Groundwater

Commingled Fluids in Abandoned Boreholes: Proximity Analysis of a Hidden Liability

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Abstract

The interactions between old abandoned wellbores of suspect well integrity with hydraulic fracturing (HF), enhanced oil recovery (EOR), or salt water disposal (SWD) operations can result in upward leakage of deep aqueous liquids into overlying aquifers. This potential for upward fluid migration is largely unquantified as monitoring abandoned wells is rarely done, and leakage may go unnoticed especially when in deeper aquifers. This study performs a proximity analysis between old abandoned wells and HF, EOR, and SWD wells, and identifies commingled old abandoned wellbores, which are those wells where groundwater may flow from one aquifer to one or more other aquifers, to identify the locations with the greatest potential for upward aqueous fluid migration at three study sites in the Western Canadian Sedimentary Basin. Our analysis indicates that at all three study sites there are several locations where HF, EOR, or SWD operations are located in close proximity to a given old abandoned well. Much of this overlap occurs in formations above typically produced hydrocarbon reservoirs but below exploited potable aquifers, otherwise known as the intermediate zone, which is often connected between abandonment plugs in old abandoned wells. Information on the intermediate zone is often lacking, and this study suggests that unanticipated alterations to groundwater flow systems within the intermediate zone may be occurring. Results indicate the need for more field-based research on the intermediate zone.

Introduction

Upward leakage of deep fluids through wellbores can result in the contamination of aquifers (Lyverse and Unthank 1988; Jacobs 2009), the release of greenhouse gases into the atmosphere (Kang et al. 2014), and in some cases an explosive hazard for overlying structures (Chilingar and Endres 2005). The possibility of upward leakage is pervasive in many of the globe's older oil and gas producing regions (Davies et al. 2014), with millions of oil and gas wells having been drilled within North America alone (Kang et al. 2016). Wells drilled before the late to mid twentieth century mostly targeted porous and permeable conventional formations (Zou et al. 2015). As early as the late nineteenth century, some of the initially produced conventional hydrocarbon reservoirs were depleted and enhanced oil recovery (EOR) methods such as waterflooding were used to continue production (Fettke 1929; Satter et al. 2008). More recently, in locations with lower reservoir permeability, high volume hydraulic fracturing (HF) has been used to increase oil and gas production. Saltwater disposal (SWD) of excess production water, or HF flowback fluids may also be injected into porous and permeable formations within or near oil and gas reservoirs. EOR, HF, and SWD methods result in increased pressurization of the targeted reservoir. This increased pressurization can lead to the upward movement of reservoir fluids through existing permeable faults or fracture zones, with the potential to reach shallow aquifers especially where the fractured formation is at shallow depth (Dockrill and Shipton 2010; Flewelling et al. 2013; Birdsell et al. 2015). Leaky wellbores present another potential pathway for vertical fluid migration in the subsurface. Should an inadequately sealed wellbore be located in close proximity to a stimulated formation, fluid flow may be induced through the wellbore resulting in cross-formational flow, which could also impact potable or brackish groundwater aquifers (Jacobs 2009; Darrah et al. 2014; Digiulio and Jackson 2016; Sherwood et al. 2016; Pollack et al. 2020).

The potential that an inadequately sealed wellbore could result in the cross-formational flow of groundwater and associated solutes predicated many of the early oil and gas well construction regulations in the United States

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and Canada (Pettyjohn 1971; Gass et al. 1977). Over time, knowledge gained about the causes of pollution led to improvement in well construction regulations, while better well construction practices also reduced the potential for aquifer contamination and probability of oil and gas well integrity failure (King and King 2013). Modern oil and gas wells are less likely to leak, however hundreds of thousands of older oil and gas wells in the United States and Canada were previously constructed and abandoned under less rigorous regulations and using inferior well construction practices (Richter et al. 1991). Recent studies on the integrity of old abandoned oil and gas wells have largely focused on potential impacts from carbon sequestration and HF (e.g., Watson and Bachu 2008; Dilmore et al. 2015; Carroll et al. 2016). The possibility of contaminating potable and brackish aquifers by conventional oil and gas production from wells have also been recognized (McIntosh and Ferguson 2019). While active or suspended wells can be monitored for signs of leakage, well integrity failure of abandoned wells is typically only noted in a limited number of cases where aqueous fluids reach the surface or shallow aquifers (e.g., Chilingar and Endres 2005; Jacobs 2009). It is not currently known, with a great degree of confidence, how many abandoned wells could be leaking at depths below that which is typically monitored and/or away from sparsely spread observation wells (Davies et al. 2014; Kang et al. 2016; McIntosh and Ferguson 2019; Wisen et al. 2020). This uncertainty is greatest in the intermediate zone below typically utilized potable aquifers but above historically targeted oil and gas reservoirs (Jackson et al. 2013; Council of Canadian Academies 2014; Dusseault and Jackson 2014). While the intermediate zone is not widely utilized outside of the oil and gas industry in Alberta and Saskatchewan, in Alberta and Saskatchewan there are concerns about the availability of fresh surface water to meet demand (Pernitsky and Guy 2010; Tanzeeba and Gan 2012). This future demand may lead to wider utilization of intermediate zone aquifers (e.g., Kang and Jackson 2016; Stanton et al. 2017) hence the need to investigate the potential occurrence of leakage at depth.

To investigate the occurrence of abandoned wells leaking at depth, the distribution of wells and their conditions must be identified, along with drivers of fluid flow. Many sedimentary basins around the world have old abandoned wells and ongoing oil and gas production that could be investigated; however the Western Canadian Sedimentary Basin (WCSB), specifically the provinces of Alberta and Saskatchewan, is one of the few locations with detailed records of nearly all drilled oil and gas wells (Breen 1993; Gasda et al. 2004). Such a complete record allows for an analysis of the potential for aqueous fluids to migrate upwards to brackish and potable aquifers through pre-1960s legacy oil and gas wells due to increased fluid pressurization caused by HF, EOR, and/or SWD operations or differences in fluid pressures between aquifer units. Here, this study aims to: (1) assess the potential for upward migration of brines and liquid hydrocarbons through legacy oil and gas wells due to the pressure produced from nearby HF, EOR, and SWD activities; (2) explore the potential that such aqueous fluids could be exchanged between different aquifer units through a review of well construction and abandonment records (tour reports); and (3) determine the degree to which wellbores open to multiple aquifers (commingled wellbore) may reduce the effective permeability of intervening aquitards. The probability of aquifer contamination is expected to be greatest where abandoned wells are drilled into or though formations where EOR, HF, and/or SWD has occurred (Gasda et al. 2004). This study will contribute to the understanding of how brackish and potable aquifers could be affected by legacy abandoned wells, identify some locations where upward leakage may be greatest, and help determine if current regulations adequately protect groundwater resources.

Geologic Setting

The WCSB is comprised of two sedimentary basins: the Williston Basin in the southeast corner and the Alberta Basin along the western edge (Figure 1). The Alberta Basin is monocline shaped and is filled with a wedge of Phanerozoic strata above Precambrian Bedrock. The Alberta Basin ranges in thickness from 0 m at the Canadian Shield to a maximum approximate thickness of 6000 m at the fold and thrust belt (Wright et al. 1994). The Williston Basin is also a Phanerozoic basin but has more of an irregular bowl shape and is shallower, with a maximum approximate thickness of 4875 m (Gerhard et al. 1982). Two of the study sites, the Redwater and Pembina areas, are located in the Alberta Basin, while the Southeast Saskatchewan study site is within the Williston Basin.

In the Pembina study area, hydrocarbons are primarily hosted in the sandstone units within and adjacent to the source rock shales of the Cretaceous aged Colorado Group, with production primarily occurring within the Cardium Formation and some production from the Lower Cretaceous aged Mannville Group (Michael and Bachu 2001). In the Redwater study area, hydrocarbons are typically produced from the Cretaceous aged Viking and Devonian aged Leduc formations with some production also from the Mannville Group (Schoenfeld et al. 2010; Bachu et al. 2011). In the Saskatchewan study area, oil production largely occurs in the Mississippian aged formations such as the Midale Beds and Bakken Formation (Verma and Henry 2004). At the three study sites, aquifers generally consisting of porous carbonate and sandstone formations are separated by regionally extensive shale aquitards and/or evaporitic aquicludes, with the massive shale aquitards of the Colorado Group capping all three sites (Bachu and Stewart 2002). The formations previously mentioned above, that are the target of HF, EOR, or saltwater disposal operations, are indicated with stars in Figure 2.

Within each study area, intermediate zone aquifers are located above the traditionally produced oil and gas reservoirs. These intermediate zone aquifers have total dissolved solid (TDS) concentrations that range from

Figure 1. General overview map of the three study site locations. The red, green, and orange outlines indicate the locations of the Pembina, Redwater, and Southeast Saskatchewan study sites, respectively.

1000 to 100,000 mg/L. The fresh (TDS <3000 mg/L), and brackish (TDS 3000–10,000 mg/L) intermediate zone aquifers currently see some use by domestic water wells (Ferris et al. 2017). In the Pembina study area intermediate zone aquifers include the Wapiti (TDS 7000–10,000 mg/L; Nakevska et al. 2015). In the Redwater study area intermediate zone aquifers include the Belly River (TDS 1000–2000 mg/L; Nakevska et al. 2015), Viking, and Mannville Group aquifers (TDS 40000–100,000 mg/L; Bachu et al. 2011). The intermediate zone aquifers with geochemical data available in the Southeast Saskatchewan study area include the Newcastle (TDS 3000–45,000 mg/L; Palombi 2008), and Mannville Group aquifers (TDS 3000–77,000 mg/L; Palombi 2008). There is no data available for the Belly River aquifer in the study area but to the northwest, where it is more commonly used as a potable water supply, it has TDS ranging from 950 to 4160 mg/L (Ferris et al. 2017). Underlying oil and gas reservoirs typically have increasing TDS with depth, up to about 300,000 mg/L for the Bakken Aquifer (Palombi 2008). EOR, HF, and SWD may locally alter groundwater quality from background concentrations by injection of fluids of different salinities (Jellicoe et al. 2021).

Abandoned Well Integrity and Upward Hydraulic Gradients

Reviewing the history of well regulations and well construction technology provides an estimated date before which wells abandoned would likely have appreciably worse integrity than wells abandoned after. A review of available information regarding well regulations and well construction technology in Saskatchewan and Alberta as well as the impacts of well integrity failure on regional aquifer systems can be found in Section S1 of the Supporting Information. This review concluded that old wells abandoned before January 1, 1960 in the WCSB could be expected to have worse integrity than those abandoned after, potentially leading to cross-formational flow between aquifer units over large sections of the borehole. However, in order for failed integrity to allow for migration of aqueous fluids to potable and brackish aquifers there needs to be an upward vertical hydraulic gradient to overlying aquifer units. HF, EOR, and SWD can provide the necessary pressurization to induce an upward hydraulic gradient (McIntosh and Ferguson 2019), which can induce the transfer of native pore-fluids between aquifer units and if located within the injected plume may also result in the transport of injected fluids. Furthermore, North America has seen a 10-fold increase in HF wellbores since 2000 (Weijers et al. 2019), along with an increase in the size of laterals and number of wells completed with multistage HF in Alberta (Lucas et al. 2014), and a steady increase in EOR/SWD wells in the WCSB over the same period (Atkinson et al. 2016).

By exploring the spatial relationships between wells abandoned before 1960 and HF, EOR, and SWD wells completed after 2000, the well populations where upward migration of aqueous fluids is possible can be identified. Such spatial proximity studies between a vulnerable well population and oil and gas production activity have been completed in the United States (e.g., Jasechko and Perrone 2017) and in particular Texas (e.g., Brownlow et al. 2017), Pennsylvania (e.g., Dilmore et al. 2015), and New York (Montague and Pinder 2015), but in Canada such studies have mainly focused on geologic carbon sequestration (e.g., Celia et al. 2011). Furthermore, these studies on oil and gas production activities contemplated

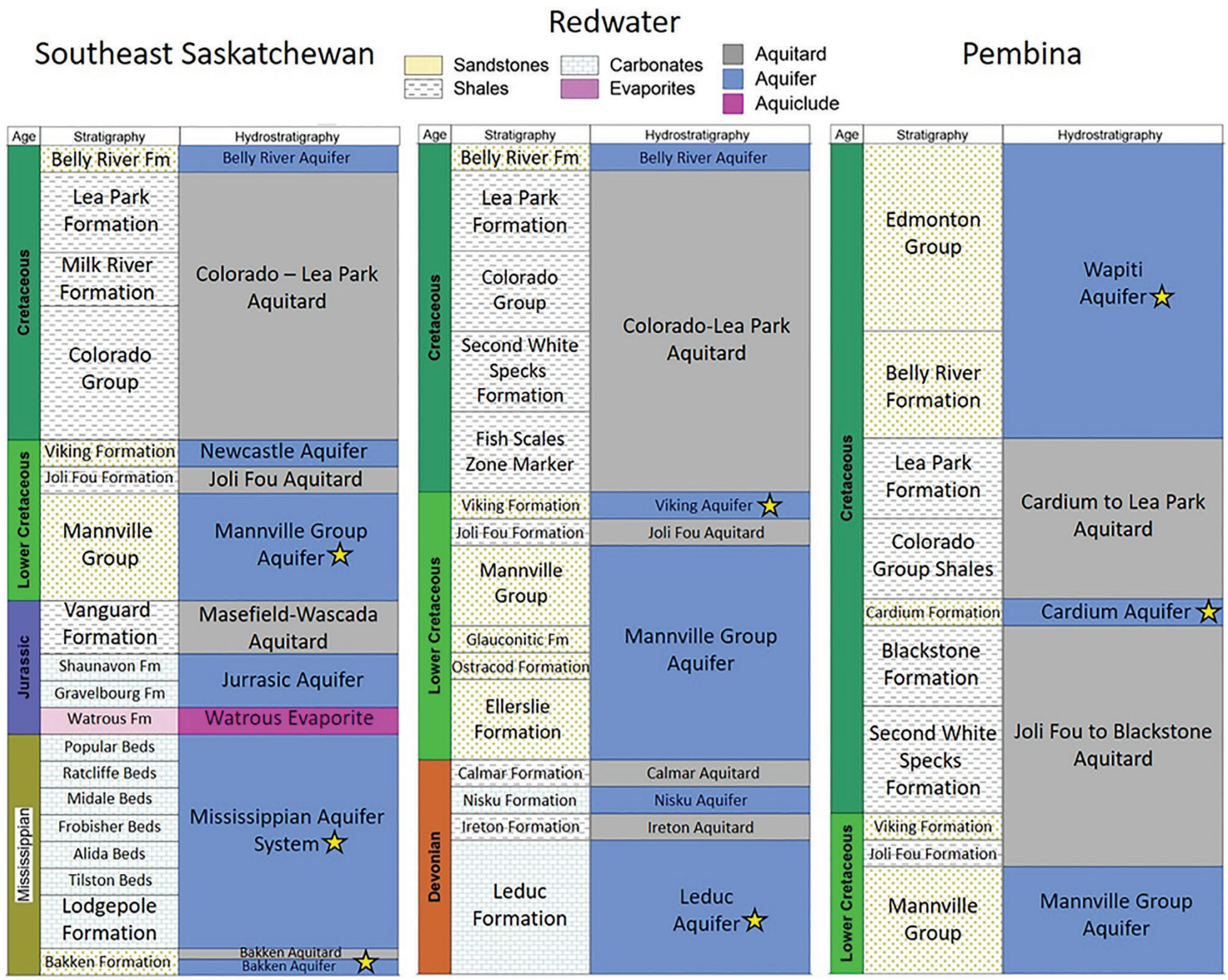

Figure 2. Simplified stratigraphic and hydrostratigraphic columns for the Southeast Saskatchewan, Redwater, and Pembina study areas. The columns are modified from Jensen et al. (2013), Brydie et al. (2011), and Dashtgard et al. (2008) for the Saskatchewan, Redwater, and Pembina study areas, respectively.

the potential for HF wells to communicate with nearby abandoned wells (frac hit) and did not include a spatial analysis on EOR/SWD wells. While the pre-1960 abandoned wells may be more vulnerable to well integrity failure, many wells may still maintain their integrity. For these wells, well construction and plug placement can still leave some formations connected within the wellbore. Information regarding old commingled wellbores is not readily available in an electronic format in Canada, but can be compiled from existing written records. This information can help identify formations that are susceptible to cross-formational flow within the wellbore.

Methods

Spatial Analysis

Accumap V29.05 (IHS Energy 2019) was used to download the records for all oil, gas, EOR and SWD, and abandoned wells located within the study areas (Figure 1) that were drilled before 1960 or had produced or injected fluids after 2000. The downloaded database includes information such as the well's surface and bottom hole locations, unique well identifier (UWI), type (oil, gas, etc.), spud and abandonment dates, depth, well construction details (when available), and the deepest formation the well was drilled into.

To investigate the spatial relationships between the three population groups: wells abandoned before 1960 and wells that have been HF or used for EOR/SWD after 2000, data preprocessing was required. Wells were split into the three population groups for each study area, each well population was further categorized by depth and formation, and some discrepancies in the data such as the number of identified abandoned wells were identified and remedied. For the proximity analysis of hydraulic fracturing wells, the HF formations included in the analysis are the Bakken, Cardium, and Viking formations (Figure 2) for the Southeast Saskatchewan, Pembina, and Redwater study areas, respectively. For the HF analysis, abandoned wells were further categorized into four different categories depending on the abandoned well's position in relation to the identified HF formation for a given study area. The four groups were divided to provide distinction between the differences in probability that a HF well may cause a frac hit on nearby abandoned wellbores of different depths (Davies et al. 2012) through the transmission of pressure and sometimes proppant (King et al. 2017). A more detailed rational for the four well groupings, are provided in Section S2.2. The four abandoned well groups are:

- Category 1: drilled into or below the HF Formation.
- Category 2: drilled to within 150 m above the Formation.
- Category 3: drilled to within 350 m above the Formation.
- Category 4: drilled to a depth that is greater than 350 m above the Formation.

The HF target formations studied here are the Bakken, Cardium, and Viking formations (Figure 2) for the Southeast Saskatchewan, Pembina, and Redwater study areas, respectively.

Distance between each abandoned well grouping and the identified HF wells were analyzed through a proximity analysis for each study area using ArcGIS 10 Model-Builder (Environmental Systems Research Institute 2018). The search distance used for the proximity analysis was double the estimated average hydraulic fracture half-length for each study area; 350 m for the Redwater study area, 625 m for the Pembina, and 700 m for Southeast Saskatchewan. These estimated values are within the range of reported values from studies documenting frac hits to offset producers (Ajani and Kelkar 2012; Watson 2013; Alberta Energy Regulator 2016; Bommer et al. 2017; Lefebvre 2017). The proximity analysis between EOR/SWD wells and abandoned wells was similar to that between HF and abandoned wells. The main distinctions between the two is only old abandoned wells that are completed into or pass through the injected formation are included, and a 2 km proximity distance is used based on estimation of pressure increases using a Cooper-Jacob approximation for EOR/SWD wells using expected parameter values (Table S2). The density of HF or EOR/SWD wells that were identified within the specified proximity distance of a nearby abandoned well was calculated using a kernel density estimation method (Silverman 1986). With an increase in the density of nearby HF or EOR/SWD wells to a given abandoned well, there is expected to be a resultant increase in fluid pressurization. For the proximity analysis of HF wells, category 1 wells are most likely to be impacted by increased fluid pressurization, with each subsequent category having a decreased likelihood. To explore the potential impact of setting a younger or older date of abandonment (cutoff date) for abandoned wells, a sensitivity analysis on the spatial analyses was also performed using additional abandoned well cutoff dates of 1955 and 1965. Further information on data preprocessing, the spatial analysis between HF, EOR/SWD, and old abandoned wells is available in Sections S2.1-S2.3, respectively.

Review of Abandonment Reports

To better understand the vulnerability of old abandoned wells to inter-borehole flow, tour and/or completion reports were reviewed for a subset of abandoned wells that were identified as being located near an EOR/SWD well. Tour reports provide information on the daily operations taking place at the wellsite, while completion reports provide an overview of how the well was constructed or abandoned. Both reports are submitted to the respective regulatory authority by the well licensee. Tour reports were reviewed to identify which aquifer units were left uncased and connected between plugs (commingled), and behind uncemented casing (Section S2.4). Inter-borehole flow could be expected to occur where commingled fully penetrating legacy wells are located near HF or EOR/SWD, which would create strong vertical hydraulic gradients between adjacent aquifer units in most cases (e.g., Energy Resources Conservation Board 2012). If the density of abandoned wells with the same formations commingled together approaches 1/km^2 over a given area then the commingled boreholes effect on any intervening aquitards' averaged (effective) vertical permeability could be significant (Hart et al. 2006). While the permeability of an open section of a borehole would be very high, the permeability of a plugged section or individual cement barrier elements, such as an abandonment plug, or annular cement, of a borehole has been measured to range between that of unfractured crystalline bedrock (10^{-21} m^2) to clean sand (10^{-12} m^2) (Table S3; Freeze and Cherry 1979). The change in effective vertical permeability (k_e) of a material with a lower permeability (k_m) crossed by a series of parallel vertical pipes of permeability (k_1) is described by a formula developed by Rayleigh (1892) and presented by Pietrak and Wiśniewski (2015):

$$k_e = k_m[1 + (k_1 - k_m) / k_m)\phi], \tag{1}$$

where ϕ is the fraction of the horizontal area of the media occupied by the pipes. k_m is examined over a range of prescribed and measured values for annular wellbore cement of active wells and plugged abandoned wells (Table S3). The case of a rigid uncased hole with an incompressible fluid is also considered by using the Hagen-Poiseuille equation to estimate k_1;

$$k_1 = r^2/8, \tag{2}$$

where r is the radius of the wellbore. The Hagen-Poiseuille equation provides an upper limit estimate of permeability for an idealized setting. Some uncased boreholes that pass through shale caprocks may become mostly to partially sealed due to shale creep (shearing due to in situ stresses) or sloughing (Nicot 2009). We consider k_m over the range from 10^{-20} to 10^{-16} m^2, which covers much of the observed range for intact shales and clays (Neuzil 1994) and is likely representative of Colorado

Group Shales (Neuzil 1994). The range of abandoned well densities (ϕ) present within the three study sites are also examined.

Results

Oil and Gas Well Data Overview

Each study area has substantial differences in the number and type of oil and gas-related wells present as of 2019 (Table S4). Total well counts for each study area range from 41,747 for Southeast Saskatchewan to 5223 for the Redwater study area. These substantial differences in total well counts are also reflected in the total number of abandoned wells; however, the relative proportion of abandoned wells to total well count is similar between the study areas. Some other notable differences between the study areas are a low number of EOR/SWD wells in the Redwater study area, a high number of HF wells in the Pembina area, and a high number of horizontal wells in Southeast Saskatchewan. Table S5 lists the number of wells for the three well types used in the spatial analysis: wells fractured after January 1, 2000, wells that were injecting any time after January 1, 2000, and wells abandoned before January 1, 1960. The Pembina study area has over three times the number of wells fractured after 2000 as the other two study areas, likely owing to the Pembina Field being one of the first locations where HF was first used in Canada (Stevens et al. 1959). The Redwater study area has 10 times fewer wells injecting after 2000 than the other two study areas, potentially attributable to the small size of the Redwater study area. The maturity and high permeability of the conventional Leduc Formation (Figure 2) may also contribute to the lower EOR/SWD well density by allowing for reservoir pressure maintenance to be achieved with only a few EOR/SWD wells injecting at high rates (Singhal 2009; Bachu et al. 2011). The Southeast Saskatchewan study area has over twice as many wells abandoned before 1960 as the other two study areas, which could partly be due to the overall size of the Southeast Saskatchewan study area, which is about a fourth larger than the Pembina study area and about six times bigger than the Redwater study area.

Abandoned Wells Near EOR/SWD Wels

For the proximity analysis of EOR/SWD and old abandoned wells, both well types were identified if they were within 2 km of each other. The three case study areas display distinct differences in the number of both abandoned and EOR/SWD wells identified, as well as their distributions around the study area (Figure 3). The Southeast Saskatchewan study area has the highest number of EOR/SWD wells and abandoned wells with 476 and 297 wells, respectively. These wells are dispersed across the study area with several areas containing high densities of both well types. In Figure 3 a calculated kernel density of more than 0.25 is depicted with orange and typically indicates that greater than seven EOR/SWD wells are located within close proximity to each other.

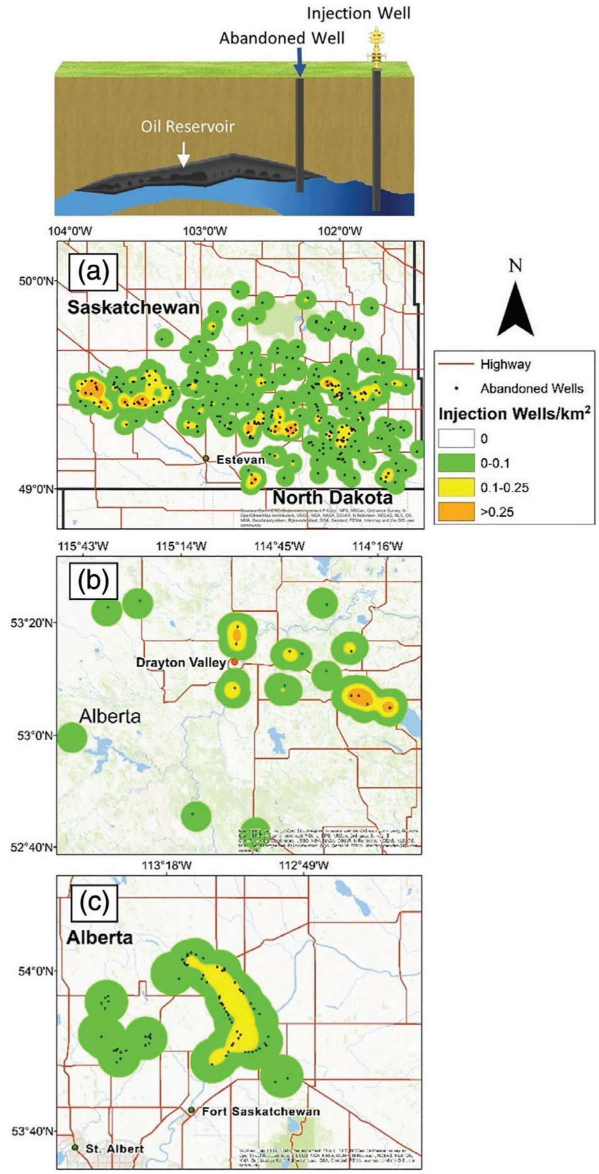

Figure 3. Density of EOR/SWD wells that are located nearby (within 2 km of) pre-1960 abandoned wells for (a) Southeast Saskatchewan, (b) Pembina Field, and (c) Redwater.

The Pembina study area, by contrast, has 73 EOR/SWD wells and only 17 abandoned wells identified. Within the Pembina study area there are locations where the EOR/SWD wells are clustered together, but the identified abandoned wells are dispersed uniformly throughout. The Redwater study area has well counts roughly opposite that of the Pembina Study area with 41 EOR/SWD wells and 71 abandoned wells identified. Rather than being dispersed throughout the study area, these wells are concentrated along a 50 km transect along the Redwater Reef. Decreasing the cutoff date of the abandoned wells included in the spatial analysis generally results in a decrease in the amount of EOR/SWD wells that are in close proximity to old abandoned wells, while increasing the cutoff date of the abandoned wells generally results in an increase (Figures S15 and S16).

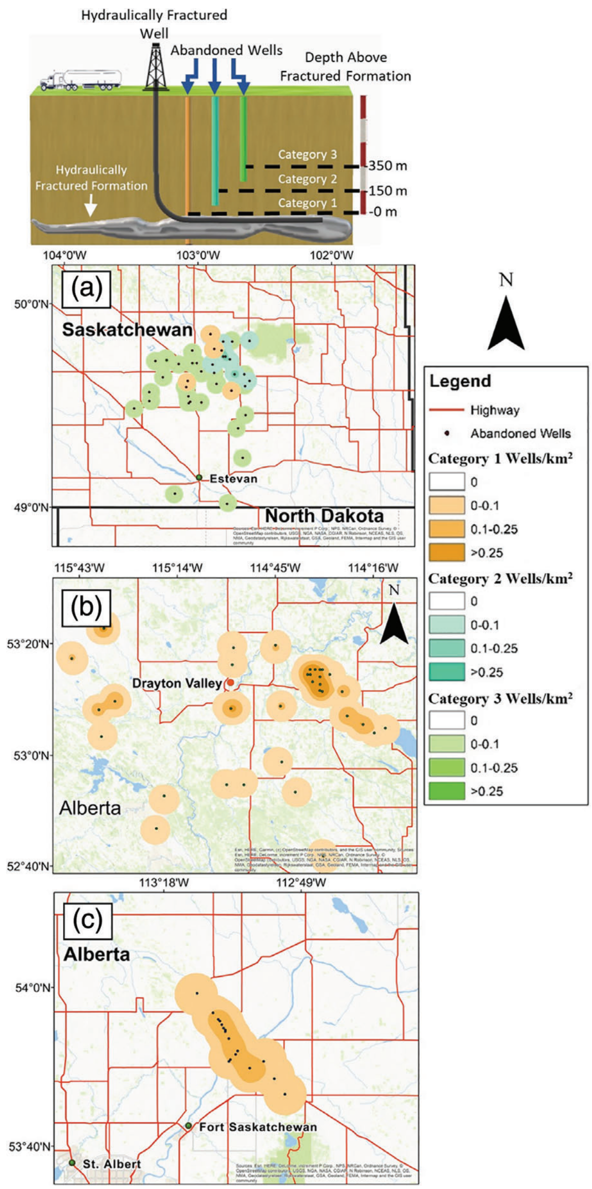

Figure 4. Density of HF wells that are located within double the estimated average fracture half-length of pre-1960 abandoned wells for (a) Southeast Saskatchewan, (b) Pembina Field, and (c) Redwater. The panel on the left depicts the three category levels 1, 2, and 3 for 0, 150, and 350 m, respectively, above a nearby abandoned well.

Abandoned Wells in Proximity to HF Wells

The results for the proximity analyses between HF wells and old abandoned wells for each of the four categories depicts distinct differences among the three case study areas (Figure 4). The Southeast Saskatchewan study area has 55 HF and 39 abandoned wells spread out among the study area, which is between the well counts of the other two study areas. However, out of the identified wells, only six HF wells are located within double the estimated average fracture half-length of five abandoned wells classified as having been drilled into or below the HF formation (category 1). By contrast, all the identified abandoned wells at the other two study areas (Pembina and Redwater) are classified as category 1, indicating the abandoned well either passes through or is completed into the formation that has been HF in the nearby production well. Notably, for all study areas there are more HF wells than abandoned wells, indicating that some abandoned wells had the potential to receive frac hits from multiple nearby production wells. This is most pronounced for the Pembina Field where there are 107 HF wells located near 34 abandoned wells, indicating that each abandoned well may be near multiple HF wells. Similar to the proximity analysis of EOR/SWD wells, decreasing the cutoff date of the abandoned wells included in the spatial analysis generally results in a decrease in the amount of HF wells that are in close proximity to old abandoned wells, while increasing the cutoff date of the abandoned wells generally results in an increase (Figures S17 and S18).

Early Well Abandonment Practices: Uncased Hole

Abandonment plug placement locations within abandoned wells were generally similar among wells within the same study area for the subset of tour reports reviewed. Typical plug placements in the Saskatchewan study area had the first cement plug placed at the bottom of the well, typically the Mississippian aged formations, with the second cement plug placed across the Vanguard Formation within the Cretaceous Colorado Group, and a final cement plug across the surface casing shoe (Figure 5). For the planned plug placement "thicknesses" as reported on the tour reports, the first plug had an average thickness of 55 m, the second plug had 45 m, and the third plug had 31 m with a minimum thickness for all plugs of 30 m. Actual plug thicknesses in the wellbore could vary from the planned plug thicknesses. Three of the uncased abandonments had intermediate casing cut and removed after the first abandonment plug. Some of the reviewed tour reports do not indicate whether an upper abandonment plug was "felt" by the drill stem, or otherwise detected (Alberta Energy Regulator 2021), which indicates that the plug may not have been successfully placed. For the plugs that did report being felt, the majority also provide the elevation that the abandonment plug was felt at, which in many cases may be tens of meters below or above the desired plug top elevation as reported on the tour report. In one instance, the reported plug top was below the elevation of the desired bottom elevation of the plug. Typical plug placements for the Southeast Saskatchewan study area likely leave the Upper Mississippian age aquifers commingled with the overlying Jurassic Aquifer (Gravelbourg and Shaunavon formations) and commingle the Mannville, Newcastle, and Belly River aquifers (Figure 2).

For the Alberta study areas, fewer tour reports were reviewed due to the prohibitive cost of procuring reports from the regulator. For the Redwater area, even with only seven wells reviewed, aquifer units appear to be mostly confined by cement plugs (Figure 6). The Viking and Belly River aquifers appear to be commingled in only 1 of the 7 wells reviewed. For the Pembina area, the uncased hole abandonments reviewed do not display a strong propensity for one formation to be plugged over

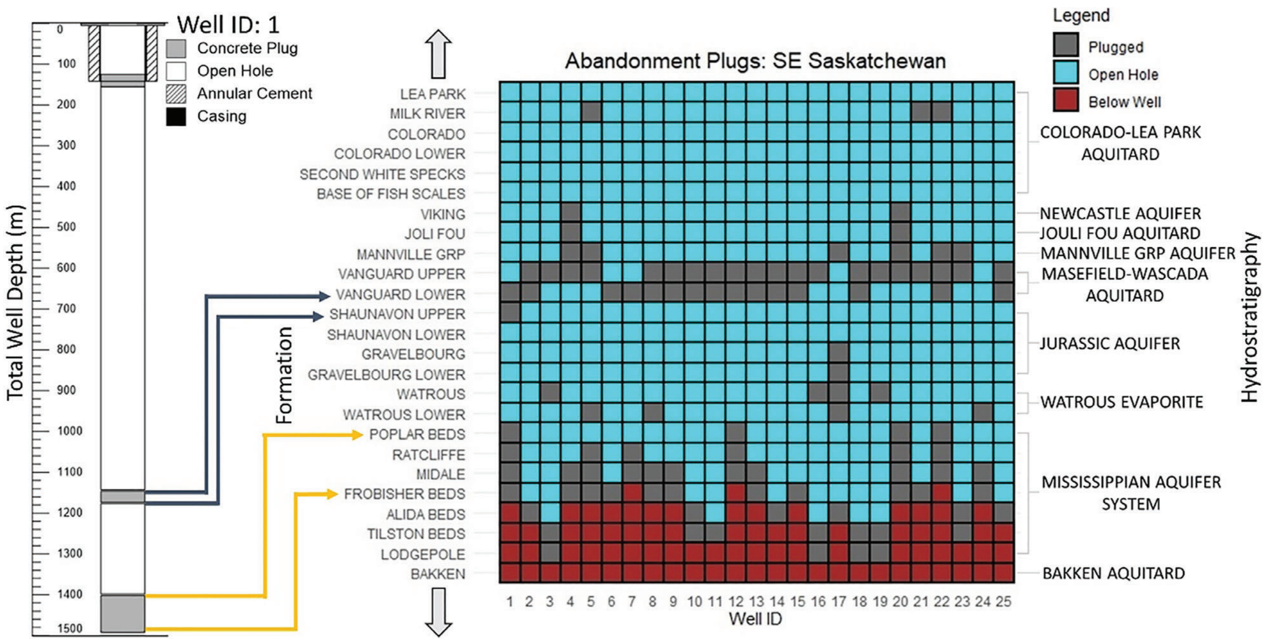

Figure 5. An example of a typical well abandonment schematic for a drilled and abandoned well on the left with plug placements in old abandoned wells on the right for the Southeast Saskatchewan study area.

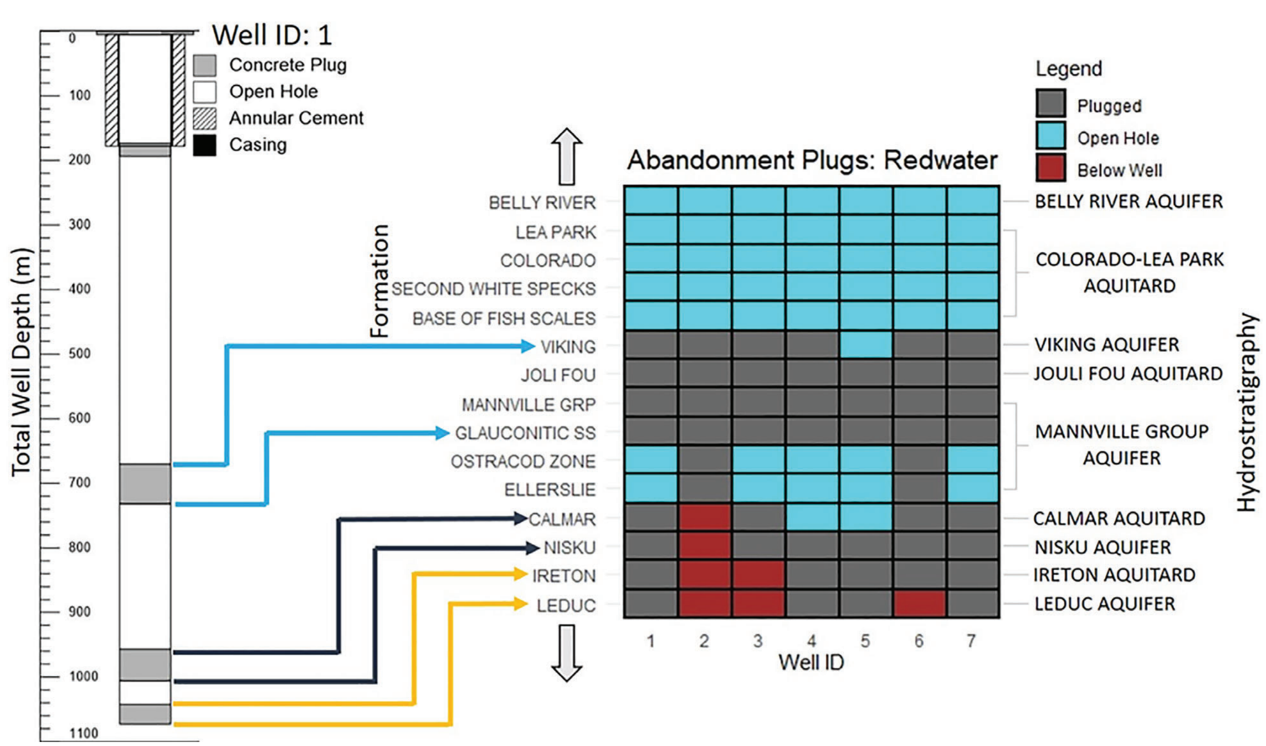

Figure 6. An example of a typical well abandonment schematic for a drilled and abandoned well on the left with plug placements in old abandoned wells on the right for the Redwater study area.

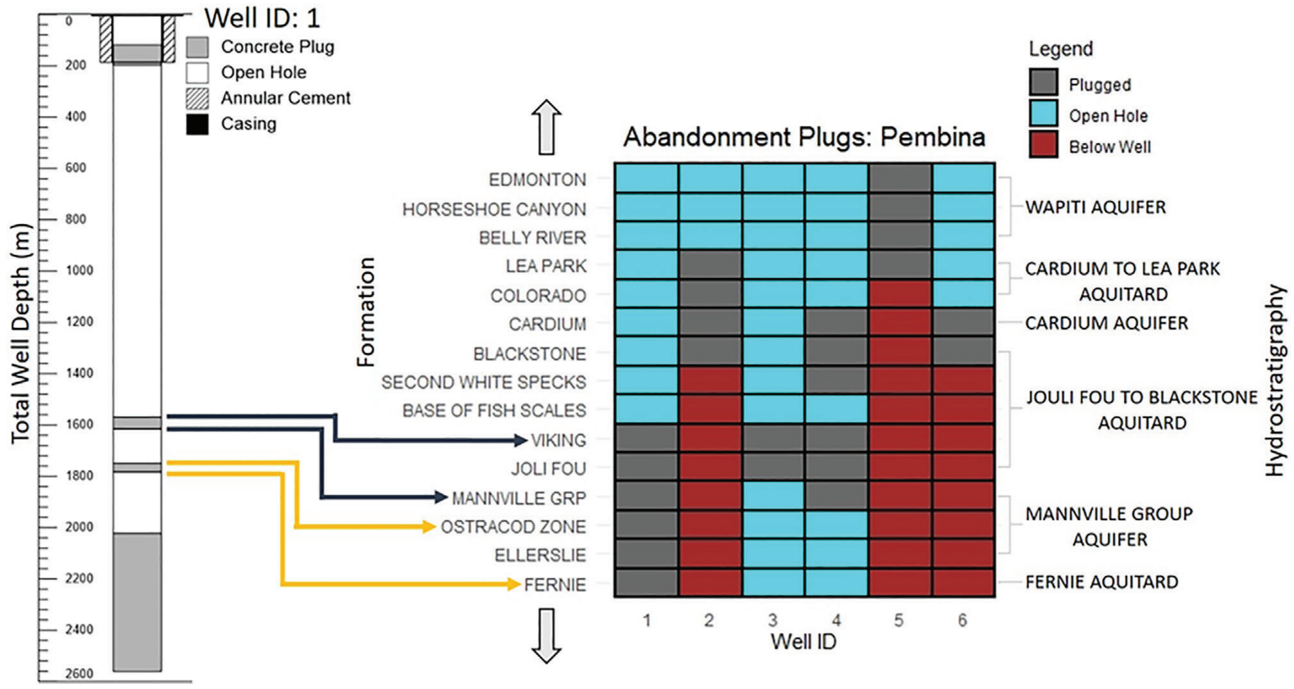

Figure 7. An example of a typical well abandonment schematic for a drilled and abandoned well on the left with plug placements in old abandoned wells on the right for the Pembina study area.

another (Figure 7). Two aquifer units that appear to be commingled within uncased abandoned boreholes for the Pembina area are the Cardium and Wapiti aquifers. It is possible that for each study area aquifer comingling is occurring in some portion of the abandoned uncased holes, with greater potential in the Pembina and Southeast Saskatchewan study areas, and lesser potential in the Redwater study area.

Early Well Abandonment Practices: Cased Wells

Cased well abandonments have generally been identified as having a greater potential of experiencing well integrity failure (Watson and Bachu 2009). Ten cased hole well abandonment reports were reviewed for Southeast Saskatchewan and three for the Redwater study area. While only a few cased hole abandonment tour reports were reviewed, similarity of abandonment methods between study areas allows for some general tendencies to be identified. In both the Redwater and Southeast Saskatchewan study areas, wells were typically abandoned with a bridge plug above the perforated interval and sometimes a cement plug across the surface casing shoe, leaving some portion of the intervening space to be covered by annular cement (Figure 8). However, while annular cement can provide hydraulic isolation in the vertical direction, it may not provide isolation in the horizontal direction (Vrålstad et al. 2019). If a cased abandonment does not have intervening plugs above the bridge plug near the bottom of the well, even though annular cement may cover many or all of the aquifers penetrated by the wellbore, those aquifers may still become connected. In some instances, a plug was not placed across the surface casing shoe, allowing for a greater possibility of commingling with shallow aquifers. For the Saskatchewan study area, the intermediate casing in some wells was cut and recovered above the top of the annular cement. In general, cased well abandonments reviewed here have a greater number of aquifer units potentially connected than within uncased well abandonments if casing and annular cement fail to provide zonal isolation.

Calculated Changes to Effective Vertical Permeability

In order to calculate the potential effect abandoned leaky and uncased wellbores may have on an aquitard's effective permeability using Equation 1 it is first necessary to determine the density of abandoned wellbores across the study areas. The three study areas mostly have pre-1960 abandoned wellbore densities between zero and one well per km^2 with sparse areas of greater density of up to five wells per km^2 (Figures S9-S11). It is thus reasonable to use one well per km^2 or less to represent zones of the study area where pre-1960 abandoned wellbores are clustered. Using Equation 1 with one plugged but leaky well per km^2 across an aquitard with a permeability of 10^{-20} m^2, changes in the aquitard's effective permeability are meaningful only across the high range of reported field measurements of plugged wellbore permeability (Figure S12). Using the highest reported field measurements of wellbore permeability (10^{-11} m^2; Duguid et al. 2011) results in a two orders of magnitude increase in the aquitard's permeability to about 10^{-18} m^2. When higher aquitard or lower abandoned wellbore permeabilities are considered, the change in effective permeability becomes low to negligible.

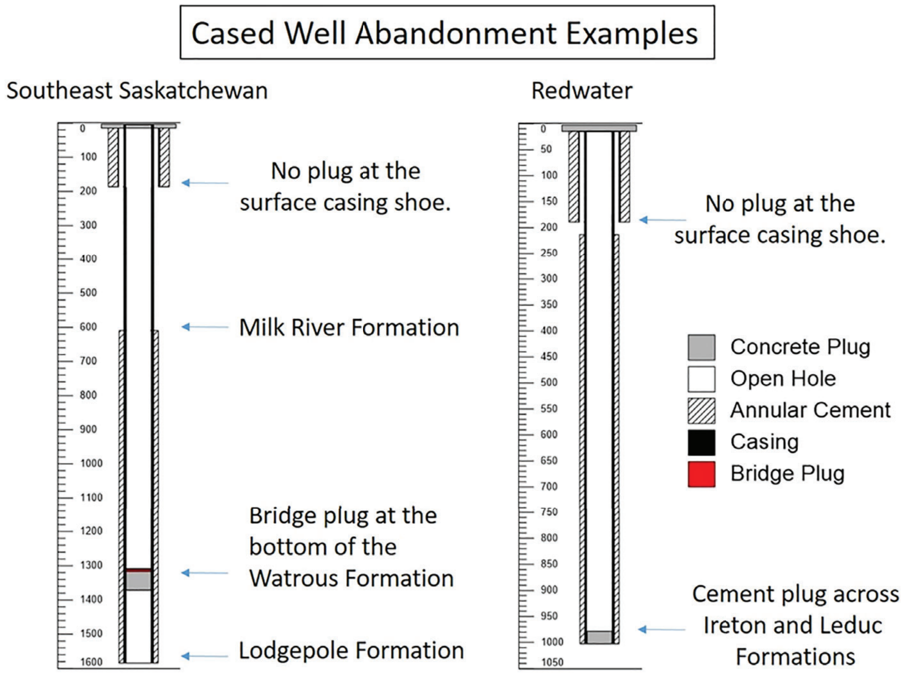

Figure 8. Cased well abandonment examples for the Southeast Saskatchewan and Redwater study areas (annular cement estimated from borehole dimensions and quantity of cement used, perforations not depicted).

The effect that uncased wellbores or uncased sections of wellbores can have on effective aquitard permeability by contrast is more striking. Using Equation 2, a 177.8 mm diameter uncased wellbore has an estimated permeability of about 10^{-2} m^2, or nine magnitudes higher permeability then the highest field measurement of wellbore permeability, which was around 10^{-11} m^2. Given a wellbore density of one uncased wellbore per km^2, the change in aquitard effective permeability for an aquitard with a permeability of 10^{-20} m^2 is 10 orders of magnitude higher to about 10^{-10} m^2. In fact if permeabilities are considered well below the values for intact shales and clay (10^{-20} to 10^{-16} m^2; Neuzil 1994), then the change in effective permeability remains meaningful up to an aquitard permeability of about 10^{-11} m^2 (Figure S13). If well densities are reduced to 0.1 wells per km^2, or 1 well per 10 km^2, the change in aquitard effective permeability for an aquitard with a permeability of 10^{-20} m^2 is still 9 orders of magnitude to about 3×10^{-11} m^2 (Figure S13). While leaky wellbores can increase the effective permeability of highly impermeable shales and clays, the impact of uncased boreholes even at low densities on aquitard effective permeability is substantial.

Discussion

All three study areas display potential for HF and EOR/SWD to impact wellbores abandoned before 1960, which likely have an increased likelihood of integrity failure. Stratigraphic position between historical and current production targets is one of the most important variables for estimating the degree of interaction between HF and EOR/SWD wells, and wells abandoned prior to January 1, 1960 common between all study sites. In the Southeast Saskatchewan study area the vertical position between past and present production targets works to decrease the probability of overlap. There the old exploration targets were the upper and middle Mississippian aged formations such as the Midale, whereas today the modern HF target is the Bakken, which is located deeper than the older typical target formations (Figure 4a). For the Redwater and Pembina study areas, the target HF formations are above and the same, respectively, as historical exploration targets leading to greater overlap with modern development (Figure 4b and 4c). These findings suggest that when the stratigraphic position of HF and/or EOR/SWD targets is above that of historical oil and gas targets one would expect greater interactions between the two compared to locations where the opposite is the case. Similar conclusions were reached in an analysis of potential leakage from hypothetical carbon sequestration projects in Alberta (Gasda et al. 2004).

While the population of wells abandoned pre-1960 identified for this study are more likely to experience well integrity failure, some unknown number of wells could maintain their integrity. For the wells that maintain integrity, abandonment plugs may still leave large portions of the wellbore open likely leading to commingling between aquifer units and rapid propagation of fluid pressure. Inter-borehole flow between commingled formations is unlikely to be significant without large vertical hydraulic gradients, such as those that can be produced by HF and EOR/SWD operation including those in the Mannville for the Southeast Saskatchewan study area (Figure 5) and in the Belly River and Cardium (Figure 7).

Impacts from EOR/SWD are likely greater than those from HF due to their significantly longer duration on the scale of decades rather than days (McIntosh and Ferguson 2019) and the decrease in pressure that occurs after HF during the production of the HF well (Taherdangkoo et al. 2019). Cased boreholes present even greater concern with the reviewed abandonment reports indicating the potential for greater lengths of the borehole to be commingled than uncased hole abandonments. These boreholes with commingled aquifers could further allow for deep aqueous fluids to flow into yet higher aquifer units through other nearby unplugged wells that pass through one of the commingled formations (Nordbotten et al. 2009). Viewed on a broader scale uncased commingled boreholes at low densities of one well per km^2 have the potential to increase the effective permeability of intact shale and clay aquitards by 6 to 10 orders of magnitude. Such a dramatic increase in effective aquitard permeability over areas as large as the presented study areas could have broad implications for deep groundwater flow systems. The locations identified with a high degree of overlap between HF and EOR/SWD would be important candidates for further study to determine what effects commingling between aquifer units by boreholes could have on deep groundwater flow systems and potentially local water resources.

The overlap of abandoned boreholes with HF and EOR/SWD wells provide impetus for reviewing current regulations regarding HF and EOR/SWD activities and their potential impact on nearby abandoned wells. Alberta recently implemented HF regulations in 2013 that address the potential for frac hits to adjacent wells and directs operators to take preventative measures (Lucas et al. 2014); however, it is unclear how operators determine if communication has occurred with an offset abandoned wellbore (Alberta Energy Regulator 2013, 2016). Saskatchewan does not yet provide regulation or guidance on how operators should address the potential for frac hits to offset wells other than to direct horizontal wells to be drilled 150 m from another offset producing well (Ministry of Energy and Resources 2012, 2016). Regulations addressing frac hits may not be necessary for the Bakken Formation of Southeast Saskatchewan, at least for wells abandoned before 1960; however, other HF formations within the province may have greater overlap with vulnerable abandoned well populations. Saskatchewan does not require brine injection well operators to search for and assess offset abandoned wells (Ministry of Energy and Resources 2018). Alberta does require an area of review to be conducted within a 1.6 km radius or within the target oil and gas pool for produced water class II waste injection wells (Alberta Energy Regulator 1994, 2020). Alberta's requirement for an area of review for class II (produced water and saline waters) wells was not implemented until April 2014 (Alberta Energy Regulator 2012), meaning that injection wells permitted prior to this requirement have not undergone an area of review. Furthermore, there is ambiguity as to how to determine if an abandoned well could allow for migration of aqueous fluids between formations and as such would be required to be re-entered and investigated. Regulations could be improved by better defining how an operator should go about determining whether an offset abandoned well creates the potential for cross-formational flow or not.

Several data gaps have been addressed by this study, but fundamental questions remain about the integrity of abandoned boreholes. There are very few publicly available field studies documenting the condition of re-entered abandon wells (e.g., Upp 1966; Isherwood 1980; Watson 2005). Larger studies containing more representative sample sizes of re-entered abandoned wells from diverse geologic settings would enable more accurate estimation of the probability that well integrity failure may occur (Watson 2005). The potential impacts from HF and EOR/SWD appear to be focused in the intermediate zone in aquifers below potable groundwater but above typically targeted oil and gas reservoirs. Often, little information is available about intermediate zone aquifers as they are above oil and gas bearing formations of interest to producers and below the focus of most water resource agencies (Council of Canadian Academies 2014; Dusseault and Jackson 2014). The intermediate zone has also been identified as the origin for much of the stray gas migration along active boreholes in the WCSB (Van Stempvoort et al. 2005; Tilley and Muehlenbachs 2012) suggesting that commingling of the intermediate zone may also promote transport of gases such as methane along abandoned boreholes (McMahon et al. 2018; Wisen et al. 2020) even without large vertical hydraulic gradients between aquifer units necessary to drive inter-borehole flow of brines. While in the WCSB direct commingling of aquifers targeted by HF and EOR/SWD activities with potable aquifers may be unlikely in boreholes due to surface casing and abandonment plugs across the surface casing shoe, as well as intervening aquifers siphoning pressure (Nordbotten et al. 2004), indirect connection through leaky or discontinuous confining units may still be possible (Council of Canadian Academies 2014). Further field based research is needed to more thoroughly understand the integrity of old abandoned wells, examine the degree to which intermediate zone aquifers may be commingled by abandoned boreholes, and determine the extent and hydraulic conductivity of confining units separating the intermediate zone from potable aquifers. Such understanding coupled with spatial analyses and investigations similar to those performed in this study would contribute to the development of risk assessment based approaches to well abandonment and construction (Natural Resources Canada 2019). Our recommendations are aligned with other studies calling for further field-focused research into the impacts of oil and gas extraction (Jackson et al. 2013; Davies et al. 2014; Cahill et al. 2018; McIntosh and Ferguson 2019; Wisen et al. 2020).

Conclusions

Old abandoned wells are commonly found in close proximity to recent HF and EOR/SWD operations in Saskatchewan and Alberta. This situation is potentially problematic where older wells were drilled at depths greater than modern operations. This situation was found in the study areas in Alberta, where HF has occurred in strata overlying conventional reservoirs that were developed in the past. In southeastern Saskatchewan, development in the Bakken Formation underlies much of the conventional development. In all three study areas examined here, the spatial density of injection wells near old abandoned wells exceeded 0.1 per km^2 over at least part of the study area.

The magnitude of the hydraulic connection between different strata due to abandoned wells is unclear due to varying abandonment practices, available documentation, and a lack of field investigations. However, some older wells were found to be abandoned in a manner that left multiple aquifers above the target reservoir connected between abandonment plugs, allowing for mixing of groundwaters. The water chemistry in these intermediate zone aquifers is poorly characterized but at least some of these groundwaters could be of strategic importance as agricultural or potable water supplies. The extent to which transport through old abandoned wells has affected groundwater supplies in the intermediate zone is unclear. These legacy effects of oil and gas development will need to be considered if these deep groundwater resources are needed in the future.

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Author's Note

The authors do not have any conflicts of interest or financial disclosures to report.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article. Supporting Information is generally *not* peer reviewed.

Appendix S1. Supporting information.

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