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**PREFACE:**

This Open-File Report presents a summary of data compiled from public Oklahoma Corporation Commission (OCC) records to update OF5-2015 with 10 more years of injection records. This report supersedes papers, reports, or conference slides previously presented by the author. Subsequent updates, though not expected to be substantial, may be required as other records and data are made available by operators or the OCC.

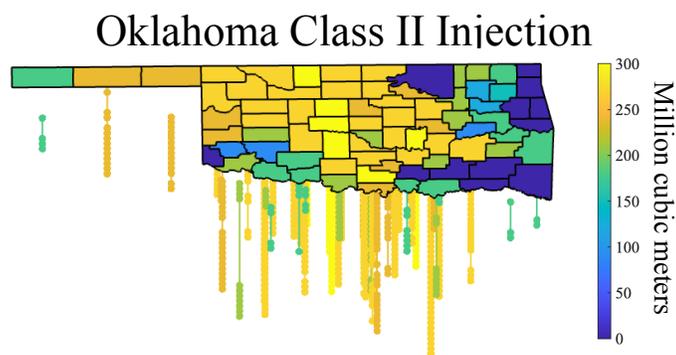
# Class II Saltwater Disposal for 2011–2025 at the Monthly-, State-, and County-Scales by Geologic Zones of Completion, Oklahoma

Benjamin Allen<sup>1</sup>

<sup>1</sup> *Oklahoma Geological Survey, University of Oklahoma, Norman OK 73071*

This report is an update of ongoing research to compile Oklahoma’s Class II underground injection control (UIC) well data by geological zone of injection following up 10 years after OF5-2015. Reports are filed monthly for all the zones in the state (excluding Osage County). Previous studies have found linkages between saltwater disposal (SWD) wells and induced seismicity within the state of Oklahoma. Records are derived from a combination of the monthly injection records (1012a, and daily 1012d for the Arbuckle Group), well completion and permitting reports filed by operators with the Oklahoma Corporation Commission (OCC).

Based on the data compiled for this report UIC injection across the state has decreased by about 40% since the peak in 2015. This decline does not match with decreasing production, but rather shows more efficient hydrocarbon production with less water usage. The significant decrease in injection is primarily from reduced injection into the Ordovician age rocks (primarily the Arbuckle), resulting in the injection volumes dropping below the injection into Pennsylvanian age strata once again. all formations see a drop in injection around the April/May of 2020. The Chimney Hill formation of the Silurian shows the highest maximum reported pressures averaged across the state and the Ordovician has reports of lower pressures on average than both the strata above and below it.



A perspective of Oklahoma’s UIC injection (in 2023)

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## I. INTRODUCTION

Oklahoma is an oil and gas producing state where Figure 1 shows the production data from EIA. Oil and gas operations will produce formation waters that are often saltier than the ocean ( $\sim 3x$  salinity) and have dissolved toxic minerals from the deep rock formations. This produced brine is then reinjected into the subsurface as remediation would be prohibitively expensive. The injection of the brine is commonly called salt water disposal (SWD). The injection of oil and gas related fluids is designated under the Safe Drinking Water Act of 1974 and monitored by the Oklahoma Corporation Commission (OCC) in Class II wells since 1984 [1] as designated by United States Environmental Protection Agency (EPA) and under the Safe Drinking Water Act of 1974[2] and the Clean Water Act of 1972 [3].

- *"No owner or operator shall construct, operate, maintain, convert, plug, abandon, or conduct any other injection activity in a manner that allows the movement of fluid containing any contaminant into underground sources of drinking water, if the presence of that contaminant may cause a violation of any primary drinking water regulation under 40 CFR part 142 or may otherwise adversely affect the health of persons. The applicant for a permit shall have the burden of showing that the requirements of this paragraph are met."*[4]

The fluid that is produced from the subsurface after removing the oil and gas for sale is then put back into the subsurface (often a lower formation so as to not interfere with oil and gas production). Formations with a high porosity and permeability are favored for injection.

### A. Induced Seismicity

Along with oil and gas Oklahoma produces earthquakes. In 2015 Oklahoma had the most recorded earthquakes in the state as can be seen in Figure 1(b). The number of earthquakes  $\geq M2$  rose by over 5000% per month starting around 2010. Almost all of these earthquakes appear to be induced by anthropologic activities and there is a spatial correlation between deep fluid injection into the Arbuckle and earthquakes reported [5] with a lag time of 3 months between peak seismicity and peak injection.

This correlation has led to changes in injection practices, locations and volumes throughout the state. A stoplight procedure has been implemented to reduce or shut down injection wells near

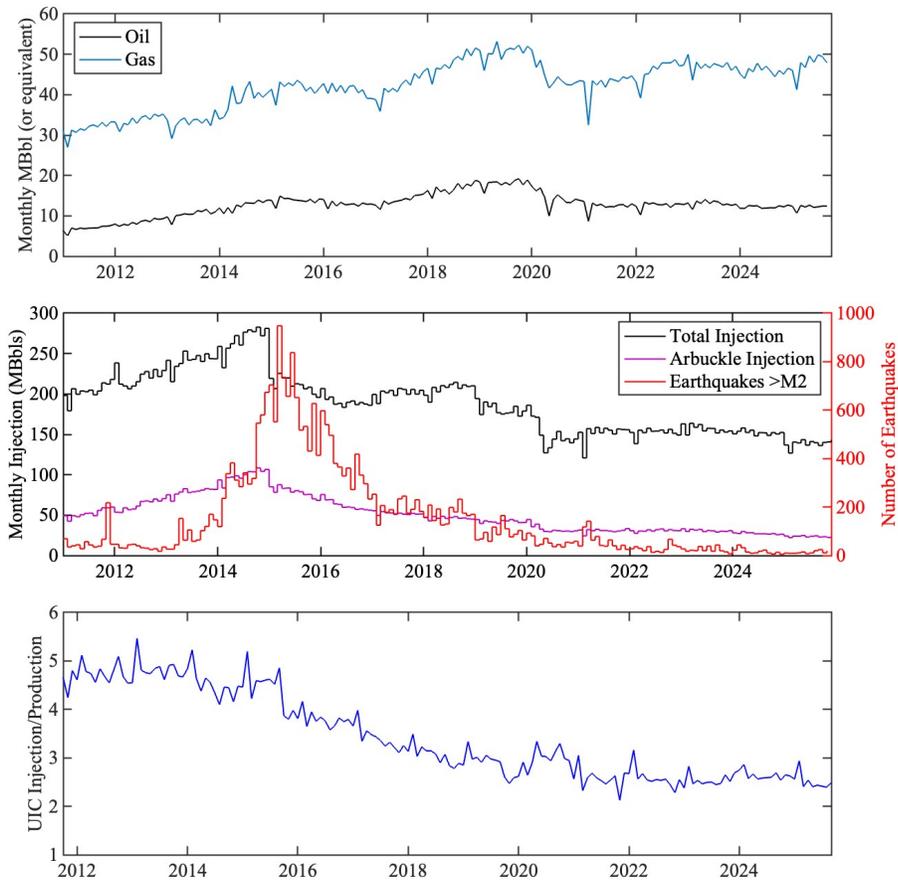


FIG. 1. (a) The production of natural gas and oil in Oklahoma (b) The statewide UIC injection and the injection into the Arbuckle, shown in red are the number of earthquakes greater than a magnitude 2 in Oklahoma [6] (c) The ratio of Class II UIC injection compared to the combination of oil and gas produced.

earthquakes that exceed a magnitude  $M > 2.5$ [7]. Due to the correlation between Arbuckle injection and seismicity additional daily monitoring (above and beyond the monthly monitoring) has been required for injection into the Arbuckle (correlated with the earthquakes), an early Ordovician geologic group which along with the potential cease and desist orders for wells near earthquakes has reduced the amount of injection into the Arbuckle by about a factor of 2. Some wells have been re-completed to higher formations, some lowered their injection volumes, and some ceased injection completely. For this reason in this dataset the UIC data has not been fully compiled by API, but sorted by API and year of injection.

The injection history is not the same in all formations, although overall injection has decreased. Oil and gas production has slowly been increasing especially in natural gas and the amount of water injected compared to production has been steadily decreasing so that it is now only about twice as much fluid is put back into the ground as is produced for sale.

## B. Injection Pressures and Pressure Monitoring

According to the 2019 OCC UIC guide [8] the basic guideline for acceptable injection pressures is 1 psi per foot to a maximum psi of 1500 psi. Additionally, operators must report the maximum recorded pressure that is measured when reporting the volume that is injected per month on the 1012a forms. There seems to be some confusion on what this maximum pressure actually is, with some operators reporting the pressure that they are injecting into the formation (which should be the maximum pressure at the surface), while others report the maximum value in between injections.

Data was compiled primarily through the monthly 1012a injection reports throughout the state. Osage County was not included because of the extra time and resources to gather and check the data as well as incorporating and standardizing the records. Unique identifiers for the wells assigned by the American Petroleum Institute (API numbers) were used to track and correlate across different documents and reports. 13,798 wells reported injection into Oklahoma's subsurface across the time period spanning from 2011-2025.

Similar to [9], the documents have been filtered to remove references to Liquefied Petroleum Gas (LPG) and Gas injection reporting. These wells are mostly within the Pennsylvanian injection interval with the most significant in the NW of the Anadarko Basin and Panhandle.

The Oklahoma Geological Survey ran monitoring of the fluid pore pressure in 15 Arbuckle wells from August 2016 - March 2020 and found that the pressure throughout the Arbuckle appears to be decreasing and shows signs of a very heterogeneous reservoir structure [10]. This study has a large dataset of fluid pressures measured every 30 seconds in the unused wells near the site of previous earthquakes [14].

## II. METHODS

### A. Injection Records

As stated previously the main source of injection data was the monthly 1012a injection report submitted to the Oklahoma Corporation Commission. Operators reported the monthly volume of injection and the maximum pressure over that month measured at the wellhead to the OCC. Oklahoma has many wells drilled into numerous formations in the subsurface and some of the wells were drilled before standardization of reporting was developed and early injection records were voluntary and there are very many records that do not contain full information, or unclear

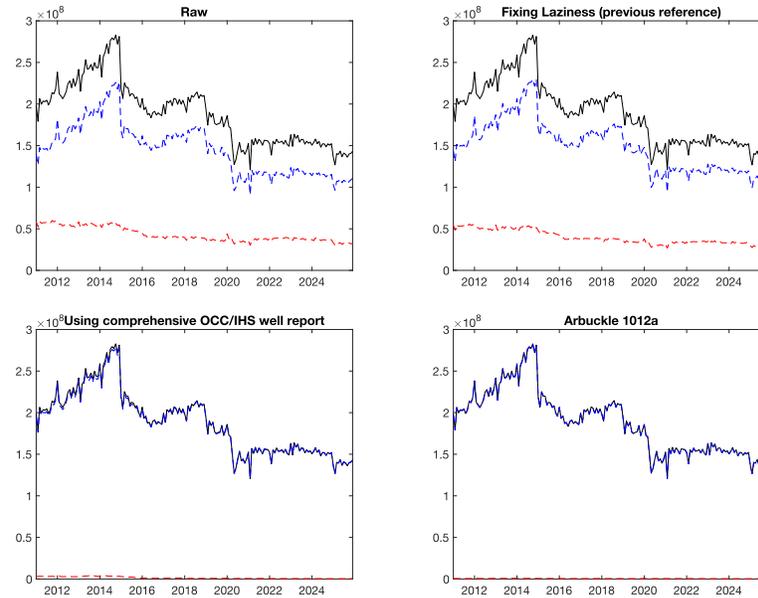


FIG. 2. Showing the number of unlabeled formations of well records at each stage in the correlation process. (a) The raw 1012a records (b) Fixing APIs that have previous records (c) Checking against IHS records (d) Correlating with wells permitted for Arbuckle injection and 1012d reports.

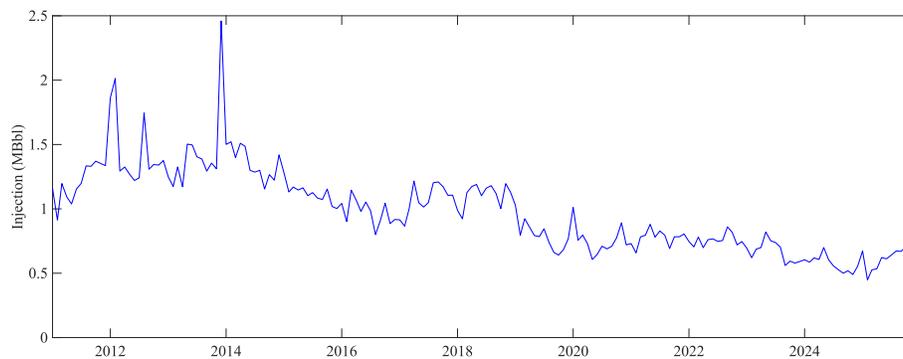


FIG. 3. The recorded injection in the ambiguous and unknown injection zones.

formation names.

Some of the unknown formations and injection intervals could possibly still be connected to specific formations but that is a much greater task. Additionally, many of these older wells have been retired and there amount of injection that is into ambiguous formations is decreasing as records are further updated and become more up to date as shown in Figure 3. *Therefore, this record is not fully accurate due to a missing number of proper reports (see Figure 3) or bad record keeping, but is a fair representation of what is seen within the state of Oklahoma with a*

TABLE I. List of unknown and ambiguous formation names

- "CONGLOMERATE"
- "DOLOMITE"
- "DRY"
- "GRANITE" - Assumed to be Precambrian/Cambrian
- "GRANT"
- "MUNCRIEF"
- "N/A"
- "NA"
- "NULL"
- "OOOO"
- "SAND—SEE ORIGINAL"
- "UNCONF SD"
- "UNCONFORMITY"
- "UNCONFORMITY /SD/"
- "UNCONFORMITY LOWER /SD/"
- "UNKNOWN"
- "UNKNOWN FORMATION"
- <missing>

*small amount of injection unaccounted for ( $\sim 0.5\%$ ).*

Initial compilation combined the 1012a forms from 2011 through 2024. Following this, well APIs that had a formation within the compilation but not on the yearly recorded spreadsheet were matched and updated. Well records were then checked with the (IHS) database for completion records and the completion depth was taken when possible. Wells with still missing formations that then had 1012a (daily Arbuckle reporting) were updated with the Arbuckle as their permitted injection formation. There remains 313 wells that have unidentified formations or injection zones after the sorting of the data. These list either 'UNKNOWN' on the permitted formation or ambiguous designations such as 'SAND' or 'LIME'. The unknown injection zones accumulate to just over 1 MBbls per month before 2019 with a peak of 2.2 MBbls December of 2013 and decrease significantly after 2019 to just over 0.5 MBbls near the end of 2024. A list of the ambiguous and unknown well formation levels left over (310 wells with a total of 164 MBbls over the period between 2011-2024):

Additionally, some of the records report the measured depth instead of the true vertical depth. These are horizontally drilled wells and tend to show up as much deeper than they actually are as there is a horizontal length of up to thousands of feet. These wells can be identified from the well survey records and generally be much longer than vertical wells in the same area, but this requires looking through individual wells and matching them up with individual documents. This has not been done in this report. We will note that the top of the injection interval won't change significantly, while the recorded bottom of the injection interval can be off by over a thousand

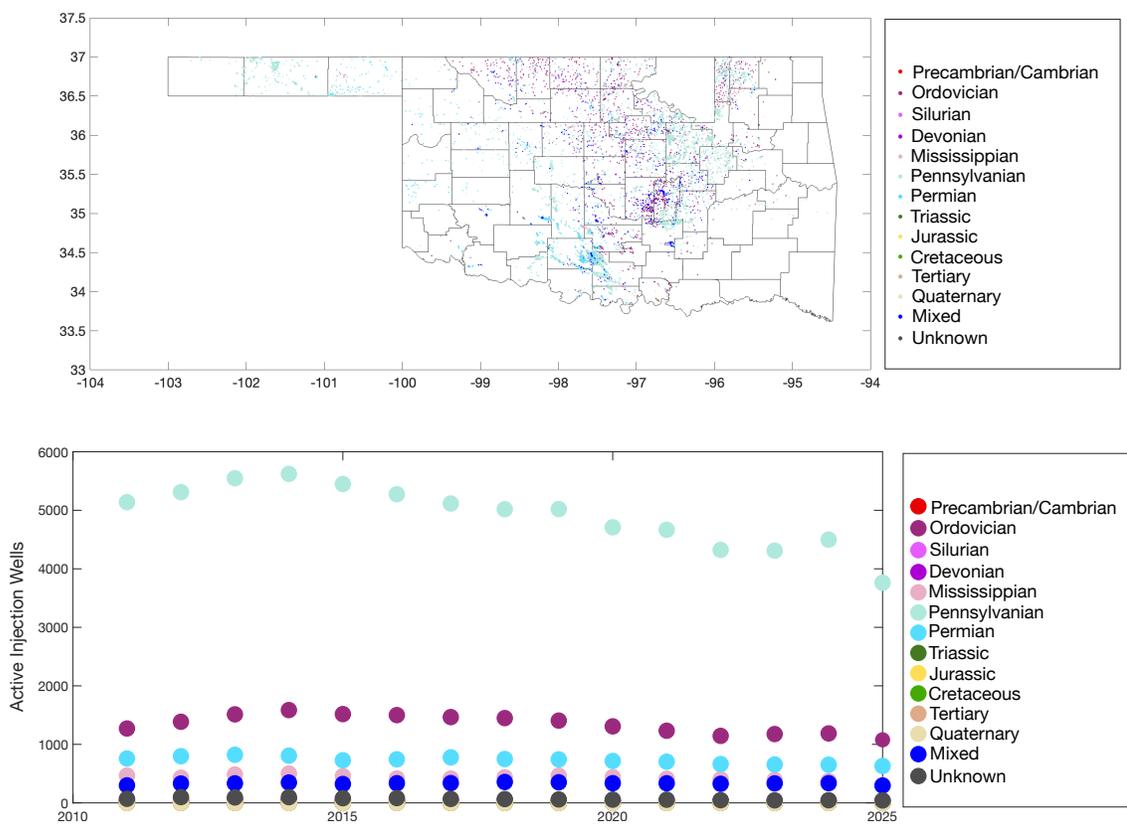


FIG. 4. (a) The location of UIC injection in Oklahoma (b) Number of active injection wells per geologic interval per year.

feet or more. *The deep wells in Kingfisher I believe are at least 3 Continental horizontal wells that register as >10k feet instead of about half of that.*

## B. Injection by Formation

Over 200 unique formations are represented within the SWD wells records simplified from just under a thousand different combinations (982), misspellings, abbreviations, and subzones (i.e. Deese A, Lone Grove 7, 1st Wilcox). These formations are then sorted into the broad geologic ages.

Some of the injections spanned across multiple groups and formations. When possible these were assigned the proper geologic age (i.e. Red Fork + Atoka + Cherokee  $\rightarrow$  Pennsylvanian), but injections that spanned over multiple broad geologic ages were labelled as Mixed. For example, the Hunton group is Devonian and Silurian and was denoted as mixed or an injection that was permitted for both the Wilcox (Ordovician) and the Deese (Pennsylvanian) sandstone would also

TABLE II. List of Geologic Ages to sort injection formations.

- PRECAMBRIAN / CAMBRIAN
- ORDOVICIAN
- SILURIAN
- DEVONIAN
- MISSISSIPPIAN
- PENNSYLVANIAN
- PERMIAN
- TRIASSIC
- JURASSIC
- CRETACEOUS
- TERTIARY
- QUARTERNARY
- MIXED
- UNKNOWN

be 'MIXED'.

Additionally, records that recorded their injection into an ambiguous zone like 'SAND' or 'UNCONFORMITY' are labelled as 'UNKNOWN'. Some of the wells could be assigned matching the reported injection depths (a few are missing even these fields from early records) to the geologic stratigraphy of the area where they were drilled but this was determined beyond the scope of the current project.

Following the many swarms of earthquakes in 2015 and 2016 injection into the Arbuckle came with increased scrutiny (daily reporting by 1012d) and the possibility of being shut down if there were significant earthquake activity in the nearby area. This prompted some operators to move to higher stratigraphy. If this was not adjusted in the 1012a OCC records the change in injection interval could be missed within this reporting.

### III. RESULTS

#### A. Statewide Injection

The injection wells are shown in Figure 4(a) and the distribution across the state by geologic age. In the west and the south much of the injection tends to be in recent ages which lie above the older formations with a significant number in the Permian and Pennsylvanian of the Anadarko Basin. In the heavily oil producing SCOOP-STACK the injection tends towards the lower lying stratigraphy but with a scattering of Pennsylvanian and Mixed formation injection.

Injection within the state of Oklahoma peaked in 2015 after rising precipitously and then the injection fell off as the earthquakes peaked in late 2015 as injection controls became stricter.

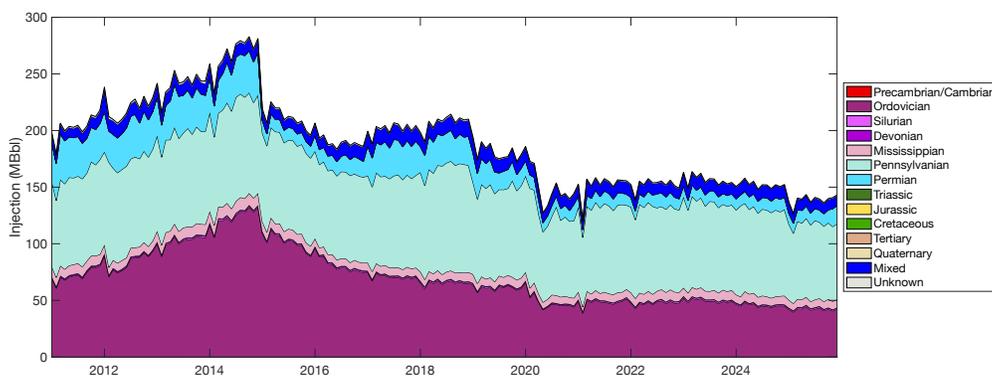


FIG. 5. (a) All the injection in Oklahoma organized by the geologic age of the zone of injection. Mixed contains multiple injection intervals. Unknown is the same as shown in Figure 3 (b) The top 5 intervals of injection. (c) The cumulative volume of injection into each formation.

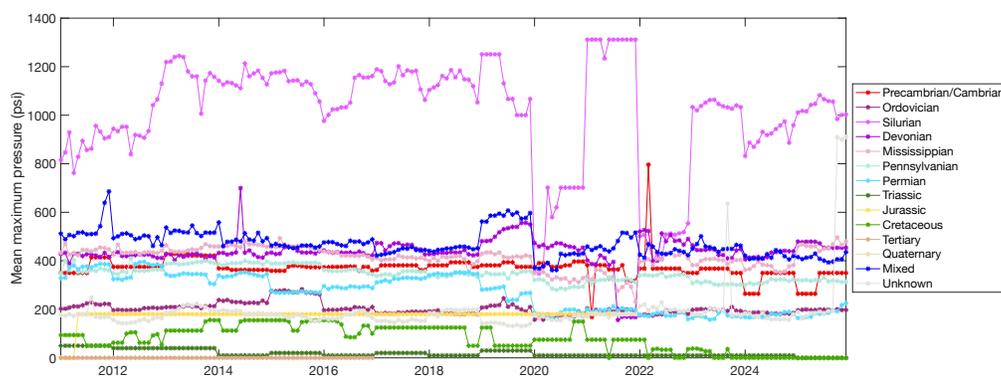


FIG. 6. The mean maximum recorded surface pressures for the different injection zones averaged across the state.

Following the peak of earthquakes injection within the state has decreased by about 25% with a drop in 2020. This offset occurred across most of the injection due to the advent of COVID19 and the drop in transportation and oil use.

Pennsylvanian injection is the most widespread throughout the state and also the most numerous. (Figure 4(b) shows that the Pennsylvanian formations with three times more injection wells than the next most frequent injection interval, the Ordovician. Together these two intervals contribute the majority of the injection within the state as shown in Figure 5

Ordovician age injection peaked in 2015 and had decreased by about a factor of 2 also showing an offset after 2020. The Ordovician injection started lower than Pennsylvanian previous to 2012 but grew to larger injection volumes in 2013-2017 but has had a lot more change over the monitored

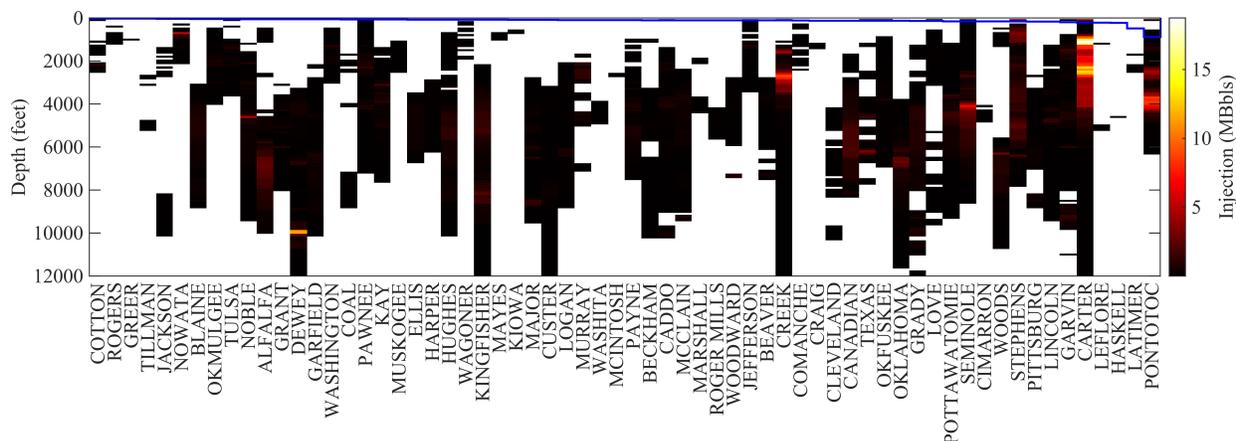


FIG. 7. Injection intervals and volume of injection across this study. Wells without injection as listed in Table III are not plotted. The blue line shows the bottom of the of treatable water for the county (drinking water).

period. Over the time period from 2011-2024 the injection in the Pennsylvanian age interval has been roughly constant with a slight drop after 2020. The Ordovician wells tend to have higher injection volumes than the Pennsylvanian wells by a factor of 2-3 $\times$ .

Figure 5(c) shows that the significant injection has been in the Pennsylvanian age strata and the Ordovician with the combination of the two intervals being approximately 90% of the injection within the state. These two geologic ages are also usually included in injection records characterized with the 'MIXED' grouping that has injection across several injection intervals.

The mean pressures measured at the surface that are reported are averaged across the state and shown in Figure 6. The Silurian injection interval (all Chimney Hill formation) shows the highest maximum pressures, and due to the large drop in pressure in 2020 when the injection significantly slowed. The other high pressures are in the lower stratigraphy of the Precambrian and Cambrian. The Ordovician shows lower fluid pressures than any of the formations above it or below; the Silurian, Devonian and Mississippi are all reporting higher pressures again suggesting that in general the Ordovician is under-pressured and continues to be to this day. It should be noted that some of these formations (i.e. Silurian) have only a few injection wells and are highly localized in the South of the state (see Figure 4) while many of the Ordovician injection wells are in the SCOOP-STACK in North-Central Oklahoma. This does not take into account the different depths, but is measuring the excess pressure not the formation pressure.

TABLE III. Counties with no reported UIC injection

- 'ADAIR'
- 'BECKHAM'
- 'CARTER'
- 'COMANCHE'
- 'CHOCTAW'
- 'CRAIG'
- 'ELLIS'
- 'GARVIN'
- 'GRADY'
- 'MAJOR'
- 'PUSHMATAHA'
- 'SEMINOLE'
- 'SEQUOYAH'

#### IV. COUNTY INJECTION

Much of Oklahoma is perforated with oil and gas wells as well as UIC injection wells. Of the 77 counties in Oklahoma 13 do not have records of injection in 2024 shown in Table III. The rest of the counties are shown in Figure 7 ordered by the maximum depth of treatable drinking water in the county as determined by the Oklahoma Water Resource Board [11].

The county with the maximum injection in 2024 is Carter County with 232 MBbls injected with the majority of the injection between 1000 - 4000'. The injection intervals quite often overlap with maximum treatable waterdepths for the county (see Figure 7), especially in the Southern part of the state. Some of these wells are known to be above the OWRB's defined base of treatable water [12], while others are still below as the base of treatable water in a county varies more locally with the stratigraphy of the subsurface.

#### DATA AVAILABILITY

Data from OCC injection reports can be found at

<https://oklahoma.gov/occ/divisions/oil-gas/oil-gas-data.html>.

OCC records between 2010-2024 have been consolidated into a single file csv file with:

- API - American Petroleum Identification Number
- COUNTY - County of the well
- LAT - Latitude
- LON - Longitude
- FormationName - Name of Permitted formation
- InjTopDepth - Recorded top of injection from the surface in feet

- InjBotDepth - Recorded bottom of injection from the surface in feet
- Yr - Year of record
- Series - Age classifier using Table II
- [Year][Month]Inj - The injection volume in Barrels for with the numerical year replaced without brackets and month abbreviated to the first 3 letters
- [Year][Month]Pres - The maximum recorded pressure in PSI for the numerical year replaced without brackets and month abbreviated to the first 3 letters

Data available *Set to download - 182.2 MB*: [https://drive.google.com/file/d/1RF0xvhHwd2vdaMuiGf1VA13SCumQ8-k7/view?usp=share\\_link](https://drive.google.com/file/d/1RF0xvhHwd2vdaMuiGf1VA13SCumQ8-k7/view?usp=share_link)

[//drive.google.com/file/d/1RF0xvhHwd2vdaMuiGf1VA13SCumQ8-k7/view?usp=share\\_link](https://drive.google.com/file/d/1RF0xvhHwd2vdaMuiGf1VA13SCumQ8-k7/view?usp=share_link)

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- [1] Federal 40 CFR 144.6 and Oklahoma Administrative Code 52:3-139.
- [2] 40 CFR 141 section 1425.
- [3] 33 USC 1251 et seq.
- [4] 40 CFR 144.12(a).
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