relatable to regional SFL measurements to evaluate the utility of this well for regional SFL mapping.

The corrections of the Class II wells show their utility as a means for better mapping the Arbuckle piezometric surface. Crucially, the observation that the SFL measurements and freshwater corrections closely match the projections from Class I wells supports the assertion that the projected SFLs are generally representative on a regional scale. Additional data farther away from the clusters of Class I wells will improve spatial coverage and enhance resolution to better characterize, understand, and monitor fluid pressures and fluid movement in the Arbuckle.

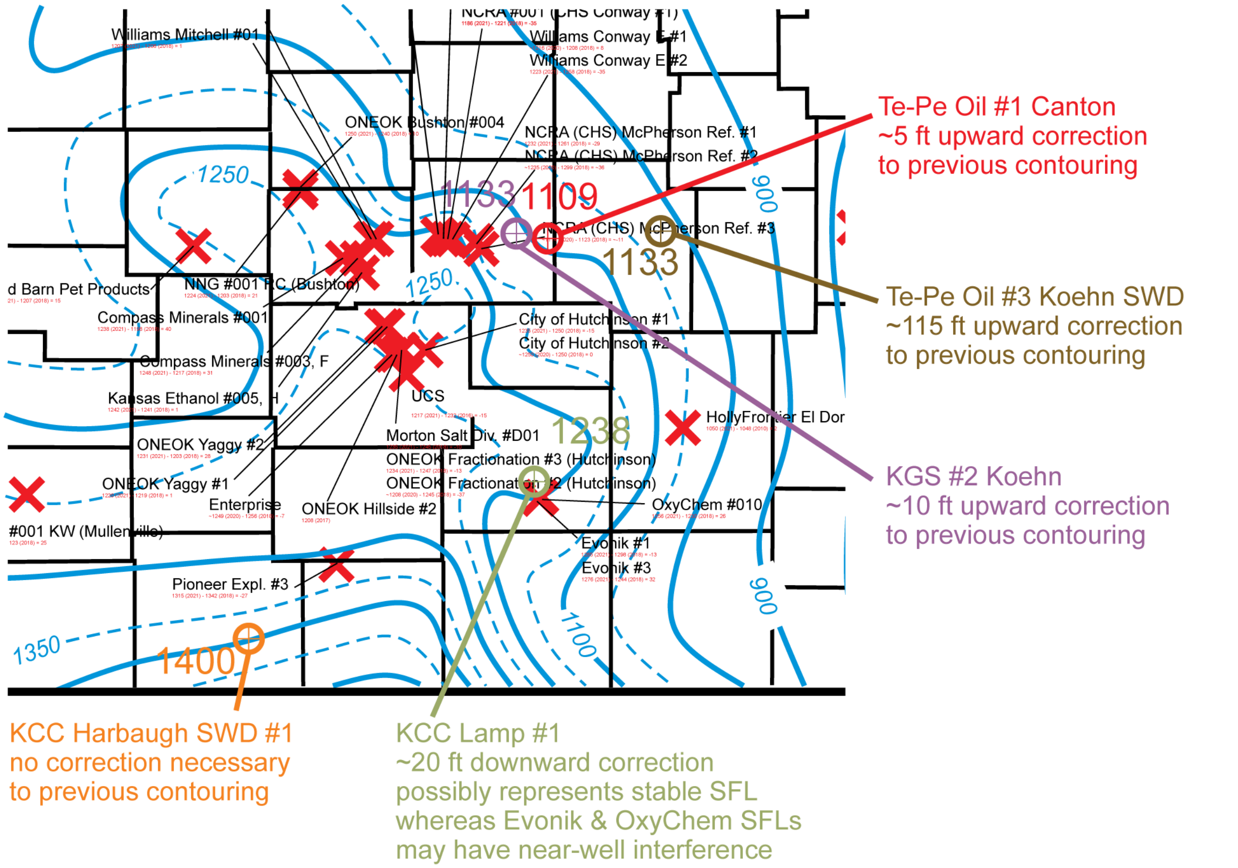

Figure 7. Freshwater-equivalent SFLs from the five Class II wells superimposed on a piezometric surface for the Arbuckle Group based solely on Class I well data. The Class II wells are used to supplement the mapping of the piezometric surface for the Arbuckle in central Kansas, compared with the contouring of the piezometric surface without the Class II wells. Because of the geographic clustering of Class I wells in central Kansas, sampling of selected Class II wells away from the Class I well aids in more accurate mapping.

3.4. Updated map of Arbuckle SFLs

An initial map of freshwater-corrected Arbuckle SFLs was created in 2018 (see Newell et al., 2020). This map was based on Class I wells and a few selected measurements supplied by Class II operators and from two disposal wells in Oklahoma (see Figure 8). The updated map from 2021 (shown in Figure 9A) is based on the 2020 and 2021 SFL values from Class I well testing. In the absence of 2021 information, 2020 values from selected wells were used. Data from the KCC Harbaugh SWD #1 and Lamp #1 wells were also used in the construction of the 2021 map. The most recent piezometric map for 2022 (shown in Figure 9B) takes into account the Te-Pe Oil Canton #1 and KGS Koehn #2 wells. In all three maps, projections beyond the sample points are contoured based on a regional Arbuckle piezometric surface map published by the USGS (Jorgensen et al., 1993).

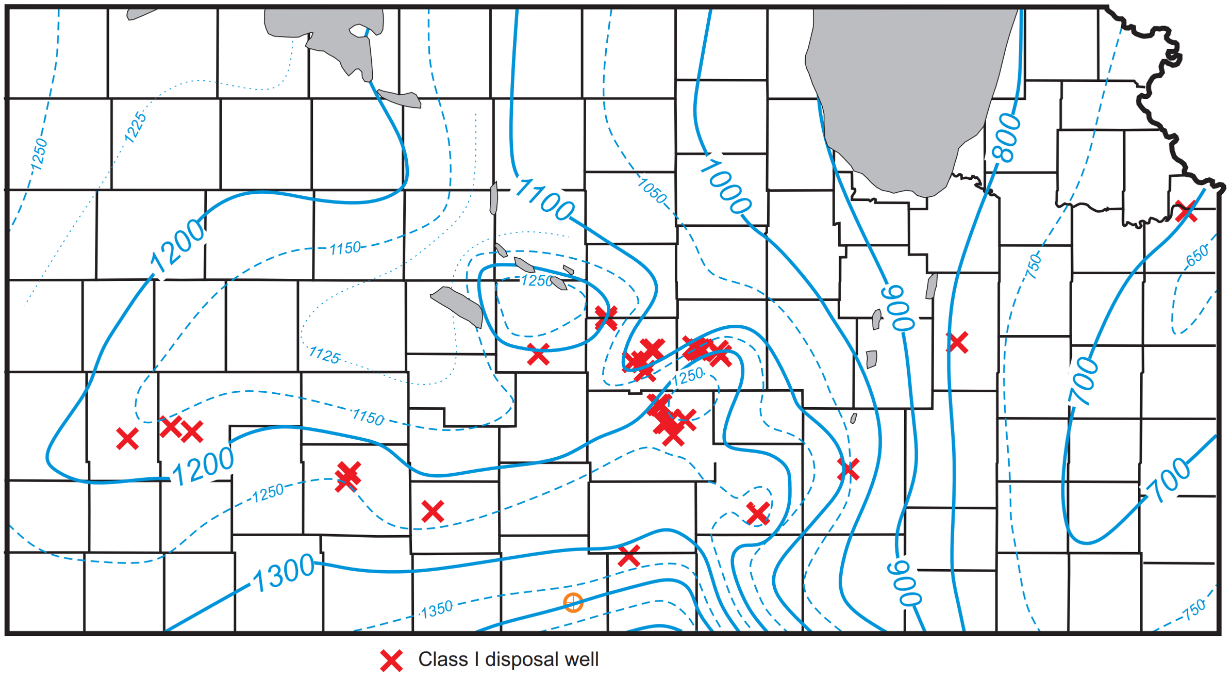

Figure 8. The 2018 Arbuckle piezometric surface map.

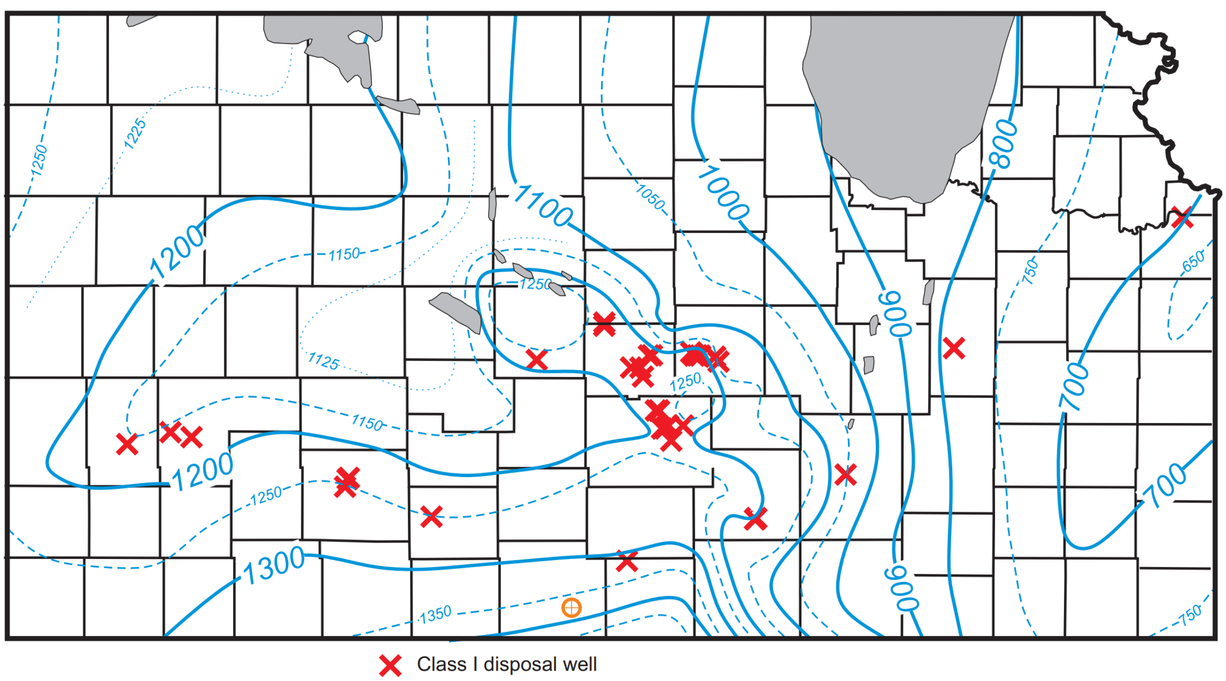

Figure 9A. The 2021 Arbuckle piezometric surface map.

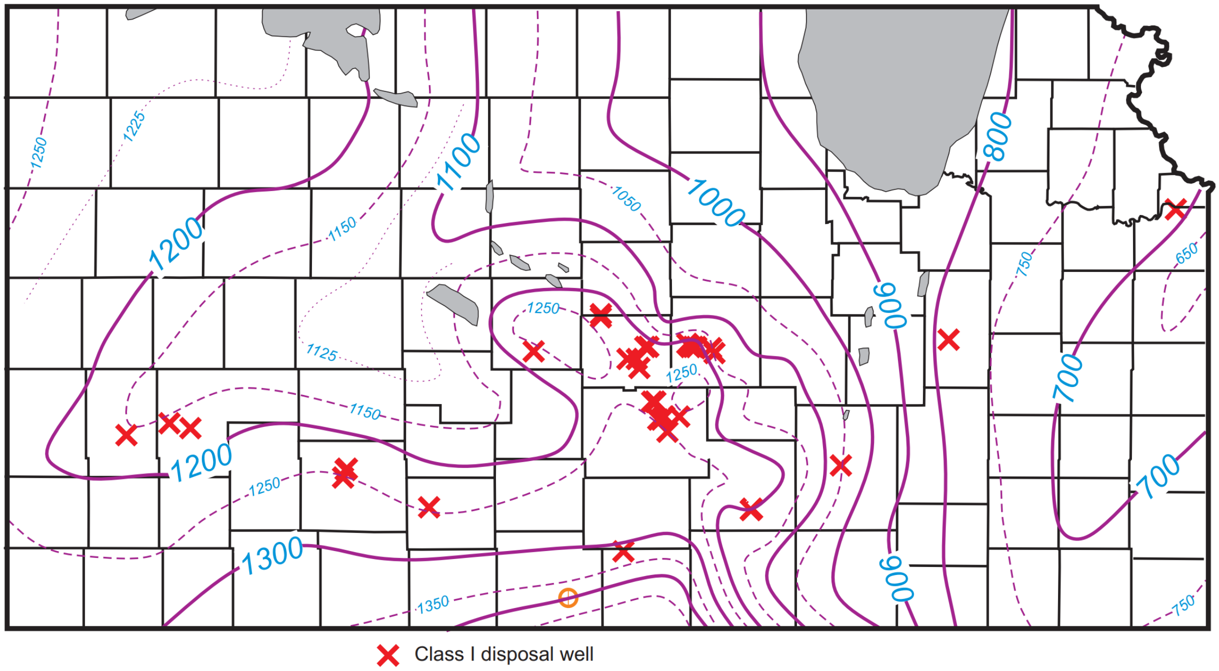

Figure 9B. The 2022 Arbuckle piezometric surface map.

3.5. Change in SFL from 2018 to 2021

The spatial distribution of data points, principally from Class I wells, does not allow a detailed map of the change in SFLs between 2018 and 2021 but does allow recognition of general trends. There are wells within one or two miles of each other that seem to have contradictory measurements, with one well showing overall fluid rise, while another nearby well shows fluid fall. The reasons for these apparent contradictions are not clear. It could be measurement error, but obscure disposal or geological conditions unique to each well also could influence the differences in the SFL. Considerable scatter in year-to-year measurements from individual wells (discussed below) impart a degree of noise or randomness to the data.

The map of SFL changes between 2018 and 2021 (Figure 10; see also Appendix B) has an intriguing major characteristic: wells west of an interpreted 0 contour/change line in central Kansas show rises in SFL, whereas wells east of this 0-line show falls in SFL. The 0-line is nearly geographically coincident with the western margin of the Midcontinent Rift. This western margin, which trends NNE-SSW, is faulted and has been periodically reactivated through the Phanerozoic, at least up through Mississippian time. Faulting during the Phanerozoic would affect the Arbuckle and thus possibly impede (permeability barrier) the lateral transmissibility of fluids in the Arbuckle. The drop of SFLs east of the 0-line implies formation fluids in the Arbuckle move eastward more freely than the fluids to the west of the 0-line; well permeability-feet in the Arbuckle is generally greater in those wells to the east of the line. The rise of SFLs to the west of the western margin faults may indicate that these faults are partial barriers to or may divert the general eastward fluid movement in the Arbuckle. Alternatively, perhaps more fluid has been disposed of into the Arbuckle in the western area and the regional

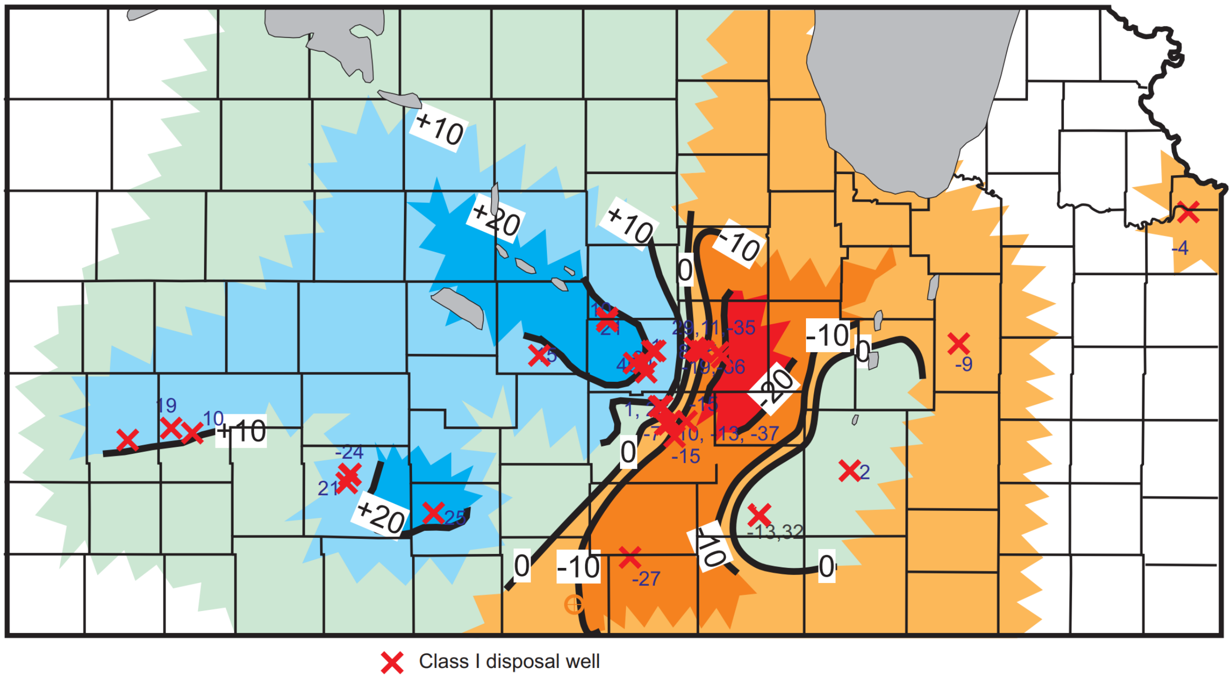

Figure 10. The relative rise or fall of Arbuckle SFLs from 2018 to 2021.

permeability is less, but this is not likely. In the last five years, almost every county in Kansas has experienced a decrease in total fluid volume injected collectively in Class I and II wells.

The long-term build-up of SFLs and subsurface pressures west of the 0-line and the concomitant drop in subsurface pressures and SFLs east of the 0-line should be the focus of more in-depth study and monitoring. If presumably the 0-line is coincident with faults associated with the NNE-SSW trending western margin of the Midcontinent Rift, the differential pressure could have implications for diminishing disposal volumes in the western ranges of Kansas. The areas east of the 0-line appear to effectively flush subsurface fluids to the east, but this ability to move fluids may be overridden by greater volumes of disposal fluids in the future. Observations such as those noted in the previous discussion strongly support the need for more spatially complete sampling of Arbuckle fluids.

A detailed map of the 2018–2021 change in freshwater-equivalent SFLs (Figures 11A, B) shows the change in freshwater-equivalent SFLs is abrupt. Preliminary data from 2022 testing of Class I wells indicate this boundary generally persisted into 2022. Preliminary data from 2022 Class I well measurements indicate the trends of SFL rise and fall between 2018 and 2021 are still apparent into 2022. Close attention to future well P* and SFL measurements may give better insight to the cause and changes in subsurface fluid movement these SFL changes may cause.

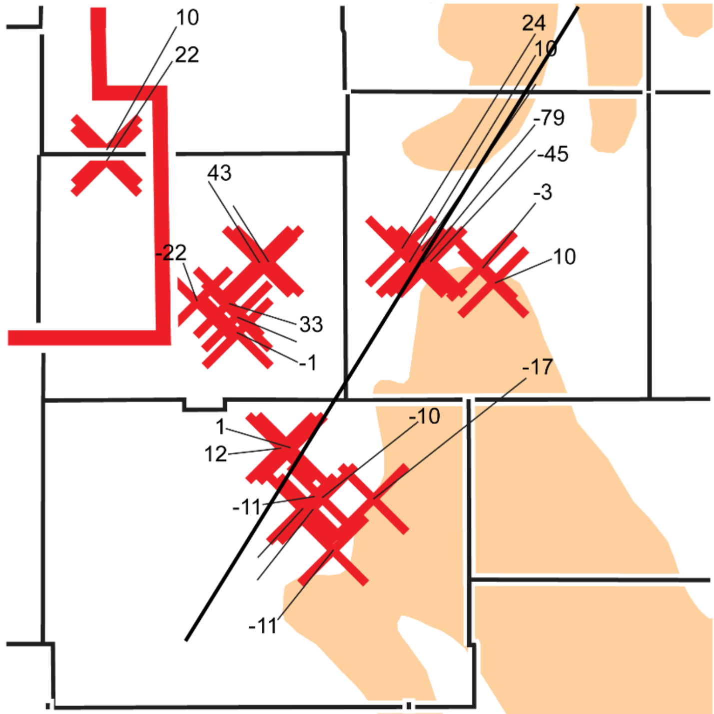

Figure 11A. A detailed mapping of the change in the elevation of the Arbuckle piezometric surface between 2018 and 2021. A NNE-SSW trending line divides the Class I wells registering fluid rise (to west) and those registering fluid fall (to east).

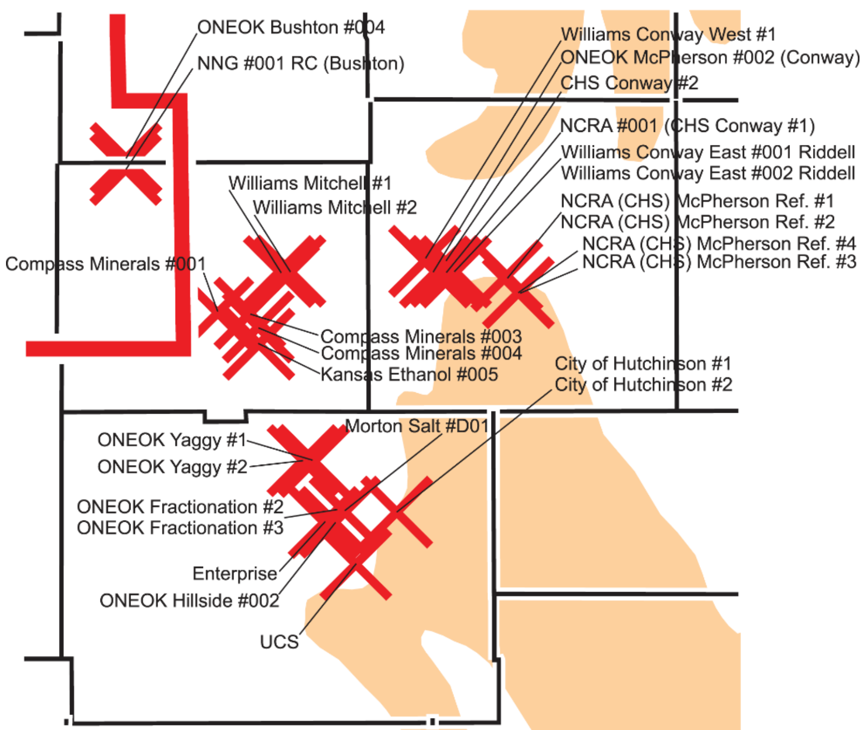

Figure 11B. Class I wells identified in the detailed map of the change in the piezometric surface between 2018 and 2021.

4. Class I and Class II Injection Volumes

4.1. Compilation of annual disposal volumes

Annual UIC (Underground Injection Control) reports (stating monthly and annual disposal volumes) for Class II disposal wells in the Arbuckle were compiled in an Excel spreadsheet. KDHE supplied disposal volumes for Class I wells. The annual volume of water disposed of into the Arbuckle for the entire state of Kansas (Figure 12) has dropped in recent years, principally due to decreased disposal volumes into Class II wells. Conversely, the volume of water disposed of into Class I wells has been relatively constant and subsidiary to the total volume disposed of into Class II wells. In turn, the drop in Class II disposal volume since 2015 is probably due to the decreasing oil prices over the last few years and their effect on profit margins for operating marginally economic stripper wells and the less frequent drilling of new wells.

4.2. Comparison of disposal volumes and SFL in selected counties

A graph of SFL elevations from individual Class I wells in selected counties superimposed on the annual Arbuckle disposal volumes (see Figure 13) shows that after disposal volumes peaked in 2015, SFLs in most Class I wells stabilized or dropped. Although only the Reno County Class I wells are superimposed on the annual disposal volumes in Figure 13A, Class I wells in Sedgwick (Figure 13B), McPherson (Figure 13C), and Rice counties (Figure 13D) mimic the Reno County SFL-elevation trends (Figure 13A).

Inasmuch as the Class I wells in Sedgwick County have the least distance between the surface and their SFLs (less than 100 ft), a more detailed review was undertaken of Class I wells in this county (e.g., Evonik [Air Products Mfg. Corp.] #001, Evonik [Air Products Mfg. Corp.] #003, and OxyChem #010) and how their SFLs respond to regional and local disposal volumes put into the Arbuckle. This study included well measurements up to 2021. Figure 14 shows the superimposition of the SFL elevations of the three frequently measured Class I wells in Sedgwick County compared to disposal volumes reported for A) all of Kansas, B) all of Sedgwick County, C) just the Class I wells in Sedgwick County, D) specific Class I wells in their specific disposal fields, and E) the disposal volume put into the specifically measured Class I well. The Sedgwick County Class I wells are similar to the other Class I wells in Kansas (cf. Figure 13 and Figure 14A) in that their SFL elevations appear to stabilize or rise more slowly after reaching the maximum disposal volume recorded in 2015.

Linear correlations were run relating the annual SFL elevation changes in specific Class I wells in Sedgwick County with the changes in disposal volume for each disposal area considered in Figure 14. Goodness-of-fit (r^2) calculations were also made. An example of this exercise (Figure 15) is the comparison of the individual well's change in SFL level with the change in disposal volume for all of Kansas. The cross-plots in Figure 15 generate the goodness-of-fit statistics as shown in Figure 16, which also summarizes the goodness-of-fit statistics for the other more regional areas, down to the disposal volumes for the individual disposal wells.

The r^2 values in Figure 16 suggest a lot of scatter in the behavior of SFLs in Class I Sedgwick County wells versus the amount of water disposed of in the Arbuckle, both regionally and locally. This scatter is also illustrated in Figure 15. If anything, the SFLs in Sedgwick County show slightly better correlation with the regional volumes of wastewater disposed of into the Arbuckle rather than the local volumes. This is puzzling, but it may indicate that the Arbuckle aquifer is very well connected laterally and responds quickly to disposal water put into it. Local disposal volumes may be quickly dispersed away from an individual well. This analysis was repeated for Class I wells in McPherson County with similar results.

4.3. Comprehensive changes in SFL and correlation with disposal volumes

A comprehensive way to study the association of SFLs and disposal volumes is to average the annual change in SFLs from all the Class I wells and then compare that to the annual disposal volumes from Class I and II wells. To facilitate the comparison, the annual changes in freshwater normalized SFL for 43 Class I wells were compiled for 2010–2021 (Appendix B). A number of variables can affect SFL from one well to another and from year to year in a given well; however, general trends can be observed. The annual changes in SFL from individual Class I wells show considerable scatter for successive years, but collectively they show an overall change that is similar to the individual wells shown in Figure 13. Histograms of the change in SFLs for these Class I wells also show considerable range (see Figure 17), sometimes in excess of 50 feet rise or fall. However, when averaged, the collective rise or fall of all the Class I wells is attenuated (see yearly average rise or fall in Appendix B). The trend of the average of all the SFL changes mimics that of SFL elevation of individual wells, with year-to-year scatter attenuated. After the peak disposal year of 2015, the average SFL change apparently stabilizes (see Figures 13, 14).

Implicit in the Figure 17 correlations are that the 43 Class I wells can effectively characterize the behavior of the Arbuckle aquifer in its entirety. Without dozens more Class I wells, this proposition is hard to test, but in central Kansas where most of these wells are located, it is encouraging that the collective behavior of these 43 wells approximates the behavior of the entire aquifer. The average SFL change minimizes in the years after the 2015 peak disposal year.

Comparison of the average SFL changes with Arbuckle disposal volumes are shown in Figure 18. When the cumulative disposal volume is cross-plotted with the cumulative average change in the SFLs (see Figure 18A), a leveling of SFL rise is evident in the years after the peak disposal year of 2015. The cross-plot between annual disposal volume and the cumulative change of the average SFL (Figure 18B) shows that the cumulative sum of SFLs does not change much from year to year (and, therefore, SFL is relatively consistent) when the annual disposal volumes are less than 800,000,000 bbls. SFLs collectively are unchanged in years when annual disposal volumes are less than 800,000,000 bbls a year. This suggests that perhaps a maximum of 775,000,000 to 800,000,000 bbls of disposal water can be accepted by the Arbuckle before SFLs show any notable rise. More years of data need to be collected and analyzed before this preliminary conclusion can be confirmed, though. Furthermore, this 775,000,000 bbls barrier depicts the behavior of the entire Arbuckle aquifer in Kansas. The apparent zonation of the aquifer in recent years into regions of SFL rise and SFL fall (see Figure 10) still needs to be studied in more detail in the context of disposal volumes. The behavior of the static fluid levels in central Kansas also needs to be studied in more detail in the immediate future for a better understanding of how this locality behaves with respect to fluid input into the Arbuckle and its effects on static fluid levels.

A weak correlation between SFL behavior and annual disposal volumes is demonstrated in Figure 18C, where there is an r^2 of 0.3625 in the linear correlation calculated between these two values. A weaker correlation of 0.2266 was calculated for the average SFL change when correlated to the disposal volume for the previous year. A negative correlation occurred between the SFL behavior and the annual disposal volume for two years prior. This indicates that the time lag between SFL rise and fall vs. the disposal volume for most wells is probably on the order of weeks or months rather than years.

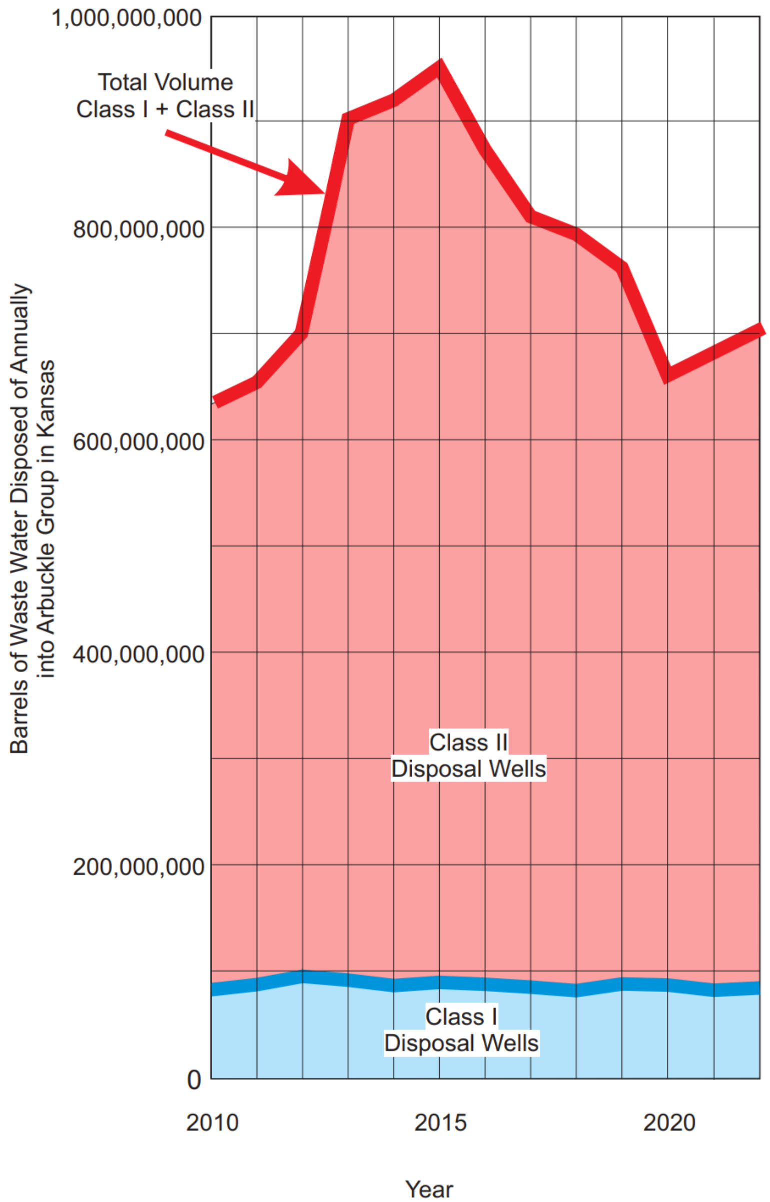

Figure 12. Annual disposal volumes into the Arbuckle from Class I and Class II wells.

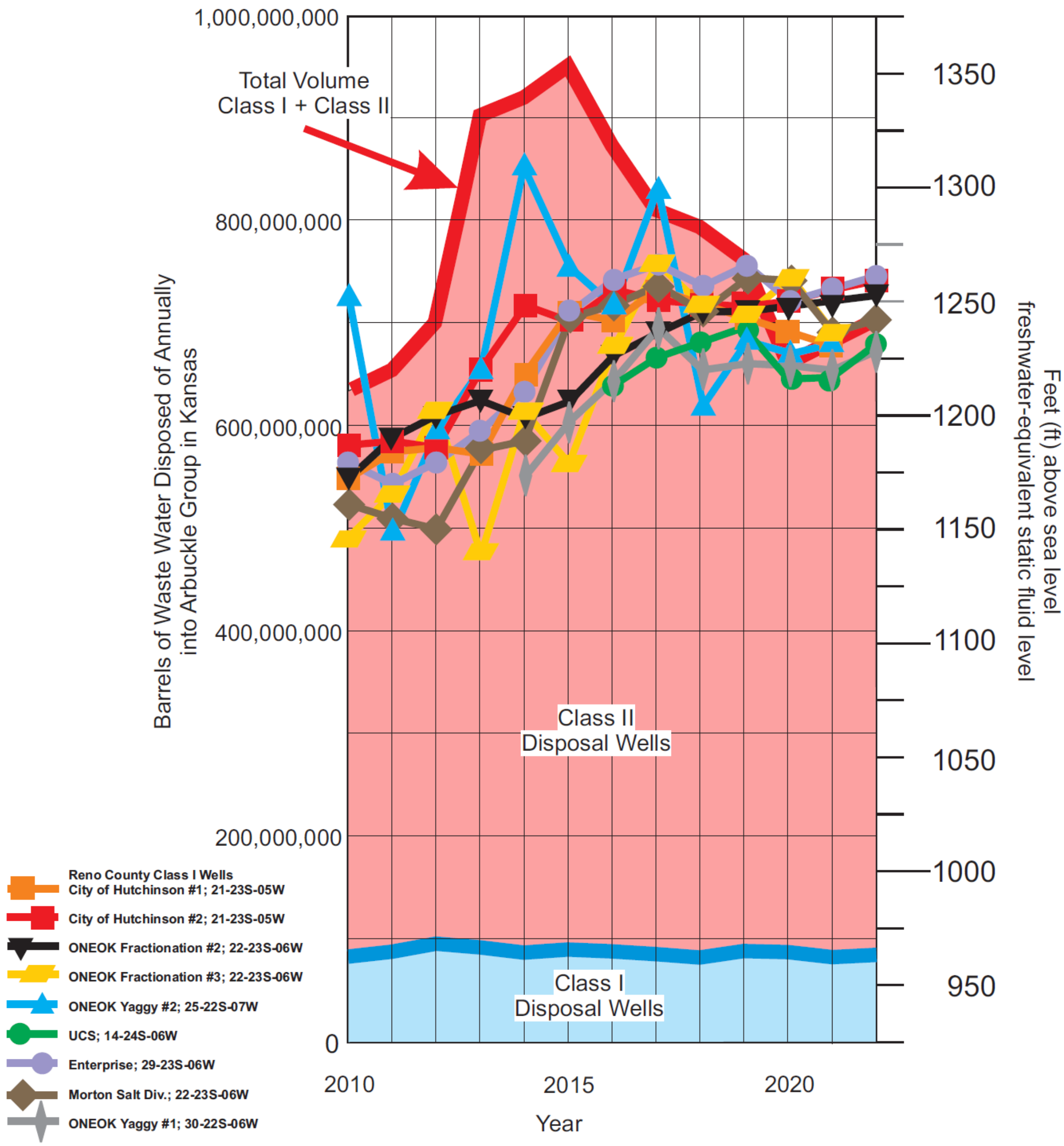

Figure 13A. Annual disposal volumes into the Arbuckle from Class I and Class II wells (from Figure 12) compared to SFL elevations for Class I wells in Reno County. SFLs level out after disposal volumes peaked in 2015. Similar SFL trends are displayed by Class I wells in Sedgwick and McPherson counties.

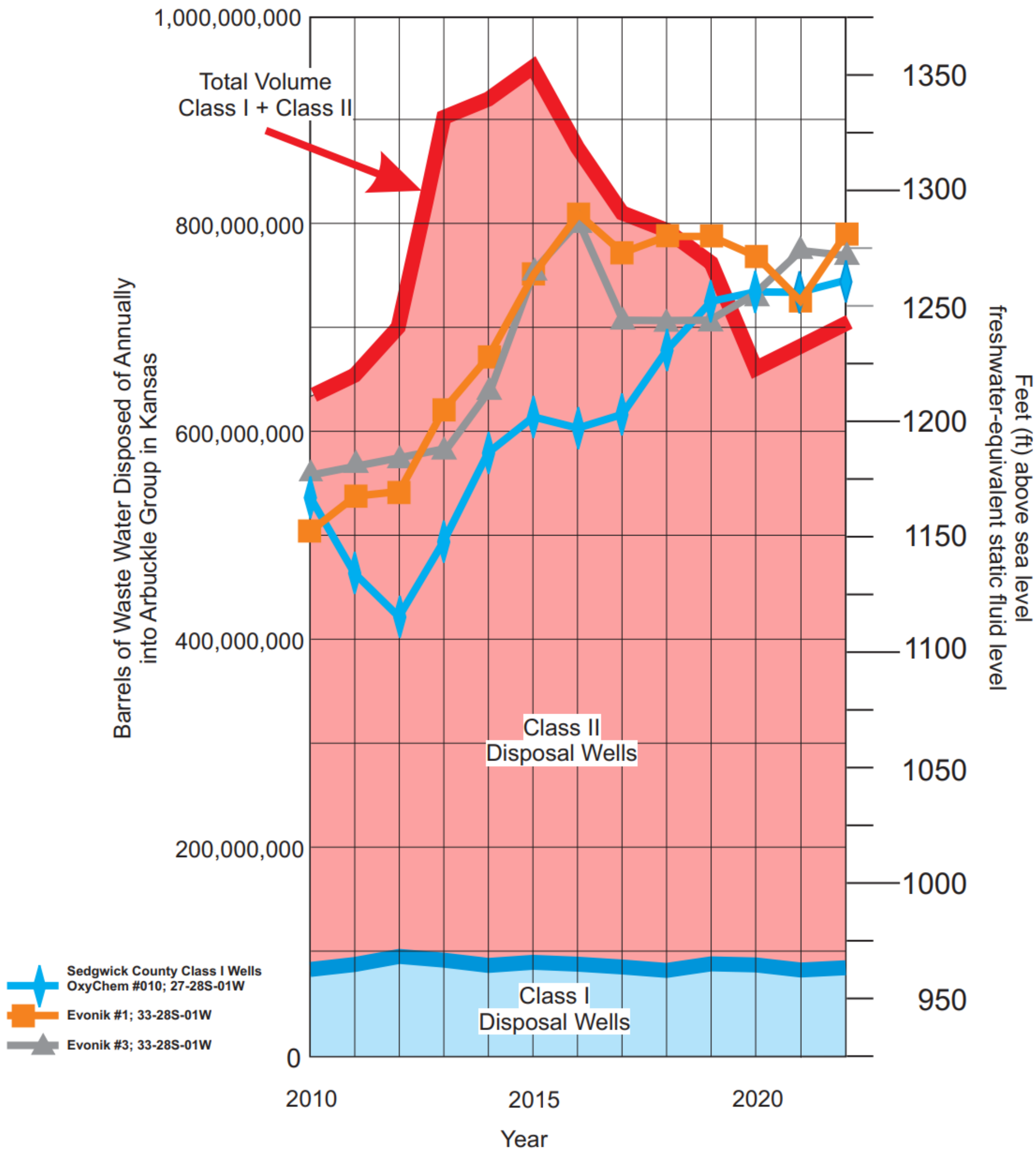

Figure 13B. Yearly volumes of disposal water entering the Arbuckle by Class I and Class II disposal wells in Kansas, compared to the freshwater-equivalent SFLs measured and calculated from Class I disposal wells in Sedgwick County. The freshwater-equivalent SFLs of the disposal wells in Sedgwick County, like those in McPherson County, have stabilized since 2016.

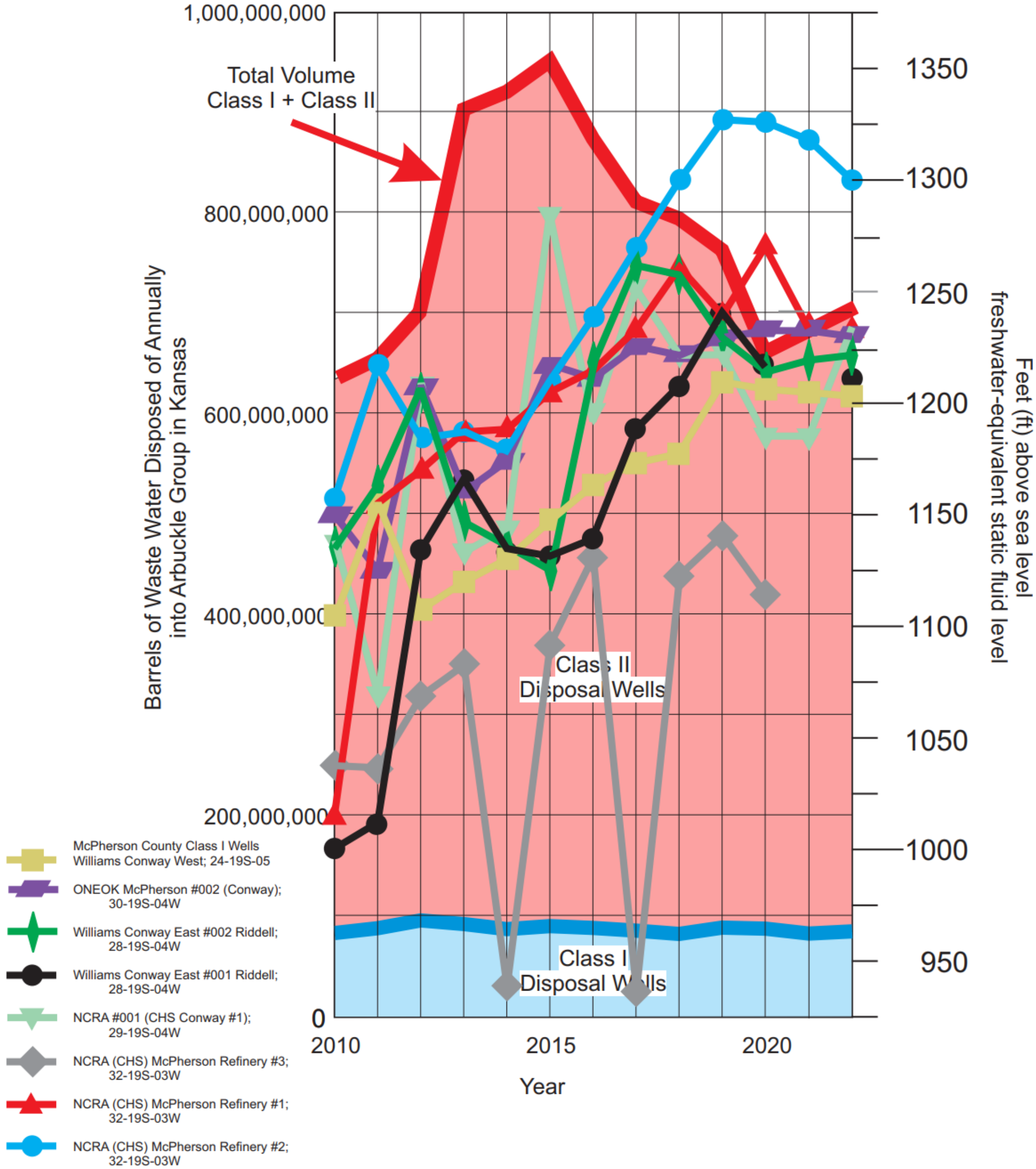

Figure 13C. Yearly volumes of disposal water entering the Arbuckle by Class I and Class II disposal wells in Kansas, compared to the freshwater-equivalent SFLs measured and calculated from Class I disposal wells in McPherson County. The freshwater-equivalent SFLs of the disposal wells in McPherson County have stabilized since 2016.

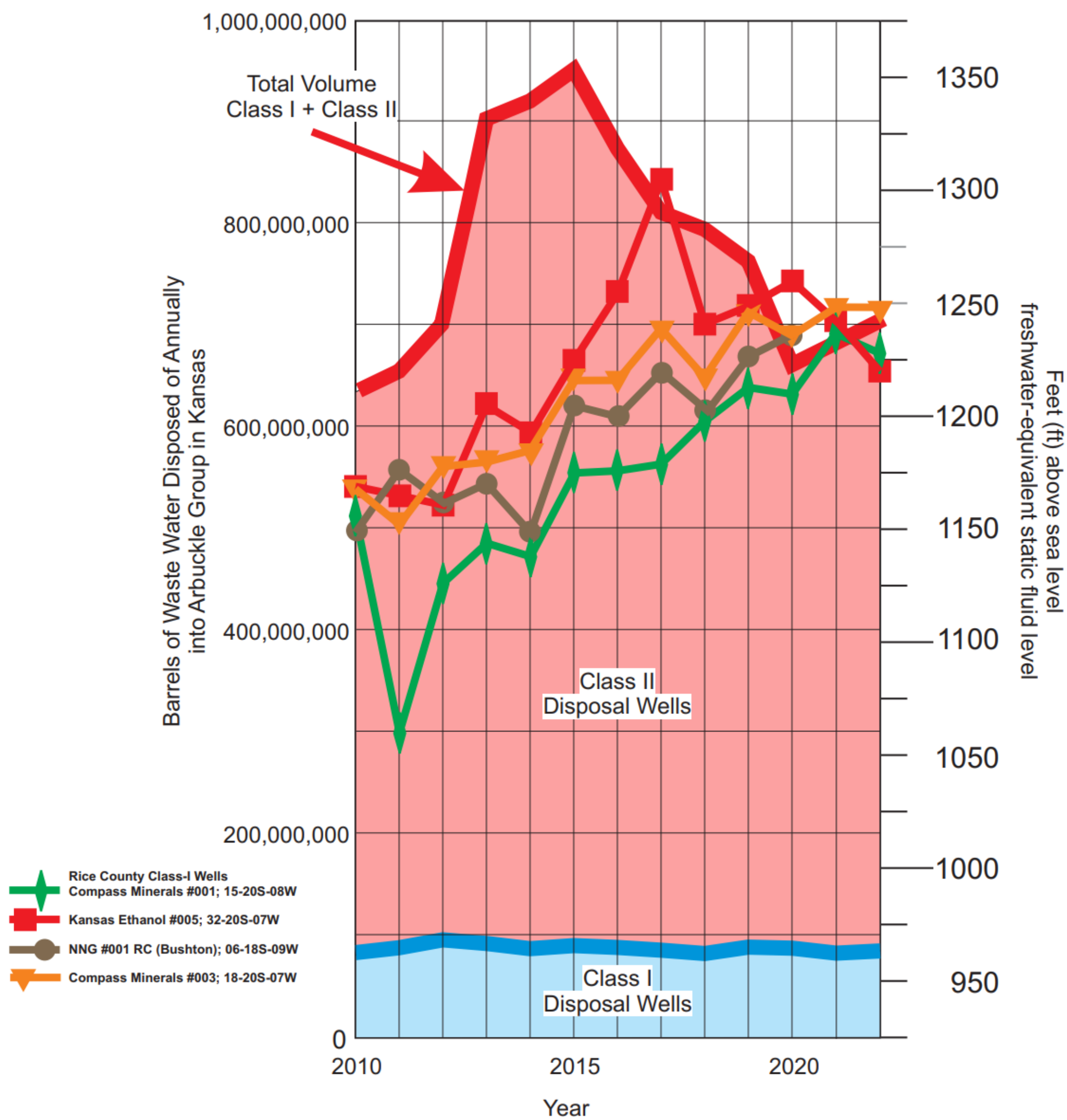

Figure 13D. Yearly volumes of disposal water entering the Arbuckle by Class I and Class II disposal wells in Kansas, compared to the freshwater-equivalent SFLs measured and calculated from Class I disposal wells in Rice County. The freshwater-equivalent SFLs of the disposal wells in McPherson County have stabilized since 2016.

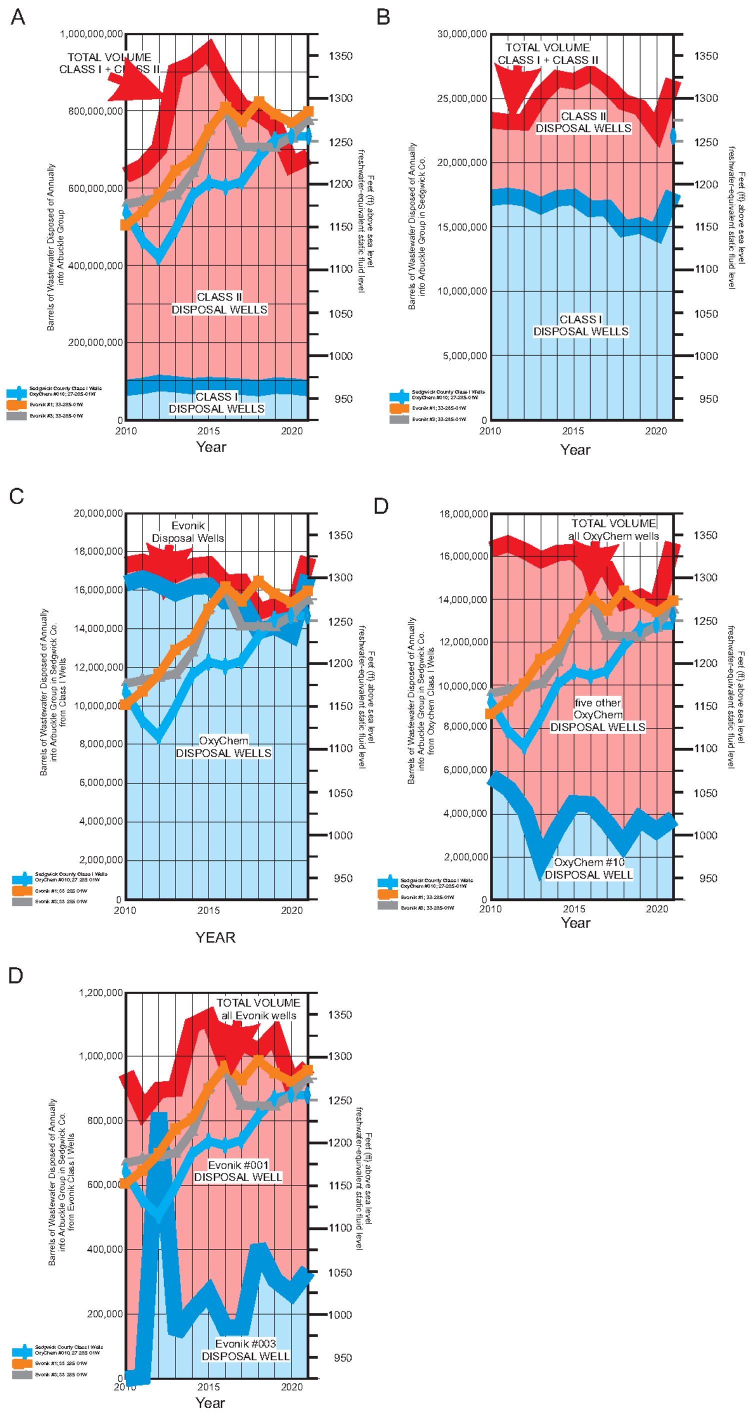

Figure 14. SFL behavior with time of Class I wells in Kansas compared to the disposal volume of successively smaller areas, starting with A) all Class I and Class II wells in Kansas, B) all Class I and Class II wells in Sedgwick County, C) Class I wells in Sedgwick County, D) the specific Class I disposal field, and E) just the disposal well itself.

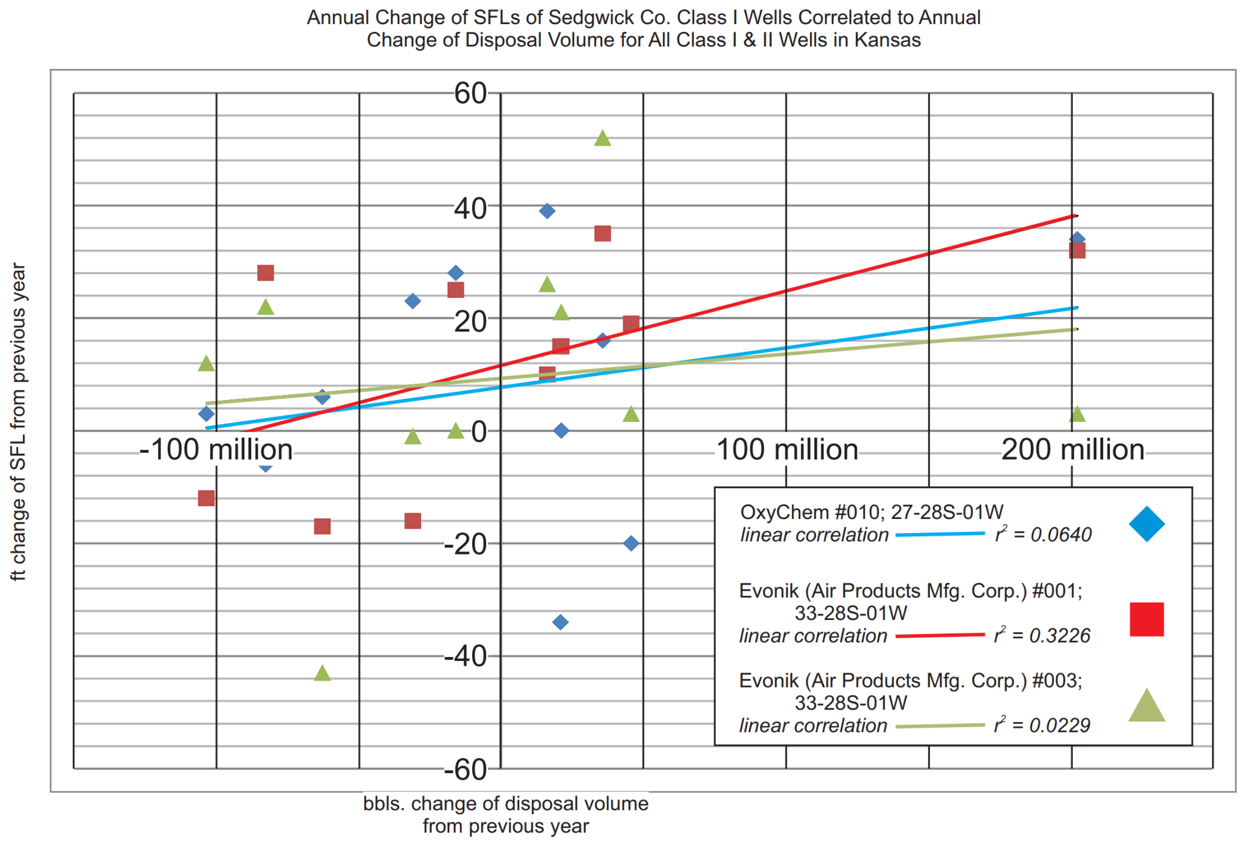

Figure 15. Linear correlation of the annually recorded change in footage of the Sedgwick County Class I wells with the annual change in disposal volume put into the Arbuckle in all of Kansas.

Goodness-of-fit of Linear Regression of Annual Change of SFLs
with Annual Change in Disposal Volumes

change in annual disposal volume

regional → *local*

change in annual SFL for	annual change in disposal volume of all Class I & II wells in Kansas	annual change in disposal volume of all Class I & II wells in county	annual change in disposal volume of all Class I wells in county	annual change in disposal volume of all Class I OxyChem wells nearby	annual change in disposal volume of only OxyChem well #010
OxyChem #010; 27-28S-01W	*r^2 = 0.0640*	*r^2 = 0.0093*	*r^2 = 0.0138*	*r^2 = 0.0022*	*r^2 = 0.0316*

	all Class I & II wells in Kansas	all Class I & II wells in county	all Class I wells in county	all Class I Evonik wells nearby	only Evonik well #001
Evonik #001; 33-28S-01W	*r^2 = 0.3226*	*r^2 = 0.0861*	*r^2 = 0.0240*	*r^2 = 0.0067*	*r^2 = 0.0004*

	all Class I & II wells in Kansas	all Class I & II wells in county	all Class I wells in county	all Class I Evonik wells nearby	only Evonik well #003
Evonik #003; 33-28S-01W	*r^2 = 0.0229*	*r^2 = 0.1374*	*r^2 = 0.0274*	*r^2 = 0.0277*	*r^2 = 0.0014*

indicates negative correlation

Figure 16. Goodness-of-fit statistics for comparison of the SFL in the three measured Class I wells in Kansas with the disposal volumes into the Arbuckle for all of Kansas, on down to the volume disposed of in the specific well.

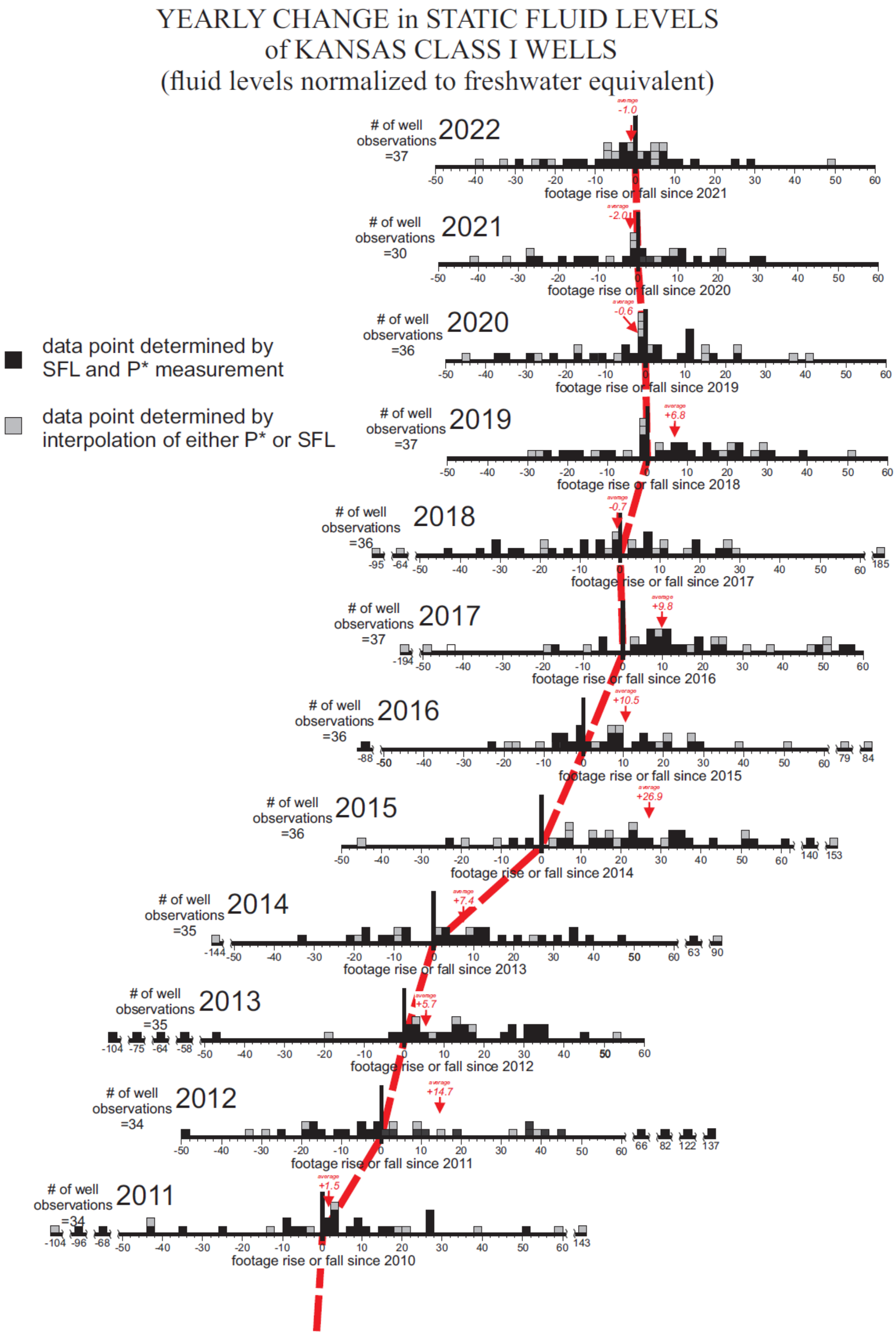

Figure 17. Histograms of the year-to-year change in SFL from 43 Class I wells (from Appendix B). An average change in SFL is calculated for each year. This change in SFL is then used as a basis for moving the entire histogram either to the right (for fluid rise) or left (for fluid fall) with respect to the previous year.

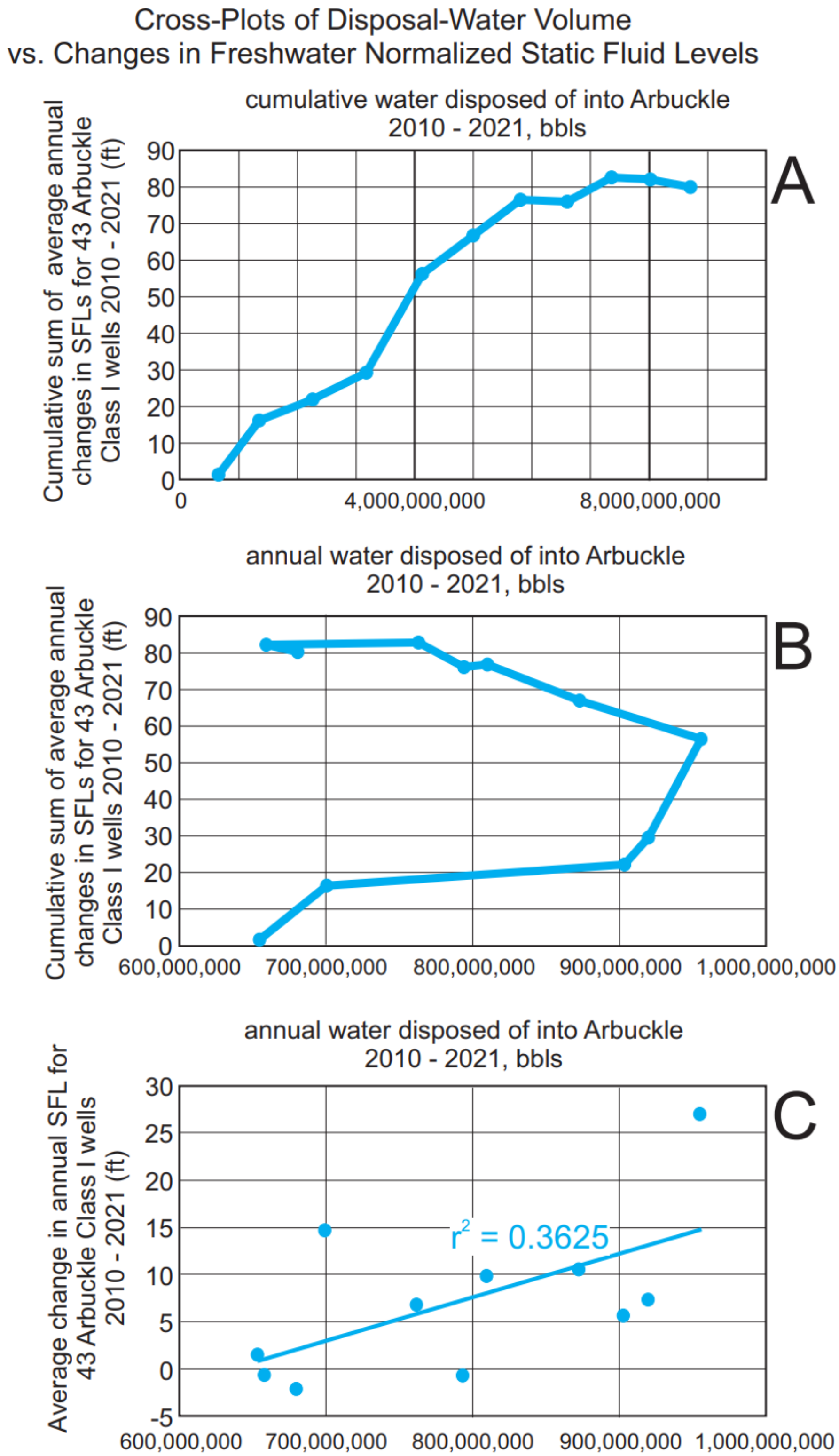

Figure 18. Comparisons of the average annual change in Class I wells with Arbuckle disposal volumes in Kansas.

5. Conclusions / Key Observations

5.1. Implications for future Arbuckle monitoring

The most accurate methods for determining BHP are a static measurement or pressure transient analysis from a PFO test. Projections from shallower depths, even within the open-hole portion of the well, would result in unacceptably large errors in the calculated freshwater-equivalent SFL due to a variable density profile in brine disposal wells. A possible solution to the segregation of fluids in the casing that are not representative of the formation fluid is to evacuate fluids within the cased portion of the borehole and allow the borehole to fill back with local Arbuckle formation fluid. This would provide a much more consistent or at least constant density profile. With a constant density profile, BHP could be more accurately projected from inexpensive shallow measurements.

SFL can be accurately estimated with a variety of methods, where calculated from a pressure gradient survey is considered the benchmark. SFL calculated using a shallow pressure and density measurement provided results consistent with the gradient survey. This is expected as shallow pressure recording is the method most frequently used for long-term water level monitoring. Another option would be to directly measure depth to water with an electrical wireline logging tool. The benefits of using this method would be to eliminate uncertainty associated with density, knowledge of SFL in advance for appropriate emplacing of a shallow pressure tool, and for providing a redundant measure of SFL for quality assurance.

Based on the results of testing in KS-01-155-008 and Class II wells, correcting pressure measurements for tidal effects is likely unnecessary since the diurnal changes are on the order of the measurement uncertainty.

The density profile in a brine disposal well (produced water injectate) will be variable, and reduced density is possible within the perforated or open-hole portion of the well. This has significant implications for projecting pressure from shallower measurements to the bottomhole depth. Due to the density inversion in the wells measured for this study, the average density of the fluid column is insufficient for pressure extrapolation and requires assumptions about density in the open-hole interval. It may be possible to use an estimate of density within this interval using assumptions derived from other measurements or sources (e.g., Arbuckle density estimated from published values of salinity). However, the uncertainty would be unknown without a direct measurement and has the potential to produce large errors in the calculated freshwater-equivalent SFL.

Although not observed in the test well, lower density fluid within the casing relative to the Arbuckle Group fluids is also a possibility. The density of the injectate depends on which formation the produced water originated in for Class II and the source for Class I. This uncertainty almost guarantees that a linear extrapolation of density throughout the well column when calculating BHP will produce inaccurate results.

Considering pumping Class II SWD wells is not feasible, in most situations a direct measurement sequence will be the best approach. Ultimately, when using any available Class II SWD wells for estimating SFL and BHP, the best approach is a bottomhole pressure measurement with the tool on the bottom for at least 12 hours. Then, record incremental pressure measurements each 500 to 1,000 ft up the hole to establish a pressure gradient. Finally, measure the current fluid level with the pressure transducer as it is raised in the borehole. With these data, a relatable SFL suitable for incorporation in contour maps that include the Class I data can be estimated.

In light of these findings and concerns regarding risk to logging equipment in the open-hole interval, pumping the injected fluid out of the borehole and then allowing the well to fill with Arbuckle formation fluid will allow a reasonably accurate projection of BHP from shallow measurements while reducing the risk to logging equipment and well integrity. Pumping would likely only be required once for wells that remain inactive between measurements. If long-term inactive wells could be incorporated into a measurement program, they would provide a cost-effective means for time-lapse monitoring that involve repeat measurements at regular intervals.

5.2. Building an Arbuckle fluid database

Studies have clearly demonstrated that the Arbuckle Group is a highly variable interval, with the Arbuckle Group at the geologic provinces scale being described as cups in an “egg carton” with respect to restrictions to and preferential pathways for fluid movement within it. Considering the spatial distribution of Class I wells, using measurements from Class I alone will not permit meaningful subregional interpretations of Arbuckle hydrology. Extrapolating more than a few 10s to 20s of miles between measurement points will not result in accurate representations of SFL, BHP, or water chemistry in the Arbuckle Group. Acquiring meaningful Arbuckle fluid data requires collaboration and cooperation with owners and operators of Class II SWD wells. It is not possible under any state funding scenario to collect the data necessary to characterize the current state of Arbuckle formation fluids and provide a science-based model of key fluid properties at the scale and resolution necessary for meaningful resource projections without partnering with the Class II SWD community.

Class II operators could provide valuable data to the study and understanding of the current state of Arbuckle fluids, any meaningful trends in the reservoir’s fluid properties, and the still untapped resource potential of the interval. For active SWD wells, during MIT or any servicing where the wellhead is removed, a sample of the injectate could be obtained and an electronic sounder could be lowered into the open well (after a short shut-in period) where the SFL could be measured. Additionally, for very little additional expense, a pressure measurement around 100 ft below the top of the water column could be taken. For inactive SWD, pumping around 10 well volumes in advance of taking a fluid sample, lowering a sounder, and taking a SFL reading after a stabilizing period would also provide extremely valuable data for better characterizing this resource. When SWD wells are idle, measuring BHP and acquiring a pressure gradient survey (requiring no more than 24 hours of access to the well) would dramatically improve the accuracy of temporal characterizations of the Arbuckle. These data from wells that penetrate the top of the Arbuckle at least 200 ft would provide an invaluable data set for preserving and protecting the Arbuckle for current as well as future uses. Key to any measurement in an Arbuckle disposal well is ensuring the fluid in the cased portion of the well has the same properties as the fluids in the uncased/screened Arbuckle interval or that the properties can be calculated or measured or are known.

5.3. Suggesting a highly hydraulically connected aquifer

Regional generalities and perceptions based on field size and smaller engineering studies evaluating drainage and fluid radius for oil and gas production have resulted in unsubstantiated suggestions that the hydraulic influence or effects of injection or removal of fluid from Arbuckle wells are confined to the size of a reservoir or near field only. Statistical analysis of change in SFL adjusted to freshwater density provides a clear indication that changes in SFL in any individual well more closely correlates to regional disposal volumes than disposal volumes recorded for an individual well.

This regional connectivity within the Arbuckle is consistent with permeability at the geologic province size (egg carton analogy) rather than the "inverted cone of depression" model. Key with this observation is the stabilizing timeframe of fluid properties in the Arbuckle. The time lag between SFL rise and fall vs. the disposal volume for most wells is probably on the order of weeks or months rather than years, with annual measurements allowing assessment of diffusion of fluid pressures well beyond the wellbore.

Future new uses of the Arbuckle Group to store, sequester, or dispose of fluids should include site-specific modeling that considers density, pressure, and temperature of the injectate and density, pressure, temperature, areal permeability, and chemical processes of fluids in the Arbuckle both before and after mixing. With consideration for density of injectate, pressure injection might need to be considered for all operators to allow disposal of lower density contaminants into the Arbuckle where SFL of Arbuckle fluids are within a few hundred feet of the ground surface. Pressure injection should only be used to overcome current SFL up to the point the SFL encroaches on the basal contact of a potable aquifer.

5.4. Recommendations for future study

Actual SFL in some Sedgwick County wells was measured within 30 ft of the ground surface in 2022 (the most recent available data). This raises the possibility of both operational concerns for wells where injection pressure would be required to force disposal fluids into the Arbuckle, as well as the <u>potential</u> for Arbuckle formation fluids to encroach on freshwater aquifers or the ground surface. A natural extension of the current study would be to correct for the actual salinity/density of Arbuckle formation fluid to characterize the true piezometric surface. Considering drilling practices a century ago in comparison to the methods and environmental safeguards built into today's drilling operations, it is reasonable to consider penetrations of the interval between the top of the Permian and Arbuckle completed prior to the latter half of the 20th century potential (although rare) candidates for a source of connectivity between the two aquifers.

Understanding flow directions and associated fluid exchange and mixing of these aquifers requires accurate knowledge of the hydraulic head and density of fluids in both units. In the absence of those, data extrapolations and projections provide the best source for estimating the status and fluid transport potential. Correcting the freshwater-equivalent SFL for salinity/density and subtracting the elevation of the top of the Permian would provide an estimate of distance between Pliocene-Pleistocene unlithified sediments and Arbuckle fluids and facilitate assessment of hypothetical environmental risk in the unlikely event of a casing breach in an Arbuckle well. Additional sampling in areas where the actual potentiometric surface is near the base of potable aquifers (whether in existing, redrilled, or newly drilled wells) is crucial for confidently constraining the depth to the piezometric surface and assessing environmental risk.

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APPENDIX A

2020 Fall-off Test
Class 1 Non-hazardous
Saltwater Disposal Well #1
KDHE permit #KS-01-155-008

Report available from KDHE upon request.

APPENDIX B

Year-to-Year changes in SFLs
for 43 Class I Wells in Kansas

Appendix B. Year-to-Year Changes in SFLs for 43 Class I wells in Kansas

			Potentiometric freshwater-equivalent static (elevation, ft above sea level); using TD as a basis for determining FWE SFL)												
COUNTY	WELL NAME, STR LOCATION	WELL #	YEAR												
			2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Barton	Red Barn Pet Products, 04-20S-13W	KS-01-009-001	1161	1148	1131	1159	1198		1193	1252	1206	1187	1213	1224	
Butler	HollyFrontier El Dorado Refinery, 15-26S-05E	KS-01-115-001	1021	970	976	955	1011	1034	1017	1044	1056	1066	1061	1064	1067
Ellsworth	ONEOK Bushton #004, 31-17S-9W	KS-01-053-003	1130	1150	1170	1190	1210	1230	1251	1251	1260	1264	1261	1254	
Finney	Wheatland Electric, 13-24S-33W	KS-01-055-003	1166	1157	1168	1162	1157	1171	1168	1174	1165	1167	1167	1174	1156
Finney	Tyson, (Holcomb) Jones #2, 02-24S-34W	KS-01-055-002	1239	1228	1234	1199	1201	1226	1225	1203	1208	1242	1224	1254	1219
Ford	Koch Nitrogen #2, 22-26S-24W	KS-01-057-001	1156	1194	1167	1221	1230	1240	1247	1238	1254	1233	1275	1272	1270
Ford	Koch Nitrogen #3, 15-26S-24W	KS-01-057-002	1167	1125	1164	1180	1196	1217	1298	1252	1261	1230	1267	1234	
Ford	Sunflower Ft. Dodge Station, 04-27S-24W	KS-01-057-003		1168	1179	1161	1223	1231	1238	1250	1249	1250	1261	1230	
Harper	Pioneer Exploration #2, 05-31S-08W	KS-01-007-001										1317	1317	1316	
Harper	Pioneer Exploration #3, 05-31S-08W	KS-01-007-001	1185	1189	1232	1268	1319	1337	1345	1369	1342	1320	1335	1312	
Johnson	Deffenbaugh Industries #02, 01-12S-23E	KS-01-091-002	720	723	709	711	688	718	696	708	719	686	711	713	704
Kearny	City of Lakin WWD #1, 16-24S-36W	KS-01-092-002			1140	1145	1150	1155	1160	1165	1177				
Kiowa	Northern Natural Gas Co. #001 KW (Mullinville), 20-28S-19W	KS-01-097-001	1170	1173	1173	1188	1210	1234	1235	1254	1223	1262	1273	1248	1250
Lyon	Tyson, Lyon Co. (Emporia), 17-19S-11E	KS-01-111-001	796	798	788	790	795	806	796	822	789	777	789	777	803
McPherson	NCRA (CHS) McPherson Refinery #1, 32-19S-03W	KS-01-113-008	1012	1158	1172	1189	1190	1207	1218	1238	1265	1252	1274	1233	
McPherson	NCRA (CHS) McPherson Refinery #2, 32-19S-03W	KS-01-113-009	1164	1221	1188	1189	1179	1212	1242	1275	1304	1307	1310	1314	1319
McPherson	CHS Conway #2, 20-19S-04W	KS-01-113-014											1213		
McPherson	Williams Conway East #001 Riddell, 28-19S-04W	KS-01-113-003	1047	1074	1196	1228	1196	1178	1200	1263	1284	1330	1280		1280
McPherson	Williams Conway East #002 Riddell, 28-19S-04W	KS-01-113-004	1206	1216	1260	1189	1178	1178	1274	1322	1316	1285	1265	1271	1282
McPherson	NCRA #001 (CHS Conway #1), 29-19S-04W	KS-01-113-002	1195	1118	1273	1194	1206	1357	1236	1297	1266	1266	1187	1187	1238
McPherson	ONEOK McPherson #002 (Conway), 30-19S-04W	KS-01-113-006	1224	1197	1286	1225	1240	1285	1275	1292	1289	1299	1304	1299	1295
McPherson	Williams Conway West #1, 24-19S-05W	KS-01-113-001	1152	1209	1162	1173	1182	1204	1218	1230	1235	1263	1257	1259	1259
McPherson	NCRA (CHS) McPherson Refinery #3, 04-20S-03W	KS-01-113-010	1032	1030	1062	1076	933	1086	1126	931	1115	1132	1105		
McPherson	NCRA (CHS) McPherson Refinery #4, 05-20S-03W	KS-01-113-011										1198			
Reno	ONEOK Yaggy #1, 30-22S-06W	KS-01-155-005				1164	1194	1218	1240	1220	1223	1222	1221	1229	
Reno	ONEOK Yaggy #2, 25-22S-07W	KS-01-155-006	1357	1248	1199	1232	1382	1395	1371	1415	1310	1330	1320	1322	
Reno	City of Hutchinson #1, 21-23S-05W	KS-01-155-008	1176	1190	1189	1184	1225	1247	1241	1257	1253	1245	1244	1236	
Reno	City of Hutchinson #2, 21-23S-05W	KS-01-155-009	1184	1189	1185	1221	1252	1245	1264	1257	1258	1259	1259	1263	1268
Reno	Morton Salt Division #D01, 22-23S-06W	KS-01-155-004	1168	1162	1156	1192	1196	1250	1256	1266	1253	1268	1267	1243	1250
Reno	ONEOK Fractionation #2 (Hutchinson), 22-23S-06W	KS-01-155-002	1181	1200	1210	1217	1209	1213	1229	1241	1252	1255	1364	1257	1260
Reno	ONEOK Fractionation #3 (Hutchinson), 22-23S-06W	KS-01-155-003	1152	1171	1208	1240	1285	1266	1238	1272	1251	1229	1237	1240	
Reno	ONEOK Hillside #002, 28-23S-06W	KS-01-155-007	1073							1277					
Reno	Enterprise, 29-23S-06W	KS-01-155-008	1188	1179	1188	1203	1221	1256	1270	1271	1266	1276	1259	1263	1266
Reno	UCS (Underground Cavern Stabilization), 14-24S-6W	KS-01-155-012						1294	1306	1314	1316	1297	1300	1317	
Rice	Northern Natural Gas Co. #001 RC (Bushton), 06-18S-09W	KS-01-159-003	1150	1177	1162	1170	1148	1205	1200	1221	1202	1227	1237	1224	
Rice	Williams Mitchell #02, 26-19S-07W	KS-01-159-008		1268	1164				1161		1296		1295		
Rice	Williams Mitchell #01, 27-19S-07W	KS-01-159-002	1110	1136			1233	1253	1242		1250		1279	1293	
Rice	Compass Minerals #003; 18-20S-07W	KS-01-159-005	1165	1174	1152	1183	1185	1227	1220	1249	1219	1251	1238	1252	1251

Rice	Compass Minerals #004, 29-20S-07W	KS-01-159-006													
Rice	Kansas Ethanol #005, H, 32-20S-07W	KS-01-159-007	1171	1165	1160	1209	1195	1227	1263	1323	1245	1254	1265	1244	1219
Rice	Compass Minerals #001, 15-20S-08W	KS-01-159-001	1175	1053	1126	1162	1138	1179	1174	1176	1262	1212	1207	1240	1232
Sedgwick	OxyChem #010, 27-28S-01W	KS-01-173-010	1179	1182	1087	1182	1211	1234	1200	1199	1228	1260	1264	1258	1263
Sedgwick	Evonik #1, 33-28S-01W	KS-01-173-002	1152	1169	1168	1208	1227	1265	1296	1273	1280	1281	1269	1250	1282
Sedgwick	Evonik #3, 33-28S-01W	KS-01-173-001	1183	1185	1188	1184	1224	1267	1292	1242	1237	1241	1254	1279	1274