Documenting Known Abandoned Wells in Proximity to Potential Carbon Storage Formations in Louisiana

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Executive Summary:

Supercritical carbon dioxide (CO_2) injected into geologic formations via Class VI injection wells may migrate via abandoned wells, which can serve as vertical conduits that may rapidly transport injected brine and CO_2. Leakages of brine into surface or ground waters may limit the usefulness of waters for human consumption, and an expression of CO_2 leakage at the land surface would pose an asphyxiation hazard near buildings including residences.

The U.S. Department of the Interior estimates there are over 3.5 million abandoned wells in the United States. The location of many of these wells may be unknown. Wells constructed during early oil exploration pose the greatest risk because these wells are not documented in state records, may be relatively deep, often consisted of an open well bore, and generally have inferior construction as compared to modern standards. Open holes are susceptible to cross-migration between aquifers, especially if no plug is present, leading to a migration of injected fluids. Oil and gas wells plugged before 1953 used cement that often-lacked sufficient additives for proper cement setting, and many of the plugs in these older wells failed to set properly.

Thirty-nine (32.2%) of the 121 active or pending Class VI well permits received by the U.S. Environmental Protection Agency are located in the state of Louisiana. In this report we identify documented orphaned/abandoned wells in the state of Louisiana in relation to potential storage formations, and examine risk as a function of plugging date and underlying storage volume.

There are approximately 190,000 abandoned wells in Louisiana. Nearly 13% of these wells (n=23,539) were plugged prior to 1953, and ~13,000 of these wells overlie potential carbon sequestration formations, with an estimated storage capacity of anywhere between 1.25e+11–1.71e+12 metric tons of CO_2. There appears to be a hotspot of risk located at approximately 30.25° N latitude, where there is a relatively concentrated band of abandoned wells that were plugged prior to 1953. Given the expense and difficulty of conducting field campaigns to assess the presence and/or integrity of abandoned wells, initial campaigns should consider targeting this this area.

About the Authors

Dr. Rossi completed a B.S. in Civil and Environmental Engineering from Penn State in 2009 and received his Ph.D. in Geology and Environmental Science at the University of Pittsburgh in 2016. His dissertation research focused on soil biogeochemistry and how land use and human activities affect hydrologic regimes, and by extension, major and trace metal dynamics. Following the completion of his dissertation, Dr. Rossi was a visiting scholar at the University of Pittsburgh and devised a project to reconstruct the environmental legacy of industrial activities and coal-fired electricity generation in the Pittsburgh Metropolitan Area. Dr. Rossi held his first postdoctoral appointment in 2017 at Temple University, where he examined the impact of land use and green infrastructure on surface and groundwater hydrology within the Philadelphia Metropolitan Area. In 2017 Dr. Rossi was awarded a NatureNet Science Fellowship with the Nature Conservancy and conducted postdoctoral research on oxygen dynamics in agricultural soils at Stanford University. Recently, Dr. Rossi's work has examined the impact of produced water from oil and gas activities on groundwater systems.

Dr. DiGiulio is an affiliate at the Department of Civil, Environmental, and Architectural Engineering at the University of Colorado. Dr. DiGiulio completed a B.S. in environmental engineering at Temple University, a M.S. in environmental science at Drexel University, and a Ph.D. in soil, water, and environmental science at the University of Arizona. During his 31 years with the U.S. Environmental Protection Agency (EPA), he conducted research on gas flow-based subsurface remediation (soil vacuum extraction, bioventing), groundwater sampling methodology, soil-gas sampling methodology, gas permeability testing, intrusion of subsurface vapors into indoor air (vapor intrusion), subsurface methane and carbon dioxide migration (stray gas), and solute transport of contaminants in soil and groundwater including that associated with hydraulic fracturing and pits used to dispose oil and gas waste. He assisted in the development of EPA's original guidance on vapor intrusion and the EPA's Class VI Rule on geologic sequestration of carbon dioxide. While with the EPA, he routinely provided technical assistance to EPA regional offices and assisted in numerous enforcement actions. Dr. DiGiulio's work has focused on understanding the environmental impact from oil and gas development in the United States and abroad, especially in regard to surface and groundwater resources. He has served as an expert witness in litigation relevant to oil and gas development, has testified before State oil and gas commissions on proposed regulation, and has testified before Congress on the impact of oil and gas development on water resources.

Background

Supercritical carbon dioxide (CO_2) injected into geologic formations via Class VI injection wells may migrate via orphaned/abandoned wells, which can serve as vertical conduits that may rapidly transport injected brine and CO_2. Leakage of brine due to aquifer over-pressurization from injection of produced water into Class II disposal wells has already been observed in Texas (Gold, 2022) and Ohio (Harvilla, 2021a, 2021b). Leakages of brine into surface waters or Underground Sources of Drinking Water (USDWs) may introduce contaminants (e.g., heavy metals, organic compounds, radionuclides) and/or induce geochemical changes that may limit the usefulness of waters for human consumption. Similarly, an expression of CO_2 leakage at the land surface would cause a denser than air plume of gas and pose an asphyxiation hazard near buildings including residences. This would be of particular concern where abandoned wells are co-located with buildings, such as Pennsylvania, where recent work found nearly 25% of documented abandoned wells are within 100 meters (328 feet) of buildings (DiGiulio et al., 2023).

The U.S. Department of the Interior estimates there are over 3.5 million abandoned wells in the United States (U.S. Department of the Interior, 2022). This number includes oil and gas wells with no recent production (plugged, inactive, temporarily abandoned, shut-in, idle) with or without a responsible owner (orphaned). The location of many of these wells may be unknown. For example, a recent (November 2022) review of a publicly accessible database hosted by the

Pennsylvania Department of Environmental Protection (PADEP) contained 24,619 documented abandoned wells in Pennsylvania of which only 18,608 had associated geographical coordinates (DiGiulio et al., 2023). The PADEP estimates that there are approximately 200,000 abandoned oil and gas wells that remain unaccounted for in state records. Hence, in Pennsylvania, the number of undocumented abandoned wells with unknown locations exceeds the number of documented abandoned wells by almost an order of magnitude, and may be the case in other states having relatively long histories of oil and gas development (e.g., California, Texas, Louisiana).

Wells constructed prior to federal or state regulation (i.e., in the late 1800s or early 1900s) during early oil exploration pose the greatest risk because these wells are generally not documented in state records, may be relatively deep, often consisted of an open (i.e., non-cased) well bore over much of their length, and generally have inferior construction as compared to modern standards. Open holes are susceptible to cross-migration between aquifers, especially if no plug is present, leading to a migration of injected fluids into nearby USDWs. The steel casings sometimes present in early abandoned wells were often removed due to address material shortages during World War II (de Smet et al., 2021). Steel casings are the primary detectable portion of the well through magnetic surveys, thus their absence requires field campaigns to locate suspected wells.

The presence of a plug in an abandoned well does not eliminate the possibility of fluid migration however. Oil and gas wells plugged before 1953 (when the American Petroleum Institute first published plugging standards) (Calvert & Smith, 1990) were unlikely properly plugged. Prior to that, cement often lacked sufficient additives for proper cement setting in conditions experienced in oil and gas wells. As a result, the plugs in many of these older wells failed to set properly and may have experienced channeling and/or cement failure because of fluid intrusion. More recently constructed wells might also have not been plugged proper either, as bankrupt owners may have used substandard materials. Even “properly” plugged wells may contain annular spaces that could facilitate fluid movement, have well plugs that have degraded over time due to a poor cement job and/or corrosive conditions, and degrade when in contact with a CO_2 plume.

There are currently two active Class VI wells in the United States, and of the 121 active or pending Class VI well permits received by the U.S. Environmental Protection Agency (US EPA), the largest number (n=39, or 32.2%) are located in the state of Louisiana (US EPA, 2023), a state with more than a century of oil and gas development activity (Wells, 2022). The Class VI Rule requires owners/operators to determine abandoned wells within an area of review (AoR) that have been plugged in a manner that prevents the movement of CO_2 or other fluids that may endanger USDWs and to perform corrective action on wells in the AoR that may not do so (40 CFR § 146.84, 2023). Depending on the cumulative injection volume, an AoR for a Carbon Capture and Storage (CCS) project could be more than two orders of magnitude greater than that for a Class II disposal well (typically ¼ mile). In other words, the AoR for a CCS project could have a radius of 2.5 miles or more. Locating all abandoned wells within a large AoR, especially in areas having historic (i.e., early 1900s) oil and gas development will be challenging in some cases and likely infeasible in others. Here we identify documented orphaned/abandoned wells in the state of Louisiana in relation to potential storage formations, and examine risk as a function of plugging date and underlying storage volume.

Methodology

We conducted a literature review to construct a timeline of regulations concerning plugging and abandonment in the state of Louisiana. To determine the number of orphaned and/or abandoned wells (hereafter collectively referred to as “abandoned wells”) in Louisiana all oil and gas wells in the state SONRIS GIS web viewer were downloaded (Louisiana Department of Natural Resources, 2023). Next wells were classified as abandoned using the methodology in the US EPA 2022 greenhouse gas inventory (US EPA, 2022). In short, in addition to wells with “orphan” or “plugged and abandoned,” any wells with status codes such as inactive, temporarily abandoned, shut-in, dormant, and/or idle were considered to be abandoned wells. Plugged abandoned wells were further classified based on the status change date, which was assumed to be the date of abandonment/plugging. Cutoff years were determined after constructing the timeline of plugging regulations.

The extent, storage estimates, depths, and thicknesses of saline aquifers was taken from the National Carbon Sequestration Database and Geographic Information System (NATCARB) maintained by the National Energy Technology Laboratory (NETL) (NETL, 2015, 2022). However, the majority of the storage grid cells had 0 feet recorded as the depth to the top of the storage formation. We assumed 0 represented a placeholder for a lack of data, and replaced depths of “0” with “NA”, and did not consider them in our depth-based comparison. Additionally, the NATCARB data provided 4 different depth measurements; the average depth of the formation top from the land surface, the minimum depth of the formation top from the land surface, the maximum depth of the formation top from the land surface, and an updated average depth of the formation top from the land surface. We took the minimum value of these measurements and used that value as the top of the storage formation in our depth-based comparisons. We encountered similar issues for the formation thicknesses, and replaced thicknesses of “0” with “NA.” However, instead of aggregating across the 4 different thickness measurements, we chose to use the updated average thickness of the formation in our depth-based comparisons, as this column had the largest amount of data. The bottoms of storage formations were calculated by adding the formation thickness to the top depth. Wells that penetrated the storage formation were determined by seeing if the lower perforation(s) depth fell between the top and bottom depths of the storage formation.

All data analyses were conducted in R (R Core Team, 2020) and all maps were created in the sf package in R (Pebesma, 2018).

Findings

Regulation Timeline

The first oil well in Louisiana was drilled in 1901 in Jennings (Wells, 2022), 42 years after the first commercial oil well was drilled in the United States. In 1906 regulations were enacted that required abandoned wells to be plugged with drilling mud and wood (Conservation Commission of Louisiana, 1915) (**Figure 1**). In 1910 these regulations were updated to call for “well-seasoned pine wood” plugs and cement to be added to the bottom of wellbores (Conservation Commission of Louisiana, 1915). Soon after (1913), regulations required surface casing to be cemented to the well bore (Conservation Commission of Louisiana, 1915). Seven years later, regulations mention that cement plugs may be used (Conservation Commission of Louisiana, 1920), and cement plugs were not required until the issuance of Statewide Order 29 in 1941 (State-Wide Order Number 29, 1941), which was revised in 1943 (State-Wide Order Number 29-B, 1943) and eventually incorporated into the Louisiana Administrative Code (La. Admin. Code Tit. 43 § XIX-137, 2015). Thus, abandoned wells in Louisiana appear to have been plugged with cement twelve years prior to the American Petroleum Institute (API) issuing standards for plugging cement (**Figure 1**).

Well Counts

A total of 245,322 oil and gas wells were downloaded from SONRIS. After using the US EPA methodology, 186,618 wells were classified as abandoned, and approximately 85% of these wells (n=158,457) are plugged. Five wells had incorrect coordinates that we were unable to correct with the available data and were dropped from further analysis. The final count of

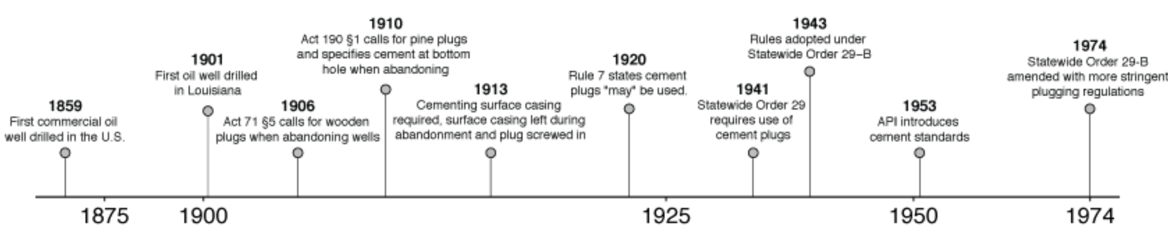

Figure 1. Timeline of well construction and abandonment regulations. Note: x axis is not to scale.

wells considered in our analysis is 186,613, approximately 76% of the oil and gas wells in the SONRIS database. These wells span the entire state of Louisiana and are present in all of the parishes having Class VI well permits (Figure 2a). A total of 120,715 abandoned wells overlie potential CCS formations (Figure 2b).

The recently released Upstream dataset has far fewer wells directly classified as abandoned as compared to our dataset (3,372 as compared to 186,618). This discrepancy likely stems from a difference in terminology — if the count of abandoned wells is considered to be wells that are labeled as non-producing, the count of abandoned wells in the Upstream dataset increases to 196,026, roughly 9,400 more wells than in our dataset. Conversely, our dataset contains more plugged abandoned wells (n=158,457) than the Upstream dataset (n=147,757). The difference between the count of plugged abandoned wells in the Upstream dataset and our dataset is 4.4% of the total wells in SONRIS dataset. Each dataset appears to have plugged wells that are unique to it, for example there are 11,654 wells that we classified as plugged, that have not been classified as plugged in the Upstream database. There are only 454 plugged abandoned wells in the Upstream dataset that are not in our plugged dataset.

Of the 186,613 abandoned wells we identified, 4,567 were classified by the state of Louisiana as orphaned.[1] This count generally agrees with recent counts reported by Boutot et al. (2022) (n=4,588), and Grove & Merrill (2022) (n=4,484). However, our count of orphan wells (n=4,567) is higher than the count (n=4,178) in the recently released Upstream database (The Capitol Forum, 2023). Despite our dataset containing 389 more orphan wells than the Upstream dataset, there are a total of 78 wells classified as orphaned by Upstream that are not classified as orphaned in our dataset. Of these 78 wells, 17 are not in our dataset of abandoned wells, but they are present in the SONRIS dataset. Sixteen of the 17 wells were not included in our dataset because they were reported as active in the SONRIS dataset and thus eliminated by

[1] Orphan wells are oil and gas wells which lack a responsible party (i.e., owner).

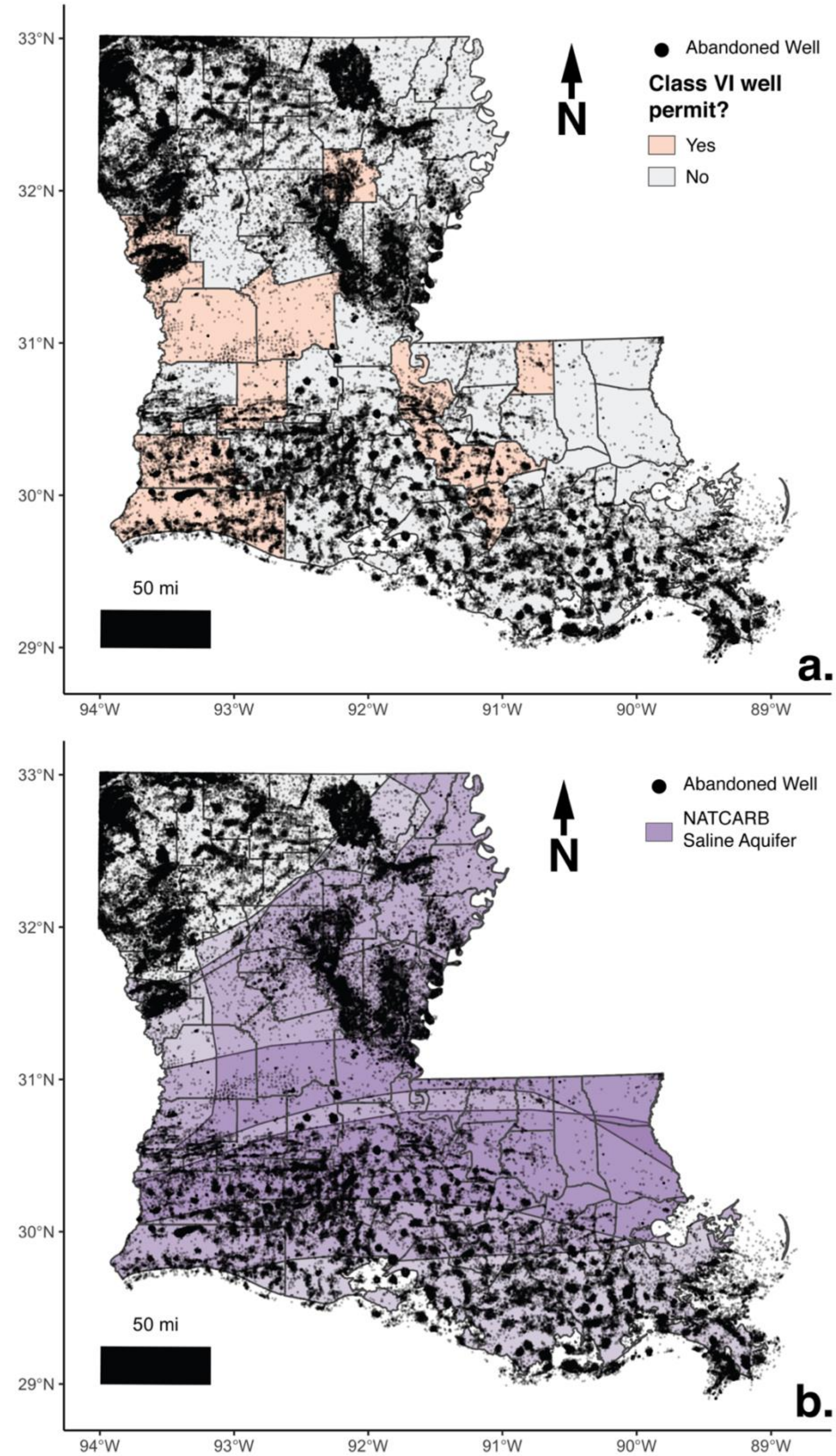

Figure 2. Locations of abandoned wells in the SONRIS database in relation to parishes with pending or active Class VI well permits (US EPA, 2023) (a), and NATCARB saline aquifers (NETL, 2015) (b).

our filtering methodology. The remaining one well has an “unknown” status, which we assumed indicated poor data quality and did not include in our analysis.

In general, the difference in the counts of orphaned wells in these two datasets likely stems from Upstream cross-referencing ownership and production records with the SONRIS well dataset. Our study did not perform such a cross-referencing. Given that the difference between the two orphaned well datasets represent 0.16% of the wells in the SONRIS data, our overestimate likely has a negligible effect on estimating risk. Likewise, while differences between the plugged well datasets are relatively more pronounced (i.e., our data set has an additional 11,200 plugged abandoned wells as compared to the Upstream dataset), given their equal spatial distribution across the state, and the fact that the difference constitutes less then 5% of the total wells in the SONRIS dataset, these differences are unlikely to significantly affect risk estimates.

Plugged Abandoned Wells

Given the wide distribution of abandoned well locations, we attempted to further highlight abandoned wells that penetrated proposed CCS formations. However, in general, abandoned wells in the SONRIS database had little data pertaining to producing formation and/or perforation depths. Specifically, every well lacked data regarding the producing formation. While the name of driller’s sands was recorded in some wells (38.9%), these lacked a standardized nomenclature, and comparison with saline aquifers was not possible. Only 53.5% of abandoned wells had the perforation depths recorded, and we conducted depth-based comparisons on this subset of wells. There are 1,200 abandoned wells that penetrate[2] potential CCS formations, 896 of which have perforations[3] within potential CCS formations (**Figure 3**). Of wells that penetrate potential CCS formations, 297 are unplugged, and 15 wells were plugged prior to 1953. There

[2] Penetrate means the wellbore is drilled through a potential CCS formation.
[3] Perforations are holes made in a well liner or casing allowing oil and/or gas from the producing formation(s) to flow into the well.

are similar numbers of wells that have perforations within potential CCS formations; 178 wells are unplugged, and 15 wells were plugged prior to 1953. Because every abandoned well had a date associated with its status change, we chose to use the plug date as a way to further explore spatial patterns of abandoned wells, and constrain potential fluid migration risk in areas having estimated CO_2 storage potential.

Spatial Distribution of Pre-API Standards Plugged Wells

Given the reliance of early plugging regulations on inferior materials (i.e., wood), wells plugged prior to the requirement of cement plugs are particularly concerning from the lens of leakage pathways. Wells abandoned prior to 1906 were assumed to have minimal plugs, if any.

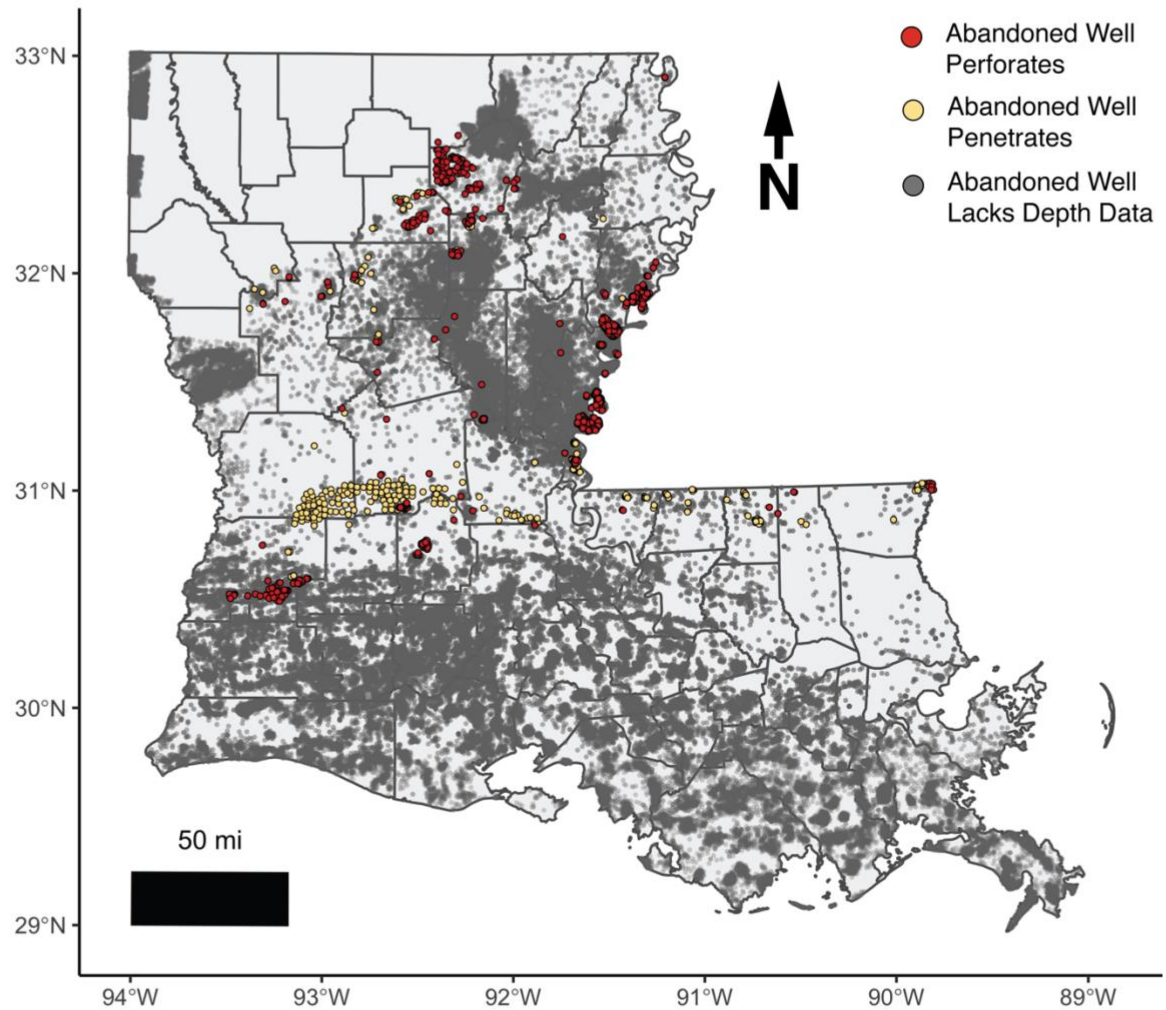

Figure 3. Abandoned wells that penetrate and perforate storage formations. Note, only abandoned wells that overlie potential storage formations are shown.

These wells appear to be very rare in the SONRIS dataset, as only two wells in our dataset have plug dates prior to 1906 (Figure 4). While cement plugs were optional starting in 1920, it is unclear how many wells abandoned at this time utilized cement plugs rather than wood plugs. As such, we assume any well plugged after 1906 and prior to 1941 were plugged with wood. While this likely overestimates the number of wells utilizing wood plugs, it also provides a conservative estimate for constraining risk. In total we found that 15,163 wells were plugged prior to 1941, 7,256 (47.8%) of which overlie saline aquifers (Figure 4). Between 1941 and 1953 8,375 wells were plugged with cement, albeit before the API published oilfield cement specifications, 5,979 of which overlie saline aquifers (Figure 4).

In general, wells plugged prior to 1941 are located across the state, but appear to be relatively more concentrated in northwestern Louisiana, an area generally not underlain by potential storage aquifers (Figure 5). Wells plugged with cement prior to 1953 (n=23,539) (i.e., before API oil well cement specifications) are also broadly located across the state, but there appear to be a relatively larger number of these wells that are underlain by saline aquifers as opposed to wells plugged prior to 1941 (Figure 5). Thus, there are a total of 13,235 wells in Louisiana that overlie potential CCS formations, and were plugged prior to modern cementing standards.

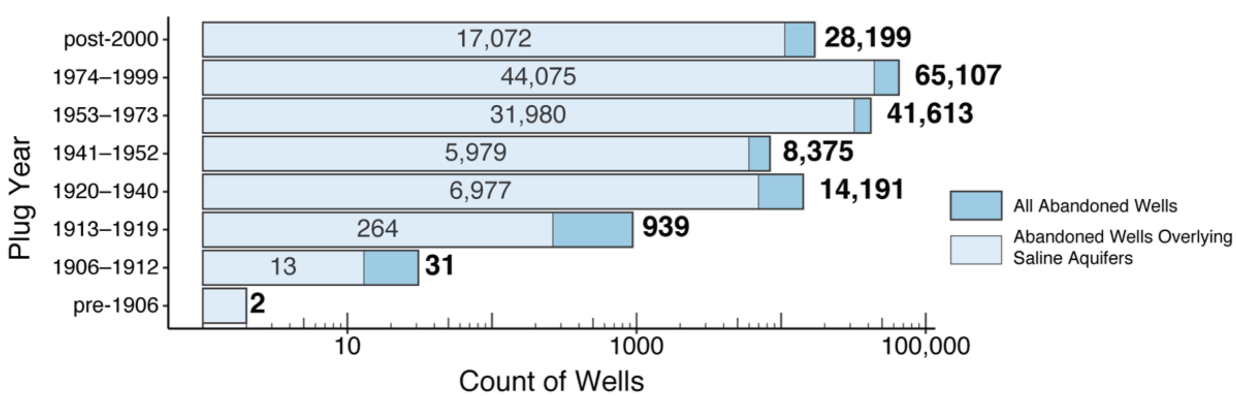

Figure 4. Count of plugged abandoned wells by plug age. Bold numbers are the total count of wells for each group, and numbers within bars indicate the count of wells overlying saline aquifers.

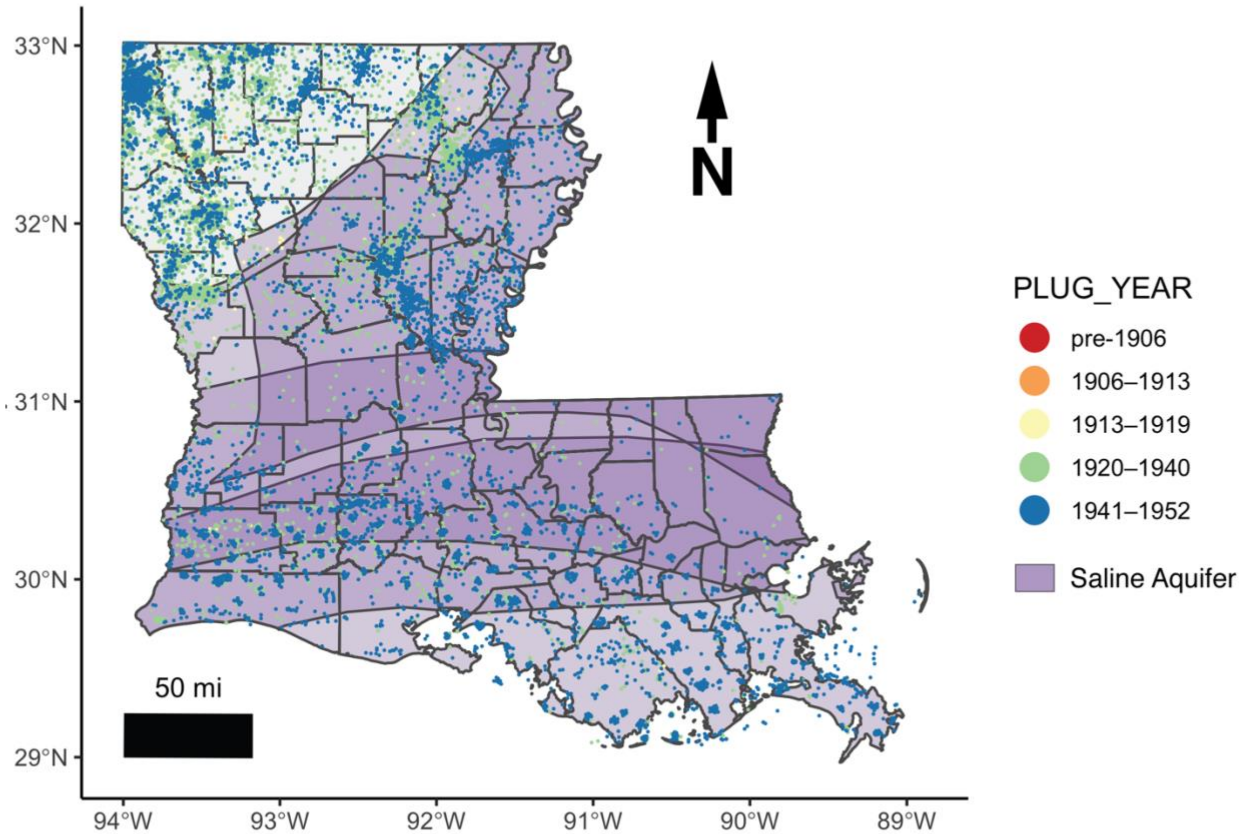

Figure 5. Locations of abandoned wells plugged prior to 1953. Wells plugged prior to 1941 likely did not have cement plugs.

There appears to be relatively little depth data related to plugged wells. Specifically, only 40% (n=74,613) of plugged abandoned wells have recorded perforation depths, and ~7.3% of abandoned wells plugged prior to 1953 (n=1,720) have recorded perforation depths. Given the age of many of these plugs, and the relatively scant amount of data concerning perforation depths, appraising plug integrity may be very difficult if not impossible.

Storage Volume Underlying Abandoned Wells

According the March 2022 storage estimates in the NATCARB database, abandoned wells in the state of Louisiana overlie an estimated storage capacity of anywhere between 1.96e+11–2.68e+12 metric tons. This total estimated storage volume underlying all abandoned wells can be further broken down into 5.69e+10–7.81e+11 metric tons underlying orphan wells and 1.95e+11–2.67e+12 metric tons underlying plugged abandoned wells (**Table 1**). Abandoned wells plugged prior to 1953 overlie an estimated storage capacity of anywhere

Table 1. Estimated storage volume (in million metric tons) of NATCARB 10 km grid cells (NETL, 2022) underlying abandoned wells.

Well Type	Estimated volume per group (million metric tons)		
	low	*medium*	*high*
Plugged Abandoned Wells			
pre-1906	240	1170	3300
1906–1913	362	1760	4980
1913–1919	4810	23,400	66200
1920–1940	73,000	355,000	1,000,000
1941–1952	108,000	526,000	1,490,000
1953–1973	159,000	772,000	2,180,000
1974–1999	172,000	833,000	2,350,000
post-2000	133,000	648,000	1,830,000
Total	**195,000**	**945,000**	**2,670,000**
Orphan Wells			
	56,900	276,000	781,000
All Abandoned Wells			
	196,000	948,000	2,680,000

between 1.25e+11–1.71e+12 metric tons, approximately 64% of the estimated storage capacity underlying all abandoned wells.

Recommendations

In the Class VI Rule, an owner/operator must: (1) identify all penetrations (including active/abandoned wells and underground mines) in the AoR that may penetrate the confining zone(s) and provide a description of each well's type, construction, date drilled, location, depth, record of plugging and/or completion (40 CFR § 146.84, 2023). However, this basic information is lacking for a large number of abandoned wells (especially those plugged prior to the modern cementing standards instituted in 1953) and the locations of a number of abandoned wells are likely unknown. To fully constrain the risk of the migration of injected fluids the locations of unknown wells should be resolved.

Given that the approximately 190,000 abandoned wells in Louisiana are distributed across the state, it would be exceedingly difficult and time intensive to mount a statewide field campaign to locate all unknown abandoned wells. One strategy may be to identify hotspots of risk, and conduct targeted field campaigns therein. One such area appears to be located at approximately 30.25° N latitude. In particular, at this latitude there is a concentrated band of plugged abandoned wells, many of which have been plugged prior to modern standards (**Figure 5**), that overlie a relatively large estimated storage volume (**Figure 6**). As resources permit, targeted field campaigns should be conducted in this general region to determine if wells with unknown locations are present.

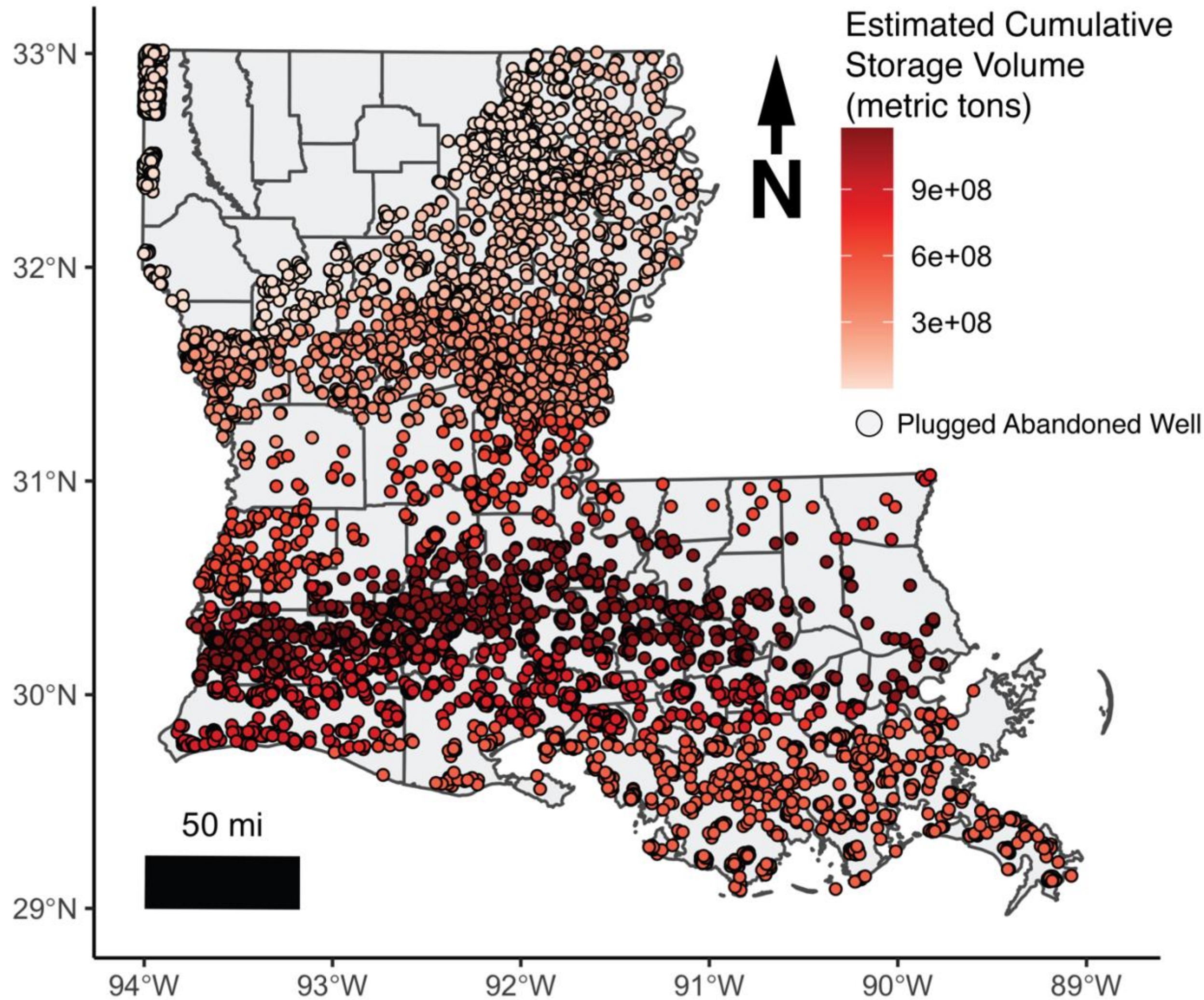

Figure 6. Locations of abandoned wells plugged prior to modern standards (1953). The color of each point indicates the estimated storage volume of the 10 km (6.21 mile) grid cell underlying the well according to the NATCARB medium storage estimates (NETL, 2022).

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