# INVESTIGATING CROSS FORMATIONAL FLOW OF FLUIDS THROUGH OIL AND GAS WELLS IN ALBERTA AND SASKATCHEWAN, CANADA

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By

Christopher A. Perra

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Head of Civil, Geological and Environmental Engineering
3B48 Engineering Building
57 Campus Drive
University of Saskatchewan
Saskatoon, Saskatchewan S7N 5A9 Canada

OR

Dean
College of Graduate and Postdoctoral Studies
University of Saskatchewan
116 Thorvaldson Building, 110 Science Place
Saskatoon, Saskatchewan S7N 5C9 Canada

# ABSTRACT

Deep fluids that are buoyant or have been pressurized due to hydraulic fracturing (HF) or injection related to enhanced oil recovery (EOR) and salt water disposal (SWD) can migrate upwards into other aquifer units, including potable aquifers, through a number of pathways. However, operational considerations typically limit the likelihood of cross formational flow occurring through natural geologic pathways such as faults, leaving anthropogenic pathways, namely wellbores, as the most likely pathway for cross formational flow in most settings. This thesis first evaluates the potential for inter-borehole flow to occur through old abandoned wells in the deep subsurface associated with nearby HF and EOR or SWD operations at three study sites in Alberta and Saskatchewan. It then predicts the occurrence of surface casing vent flow and gas migration (the surface expression of well leakage) in active or suspended wells across Alberta using iterations of the machine learning algorithm, random forest. These two studies share commonality in that the formations located below potable groundwater but above typically targeted oil and gas formations, otherwise known as the intermediate zone, are identified as being critical to understanding both deep well leakage and the surface expression of well leakage.

Results indicate that old abandoned wells at the study sites surveyed typically leave several intermediate zone aquifers commingled between abandonment plugs, increasing their susceptibility to the effects of nearby HF and EOR or SWD operations. For the surface expression of wellbore leakage the intermediate zone has generally been identified by previous studies as the origin for the majority of stray gas samples analyzed. While a modest predictive accuracy of 73% to 77% was achieved using random forest algorithms on a test dataset of wells across all of Alberta, predictive performance could likely be improved by including more predictors previously identified as being strongly correlated with well leakage that are related to the intermediate zone (e.g. well cement tops). In both studies the results can help shape future government regulations and policy but future field work on the intermediate zone is needed to improve our understanding of the integrity of oil and gas wells, the extent to which intermediate zone aquifers may be commingled by old abandoned wells, and by verifying the veracity of the existing database on the occurrence of SCVF/GM.

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| | |
|---|---|
| WCSB | Western Canada Sedimentary Basin |
| AER | Alberta Regulatory Agency |
| SCVF | Surface Casing Vent Flow |
| GM | Gas Migration |
| EOR | Enhanced Oil Recovery |
| HF | Hydraulic Fracturing |
| SWD | Salt Water Disposal |
| m | Meters |
| UWI | Unique Well Identifier |
| km | Kilometers |
| $\mathrm{k_e}$ | Effective Vertical Permeability |
| $k_m$ | Permeability of Aquitard |
| $k_1$ | Permeability of Vertical Pipes (Wells) |
| $\phi$ | Fraction of Media Occupied by Pipes (Wells) |
| r | Radius of Wellbore |
| mm | Millimeter |
| SCP | Sustained Casing Pressure |
| C | Celsius |
| ° | Degrees |
| ranger | Random Forest Generator |
| cforest | Conditional Inference Forest |
| rf | Random Forest |
| RRF | Regularized Random Forest |
| extraTrees | Extremely Randomized Trees |
| ROC | Receiver Operator Characteristic |

# INTRODUCTION

The deep subsurface is used for both the extraction of fluid resources (hydrocarbons, $H_2$, He, Li, Cu, etc.) and the storage of anthropogenic waste (brine, $CO_2$, $H_2S$, etc). The porous intervals of the deep subsurface are generally confined by one or more caprocks allowing for the accumulation of fluid resources from source rocks or the containment of anthropogenic waste. These native or injected fluids can be released to shallow aquifers through existing permeable faults or fracture zones (Dockrill and Shipton, 2010; Ferguson and Grasby, 2018) or cross-formational flow can be induced through anthropogenic activities that can impact the integrity of the caprock such as the well stimulation technique of HF or pressurization of the reservoir from fluid injection (Shukla et al., 2010), of which, the latter can also induce lateral migration of fluids beyond the areal extent of the caprock (Birkholzer et al., 2009; Peterie et al., 2018). Recently, greater consideration has been given to the possibility that contaminated fluids from deep reservoirs, such as deep reservoir fluids that are typically exploited for oil and gas, can also travel up through inadequately sealed wellbores to contaminate potable groundwater aquifers (Sherwood et al., 2016). It is this latter case, specifically fluid migration along oil and gas wells, that this study investigated.

Two billion people are estimated to rely on groundwater for drinking water globally (Morris et al., 2003). The potential risk that leaky wells pose to the water supply of this segment of the world's population has long been recognized and this knowledge predicated many of the early oil and gas well construction regulations (Pettyjohn, 1971; Gass et al., 1977). Over time, incidences of pollution have led to more effective regulation, while improved construction practices also have reduced the risk of oil and gas well integrity failure (King and King, 2013). While modern oil and gas wells may have less risk of leaking than older wells, hundreds of thousands of oil and gas wells have been previously constructed and abandoned under far less rigorous regulatory oversight and using inferior well construction practices. The locations of these older abandoned wells are often poorly documented and they can leak for some time unnoticed (Richter et al., 1990). Among the millions of abandoned wells in North America (Kang et al., 2016), some case studies have shown that a few of these abandoned wells can leak at high rates (Chilingar and Endres 2005; Jacob, 2009). However, current data suggest that the majority have much lower equivalent permeabilities for the wellbore or for specific wellbore barrier elements such as abandonment plugs; i.e., on the order of about less than a $10^{-15}$ to $10^{-12}$ $m^2$ (Kell, 2011; Tao and Bryant, 2014; Kang et al., 2015). Contamination from the surface and shallow subsurface, sometimes aided by poorly constructed or sealed wells, has been shown to contribute to wells being drilled deeper in search of better water quality (Jasechko et al., 2017). Recent research has also suggested that oil and gas development as well as waste injection is threatening our potable groundwater supplies from below (McIntosh and Ferguson, 2019). These threats from above and below have led to the realization that there is less potable groundwater available than previously thought (Ferguson et al., 2018).

Studies on the integrity of old abandoned oil and gas wells have largely been predicated upon risk assessments for carbon sequestration and HF (e.g. Dilmore et al., 2015; Carroll et al., 2016). Few studies have investigated the subsurface environmental risks posed by production of oil and gas from conventional reservoirs (McIntosh and Ferguson, 2019), let alone specifically investigating the risks posed by old abandoned wells completed into conventional reservoirs. In the Western Canada Sedimentary Basin (WCSB) which encompasses portions of the provinces British Columbia, Alberta, and Saskatchewan, well integrity studies have been undertaken near the locations of planned carbon sequestration projects (e.g. Gunter et al., 2009; Bourne et al., 2014), however no such studies have been completed that specifically assess the risks posed by old abandoned wells with regards to recent oil production. Attempts have been made at predicting the likelihood that an oil and gas well may have problems with integrity using machine learning (Montague et al., 2018), but no recorded attempts have been made to test whether predictions could be reliably completed outside the study area. If it could be shown that it was possible to extend predictions beyond the area from which the training dataset for the statistical model came, then a broad assessment of well integrity could be made for locations that do not keep rigorous records of well integrity. Such an assessment would enable better planning of subsurface activities.

## 1.1 Research Objectives

The goal of this study is to identify oil and gas wells most at risk of allowing leakage of fluids into shallow aquifers in the WCSB. The WCSB has the most complete, readily available dataset of well attributes, especially of older wells, in North America (Cahill et al., 2019). Furthermore, the WCSB also has amongst the highest density of wells in the world (Metz et al., 2005). This goal will be accomplished through a proximity analysis of old abandoned wells in relation to actively producing wells and by using statistical and machine learning methods to identify potentially leaking wells. The research objectives of this project are:

1. Identify whether there is a cutoff date for both Saskatchewan and Alberta that signifies a distinct change in the integrity of abandoned wells. Should such a cutoff date exist, wells abandoned before this date would be expected to have an elevated risk of well integrity failure.
2. Identify whether there are locations that require greater scrutiny of modern oil and gas production and injection operations through an analysis of the spatiotemporal relationships between these modern subsurface activities and old abandoned wells.
3. Indicate whether it is possible to predict whether uninspected wells in Alberta have experienced the surface expression of wellbore leakage through the use of a statistical model trained on data derived from observations submitted to the Alberta Energy Regulator (AER).

## 1.2 Research Scope

The scope of this research includes two main components: investigating leakage potential along old, abandoned wellbores in the deep subsurface, and predicting the occurrence of wellbore leakage being expressed at the surface using machine learning algorithms. For the first component, as regulations, and to some extent well construction practices, differ between regions the research was to be focused on the WCSB with a specific focus on the provinces of Alberta and Saskatchewan. Historical regulations and well construction practices were reviewed for Alberta and Saskatchewan. From this information it was possible to identify a subset of abandoned wells by abandonment date that were thought to be at greatest risk for inter-borehole flow and the cross-connecting of aquifers (commingling) in the deeper subsurface. This portion of the study was further constrained by selecting three case study locations on which to focus: the Pembina study area, the Redwater study area, and the Southeast Saskatchewan study area.

For the second component of the research, the study was constrained to the province of Alberta due to the AER's well maintained dataset recording the occurrences of the surface expression of wellbore leakage. Previous research by Montague et al. (2018) on using several machine learning algorithms to predict wellbore leakage using the AER dataset had identified the random forest algorithm as having the best performance. This research was thus constrained to modeling the surface expression of wellbore leakage in Alberta using several different random forest algorithms.

## 1.3 Thesis Structure

This thesis is organized in a manuscript format whereby chapters 3 and 4 are written in a manner suitable for publication, with references listed at the end of each chapter except for Chapter 1 whose references are combined with Chapter 2 for brevity. Chapter 2 provides background information and a review of the current theory behind the thesis topics. Chapters 3 and 4 also provide reviews specific to the subject manuscript, and although Chapter 2 provides the same information it is presented in the context of the entire work. Chapter 5 draws together the overall conclusions of this thesis and identifies potential future research.

# LITERATURE REVIEW

## 1.4 Well Integrity

Oil and gas wells are designed to act as sealed conduits between the completed producing formation and the land surface. Zonal isolation between the wellbore and the surrounding formations must be maintained not only for smooth operation of the well itself but also to protect potable aquifers from contamination, and prevent pollution of the atmosphere through the release of noxious gases such as $H_2S$ or greenhouse gases such as methane. A nested collection of barriers allow for one barrier to fail while maintaining the zonal isolation of the well. King and King (2013) provide a distinction between well integrity failure and well barrier failure. A failed well barrier occurs when one of the redundant design elements fails but zonal isolation between the wellbore and surrounding formations is maintained. Well integrity failure occurs when all barriers in a potential leak path fail and a continuous pathway is established between the fluids within the wellbore and surrounding formations.

Well integrity failure in itself may not result in contamination of potable aquifers or the atmosphere. While a continuous pathway is required for the communication of fluids with surrounding media, there also needs to be a sufficient driving force. Drive may be insufficient in conventional reservoirs with depleted pressures due to decades of production and where the migrating fluid is dense; e.g. basinal brines. However, these same reservoirs can become repressurized through waterflooding, carbon sequestration, waste injection, or gas storage (Ferguson, 2015). Buoyant fluids such as methane do not require pressurization of their native reservoir in order to reach the surface and as such have been identified as the more commonly leaked fluid (Watson and Bachu, 2009). Where the leaked fluid is methane it has been found that the origin of the methane is often from intermediate formations above the producing formation (Tilley and Muehlenbachs, 2012). The use of inferior quality cement, less protective regulations, and/or less attention to detail within the intermediate zone may contribute to the greater occurrence of fugitive emissions (Watson, 2004; Dusseault and Jackson, 2014).

Well integrity problems in locations with sufficient driving force or buoyant fluids often manifest themselves as surface casing vent flow, or sustained casing pressure. In Canada, the annulus between the surface casing and next string of casing is left open to allow for release and measurement of pressure buildup within the surface casing annulus (Watson and Bachu, 2009). In the US regulations rarely stipulate that the surface casing vent be left open, so instead of surface casing vent flow, well integrity problems in the US may result in surface casing pressure build-up. Gas migration (GM) can occur if pressure buildup is great enough to force fluids into formations beneath the surface casing shoe, or if gas bypasses the surface casing entirely (Figure 2.1; Lackey et al., 2017).

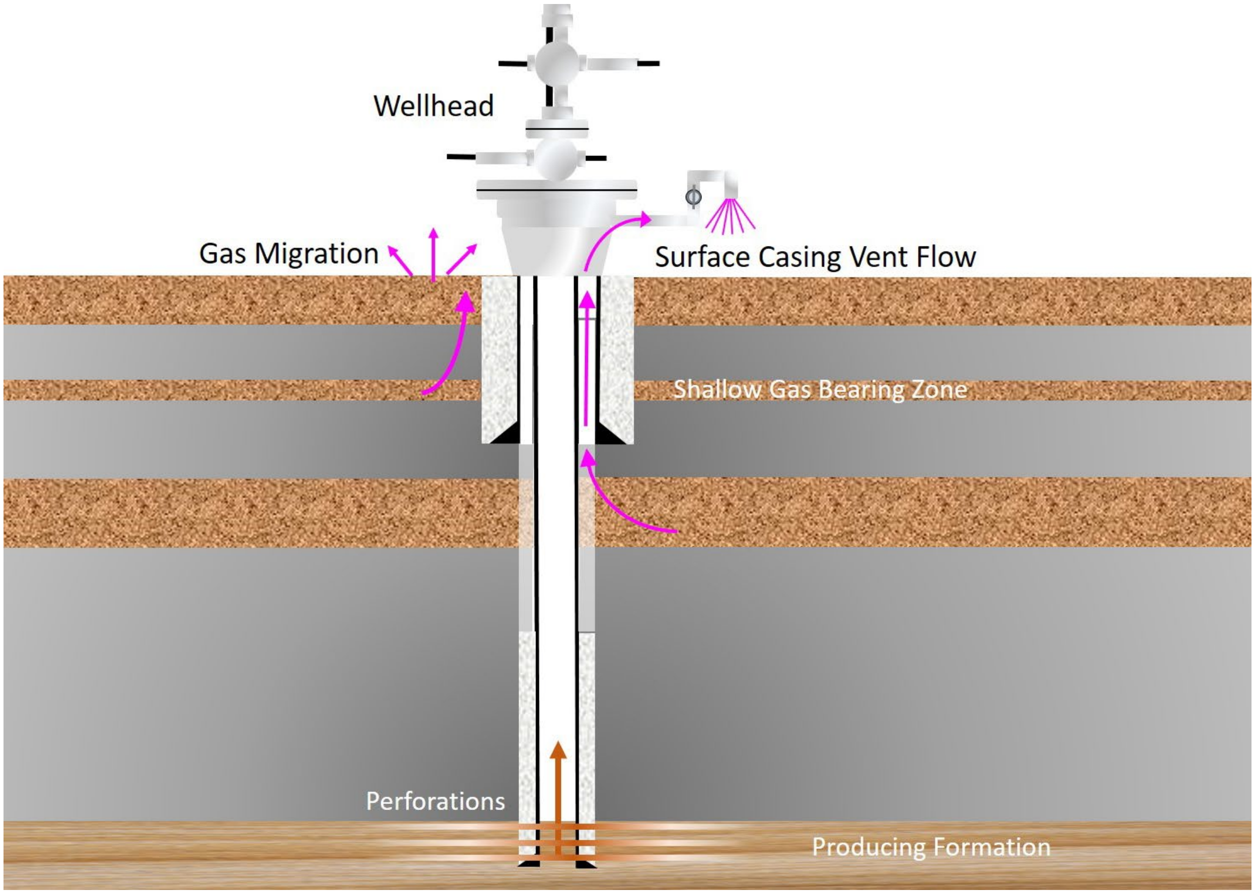


Figure 2.1: Example of gas migration and surface casing vent flow in an oil and gas well (after Watson and Bachu, 2008).

In an operating well there are numerous physical barriers such as seals, and valves, but this review will focus on the integrity of casing, cement, and abandonment plugs as these have the most influence on well leakage. Casing can lose integrity due to collapse, bursting, corrosion, thread leaks, or mechanical tears. Bursting or collapsing of casing can occur due to shearing of rock strata along bedding planes (Dusseault et al., 1998), sustained casing pressure (Kinik, 2012), and from high hydrostatic pressure on the outer surface (Huang et al., 2000). Corrosion of metal casing is of significant concern in high pressure, high temperature reservoirs with $H_2S$ or $CO_2$. In conventional reservoirs, as the field ages, increased production of saline water (water cut) with time leads to a greater risk of corrosion (Perez, 2013). Thread leaks or casing connection failure can be caused by the cyclic thermal loading experienced during the recovery of heavy oil or bitumen using steam injection methods (Teodoriu and Falcone, 2009). Thread leaks in conventional oil and gas wells have also been historically caused by improper handling and running of casing (Kerr, 1965). Wear and tear related to completion and production activities can occur due to processes such as erosion from sand proppant, abrasion from drilling, lift system changes, and drill pipe wear on casing (King and Valencia, 2016). Failure of casing or tubing is often contained by another element of the well barrier design.

Oil and gas well cement integrity has been identified as the most important barrier to consider when assessing whether a well may be at risk of losing or has already lost zonal isolation (Dusseault et al., 2000; Hawkes et al., 2011). Problems in well cement integrity are generally related to cement strength (in relation to shearing of rock strata), cement bond to rock and casing, cement shrinkage, and chemical reactions with subsurface fluids. Previous research has also indicated the importance of gas channeling during the hydration of cement, mud channeling, and poor mudcake removal on cement integrity. Dusseault et al. (2000) contends that these are minor in relation to the other cement behaviors mentioned above. However, these behaviors do impact each other, continue to be cited as causes for well integrity failure, and as such are mentioned here. As with well casing, shearing of rock strata along bedding planes can easily overcome the strength of cement (Dusseault et al., 2000). Induced shear failure is a greater risk in reservoirs with high reservoir compressibility, stiff caprock, and large pressure changes either from production or injection (Hawkes et al., 2004). In the WCSB, failure from shearing is a known problem in the heavy oil fields around Lloydminster and Cold Lake with failure occurring in the shale layers above the producing formation (Talebi et al., 1998; Wong et al., 2011).

Cement bond to rock and casing (tensile strength at the cement/rock casing interface) is influenced by mud film or channels, cement bulk shrinkage rates, and cyclic stresses such as thermal or pressure stresses associated with well completion and production. The effect of mud on the bond at the cement/rock interface was identified early on as being detrimental because mud has very little tensile strength and reduces adhesion. Not only can mud reduce cement bond strength it also can lead to the formation of mud channels promoting interzonal communication of fluids. Removal of immobile mud is made more difficult in poorly drilled holes with washouts (Parcevaux et al., 1990). Cement shrinkage is caused by excess water being expelled into the surrounding formation or from osmotic dewatering by formation brines. Low shear strength between the cement and rock are needed to support the cement column, which impedes the settling of the cement and promotes shrinkage of the cement sheath promoting fracture development (Dusseault et al., 2000). Cyclic stresses from temperature or pressure can cause stresses in casing, cement sheath, and adjacent formations. These stresses can damage the cement sheath and debond it from the casing or rock (Zhang and Bachu, 2011). Gas channeling occurs during cement hydration as the cement slurry transitions into a gel and no longer transmits in-situ hydrostatic pressure. This reduction in pressure creates a fluid pressure difference between the cement slurry and adjacent rock, and can promote gas invasion of the slurry creating micro-annuli and small fractures within the cement reducing its strength. These pathways may not be continuous (Kiran et al., 2017). Typically the cement sheath is the last barrier in a flow path, should it fail, well integrity failure is likely.

Well abandonment and plugging procedures seek to seal a well indefinitely. However, cement plugs emplaced during abandonment can be degraded or damaged from many of the same processes impacting the cement sheath. Damage to abandonment plugs can either occur due to improper emplacement or can occur due to changes in downhole conditions. Reservoir production or injection into a reservoir causes pressure, thermal, and total stress changes, which can lead to the degradation or debonding of well plugs (Mainguy et al., 2007). In Alberta the cement bailed on top of bridge plugs has been identified as being susceptible to failure over time (Figure 2.2), with an estimated failure rate of 10%. If the plugs are within an acidic environment due to the presence of sour gas or the injection of $CO_2$ the failure rate could be higher. Other types of plugs such as the balanced plug method are expected to have much lower rates of failure (Watson and Bachu, 2009). In some cases, a legally abandoned well may not provide adequate zonal isolation to protect resources if the reservoir is repressurized. This can occur in cases where a drill string becomes stuck or other item is lost downhole, preventing full isolation of porous zones during abandonment (e.g. Diller, 2011). Overall there are several modes of failure that can result in the loss of zonal isolation in a well. Wells can have barrier elements fail either due to poor materials or methods used in creating the barrier element or due to changes in stress due to fluctuations in pressure or temperature. Due to the generally complex combination of materials and processes by which process by which pathways may develop, it has proven difficult to predict whether a given well may develop a pathway or not (Montague et al., 2018).

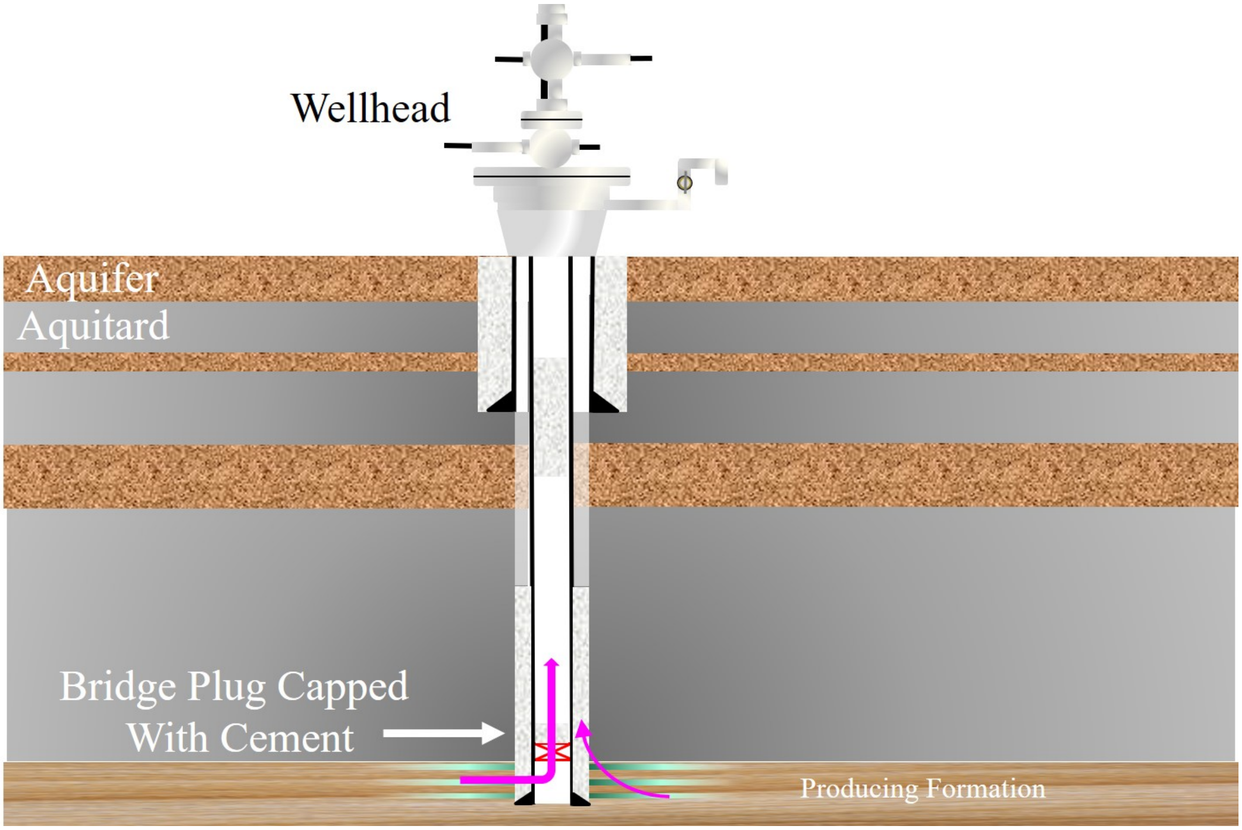


Figure 2.2: Abandoned well with a bridge plug just above the producing formation, and a cement plug across the surface casing shoe. Arrows indicate leakage pathways (after Watson and Bachu, 2008).

## 1.5 Well Construction and Abandonment Regulations in Saskatchewan and Alberta

### *1.5.1 Pertinent Modern Well Construction Regulations*

Alberta and Saskatchewan have similar well construction and abandonment statutes and regulations; however, Alberta's regulations tend to be more prescriptive. Surface casing vent flow (SCVF) measurement is required in both provinces, but in Alberta it is to be measured prior to abandonment operations as well as once abandonment operations have been completed (AER, 2003). In Saskatchewan, SCVF is measured only after the well has been abandoned (MER, 2015a).

Saskatchewan requires testing for GM after abandonment at every well while Alberta only requires GM testing within special administrative districts (AER, 2003; MER, 2015a). Alberta also requires due diligence by an operator on investigating the possibility of interborehole communication from HF, but the specifics of any such study are left up to the operator (AER, 2013). Saskatchewan does not appear to have any such requirement. Many regulations are location-specific, precluding an in-depth overview. In both provinces wide latitude is given to either the chief executive officer and the Lieutenant Governor (Alberta) or minister (Saskatchewan) respectively, to approve regulation variances, regulation waivers, or activities deemed to be "non-routine." (e.g. R.S.A., 2000; MER, 2015a; MER, 2015b; AER, 2016; AER, 2018).

Perhaps the most important statue pertaining to well abandonment in both Alberta and Saskatchewan is that a company remains liable for any problems caused by future well failure subsequent to plugging and abandonment. In Saskatchewan the statute states that:

> *"20(2) Abandonment and reclamation of a well, facility, associated flowline and their respective sites does not relieve the licensee or the working interest participants of the responsibility to undertake further abandonment or reclamation work or from the responsibility for the costs of doing that work (R. R. S., 2012, p. 12)."*

In Alberta, the relevant statute is even more prescriptive in defining a company's responsibilities after a well is abandoned. Should surface development occur within proximity of an abandoned oil and gas well the licensee of the abandoned well is required to assess the condition of the well and conduct additional abandonment operations if needed (AER, 2014). This could have significant implications given the recent Supreme Court of Canada decision, Orphan Well Association v. Grant Thornton Ltd., which came to the conclusion that well abandonment liabilities are not debts but rather constitute duties. These duties must be met prior to money being distributed to holders of a company's debt (Supreme Court of Canada, Case in Brief, 2019). It is not clear how the possible costs of future abandonment operations are incorporated into this decision, nor the extent to which either province actively enforces these abandonment liability statutes.

### *1.5.2 Era of Federal Regulations (1887-1938)*

While modern regulations assist in ensuring modern wells maintain their integrity through their operational life and after abandonment, many wells were constructed and abandoned before relatively protective regulations were put in place. The era of Federal Regulation of oil and gas in Alberta and Saskatchewan stretched from 1887-1938. During this time, for all lands west of the Dominion Land Survey third meridian (106° W) only surface rights were given to homesteaders. Subsurface mineral rights were reserved for the crown, except for Hudson's Bay Company and existing railroads. The chairman of the Commission of Conservation's Committee on Minerals brought to parliament's attention the excessive waste being flared or otherwise lost from gas wells throughout the WCSB at the time. These observations brought about stricter regulation of the oil and gas industry with the passage of the Petroleum and Natural Gas Regulations of 1914. The objectives of the law were to promote development of the resource, give the federal government complete control of the resource, and to prevent inappropriate waste. Section 29 of the act summarized the extent of regulations with respect to well abandonment at the time:

> *"The lesse shall be at liberty to withdraw the casing from the said well, but in order to prevent water gaining access to the oil-bearing formation, the lessee shall immediately close the well by filling it with sand, clay, or other material (Breen, 1993, pg. 23)."*

More prescriptive regulations were implemented in 1919 including the ability of the government to recoup costs from abandoning derelict wells; however, significant hostility by the general public and oil companies towards the enforcement of these regulations muted the impact of their implementation. In 1930, control of natural resources in Alberta and Saskatchewan was passed from the federal government to the provinces (Breen, 1993).

### *1.5.3 Alberta Historical Well Construction Regulations (1930-1952)*

Alberta quickly implemented new oil and gas regulations when control over the resource was passed from the federal government. The first Oil and Gas Act was passed in 1931. Wells then required a permit before drilling, bonds of $50,000 to cover well liabilities for individual operators, and drilling methods had to be approved by the minister. Abandonment methods also required approval. The isolation of water bearing formations was required (APG, 1931). The essence of these first regulations with regards to well construction would only see slight incremental change until the 1950s, although it is likely that the methods of drilling and abandonment deemed acceptable by the board changed with improved technology and experience. Some of these incremental changes included requiring deviation surveys and more detailed drilling reports in 1939 (APG, 1939), and licensing of well drillers in 1945 (APG, 1945). In 1950 the passage of the Oil and Gas Resources Conservation Act likely brought improved regulation (S.A., 1950).

While on paper the regulatory requirements for well construction and abandonment do not appear to have changed significantly during the 1930s to 1950s, significant political events and technological advancements had a marked effect. Early regulations may not have been effectively implemented due to court decisions that limited the regulator authority (Spooner Decision) and the onset of the Great Depression (Breen, 1993). World War II also brought challenges to the regulatory agency with variances being made to allow wells to be drilled with shorter surface casing lengths, and then a single string of casing to the producing zone. Some drillers choose to forgo using surface casing entirely (Gow, 2005). Due to the economic conditions at the time, half of the regulator's field engineers quit in 1941 (Breen, 1993). During the 1940's drilling technology improved with, rotary drill rigs largely replacing cable tool rigs, improved Portland based cement mixtures, high pressure pumps fed by high volume cement mixers replaced paper bagged cement, and centralizers and scratchers were introduced in 1949. Still, techniques remained imperfect as evidenced by the catastrophic blowout of Atlantic #3 in 1949 (Gow, 2005).

### *1.5.4 Saskatchewan Historical Well Construction Regulations (1930-1960)*

Saskatchewan passed its first substantive well construction regulations in the Oil and Gas Act of 1936 (R.S.S., 1940). The regulations were similar to Alberta's but at the outset required licensing of well drillers. Some weakening of the regulations occurred in the late 1940's with a waiver of well bond requirements for a few years, although for the most part other well construction regulations remained the same (SPG, 1946; SPG, 1949). In 1953 the Oil and Gas Conservation Act completely revised existing regulations (R.S.S., 1953). Deviation surveys were required, new surface casing depth requirements and specified waiting on cement times; however, some weaknesses in the regulations remained, especially in relation to dry holes and abandoned wells such as explicit sanctioning of the complete removal of casing from abandoned wells (SPG, 1953). Improvements were made in 1957 and again in 1962 for abandonment of producing wells but still regulations remained lax for dry holes (SPG, 1957; SPG, 1962).

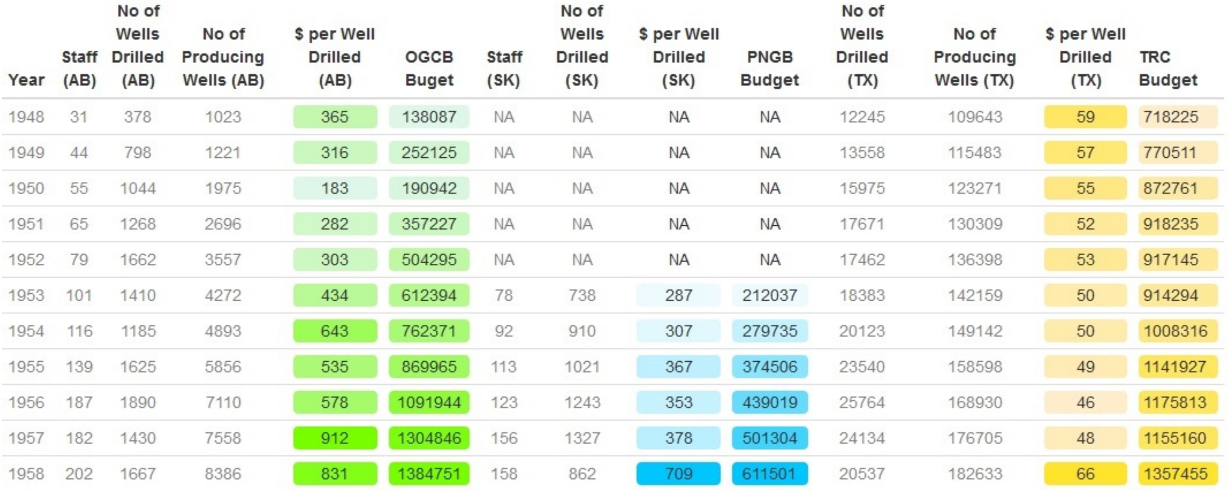
As with Alberta, political and technological events during this time in Saskatchewan had a role in influencing well construction practices. In the late 1940's the government was under immense pressure to increase the rate of development of the province's oil and gas resources. The public largely viewed the government at the time as being responsible for the slow rate of oil and gas development because they dissuaded Imperial Oil from conducting exploration by not giving the company exclusive exploration rights over large tracts of land. This slow development, threats from the small existing oil industry, and threats from American investors that they would not purchase Saskatchewan bonds caused the government to adapt oil and gas policies similar to that of neighboring Alberta (Emery and Kneebone, 2008). During the 1950's leaks from casing couplings were common (Kerr, 1965), methods used to cement surface casing did not adequately take into account cold temperatures near the surface especially during winter (Thorvaldson, 1962), and an important wireline tool allowing for the pinpointing of poor cement quality did not yet exist (the cement bond log, was not invented until 1959 (Nelson, 1990)).

### *1.5.5 Comparison of Historical Regulations between Alberta and Saskatchewan*

For Alberta, well regulations and construction practices likely would have led to wells being abandoned with higher rates of well integrity issues before 1952 than after 1952. Active enforcement of well construction regulations may have decreased and/or more allowances may have been made for poor practices (for the time) during the Great Depression and World War II. Immature drilling technology would have led to a multitude of different well construction problems. However, by the beginning of the 1950s lessons learned from the Atlantic #3 disaster were incorporated into the 1950 Oil and Gas Conservation Act (Breen, 1993), and a lull in well drilling in Alberta as the focus turned to Saskatchewan and Manitoba (Hanson, 1960) likely led to better well drilling practices.

For Saskatchewan, before 1960 the development and enforcement of well regulations lagged behind the explosive growth in the number of wells drilled within the province, likely leading to noticeable changes in well integrity before and after 1960. The province had oil and gas well regulations since 1938, but they were not meaningfully updated until 1953 in the midst of the boom. It is likely that it took time for operators and regulators to adjust to these new regulations. The province’s oil and gas regulator’s budget divided between the numbers of wells drilled each year lagged well behind that of Alberta’s until after the 1950s drilling boom, reaching its peak at the end of 1957 (Table 2.1). The drilling boom began to wane in 1959 and was over by 1960. This slowdown was caused by an oversaturation of the oil and gas market available to prairie producers at the time (Stanford Research Institute, 1959). For both Alberta and Saskatchewan, the regulators of the day were created primarily to oversee the conservation of the resource, ensuring that as much oil and gas was extracted as possible without waste, rather than ensuring the long term protection of water resources (NPC, 2011). However, even though the regulators of Saskatchewan and Alberta may not have been focused on the long term protection of water resources they still had a much larger budget relative to the amount of wells drilled per year available to them with which to manage the industry than many of their other North American peers such as Texas (Table 2.1). Based mostly on well drilling technology, King and King (2013) suggest that oil and gas wells constructed prior to the 1960s have a moderate potential to cause pollution due to leakage.

Table 2.1: Table comparing the budgets of the Oil and Gas Conservation Board (OGCB), Petroleum and Natural Gas Board (PNGB), and Texas Railroad Commission (TRC) for Alberta, Saskatchewan, and Texas respectively (adapted from Breen, 1994).



| Year | Staff (AB) | No of Wells Drilled (AB) | No of Producing Wells (AB) | $ per Well Drilled (AB) | OGCB Buget | Staff (SK) | No of Wells Drilled (SK) | $ per Well Drilled (SK) | PNGB Budget | No of Wells Drilled (TX) | No of Producing Wells (TX) | $ per Well Drilled (TX) | TRC Budget |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1948 | 31 | 378 | 1023 | 365 | 138087 | NA | NA | NA | NA | 12245 | 109643 | 59 | 718225 |
| 1949 | 44 | 798 | 1221 | 316 | 252125 | NA | NA | NA | NA | 13558 | 115483 | 57 | 770511 |
| 1950 | 55 | 1044 | 1975 | 183 | 190942 | NA | NA | NA | NA | 15975 | 123271 | 55 | 872761 |
| 1951 | 65 | 1268 | 2696 | 282 | 357227 | NA | NA | NA | NA | 17671 | 130309 | 52 | 918235 |
| 1952 | 79 | 1662 | 3557 | 303 | 504295 | NA | NA | NA | NA | 17462 | 136398 | 53 | 917145 |
| 1953 | 101 | 1410 | 4272 | 434 | 612394 | 78 | 738 | 287 | 212037 | 18383 | 142159 | 50 | 914294 |
| 1954 | 116 | 1185 | 4893 | 643 | 762371 | 92 | 910 | 307 | 279735 | 20123 | 149142 | 50 | 1008316 |
| 1955 | 139 | 1625 | 5856 | 535 | 869965 | 113 | 1021 | 367 | 374506 | 23540 | 158598 | 49 | 1141927 |
| 1956 | 187 | 1890 | 7110 | 578 | 1091944 | 123 | 1243 | 353 | 439019 | 25764 | 168930 | 46 | 1175813 |
| 1957 | 182 | 1430 | 7558 | 912 | 1304846 | 156 | 1327 | 378 | 501304 | 24134 | 176705 | 48 | 1155160 |
| 1958 | 202 | 1667 | 8386 | 831 | 1384751 | 158 | 862 | 709 | 611501 | 20537 | 182633 | 66 | 1357455 |

## 1.6 Alberta Case Study Background (Redwater Area)

The Alberta case study is to be located to the northeast of Edmonton centered on the Redwater Reef near the town of Redwater and the North Saskatchewan River. A simplified hydrostratigraphic column of the area is depicted in Figure 2.3. In the Redwater area the deepest formations of interest belong to the Beaver Lake Group. The Upper Beaver Lake consists of limestones interbeded with shale (Edward-Klovan, 1964). Above this aquitard there are a series of aquifers composed of siliciclastic and carbonate formations separated by aquitards in the form of competent evaporate and shale beds (Bachu et al., 2011). The three notable oil and gas bearing formations in the area are the Leduc (Redwater Reef), Sparky (Manville Group), and Viking formations. Most of the historic oil activity took place in the Redwater Reef beginning in 1948, while recent modern production activity is largely confined to the Viking. The oil leg of the Redwater Reef was completely developed with 926 wells using 4050 m$^2$ (40 acre) spacing by 1953 (Gow, 2005). With oil production waning, the Redwater Reef saw renewed use beginning in the late 1990s as an injection site for sour water (Bachu, 2008) and for a time was investigated as a possible carbon sequestration site (Gunter et al., 2009). Drilling of the Viking Formation on the other hand began at a tepid pace in the 1950s with few vertical wells and would not see substantial development until the high oil prices of the 2000s spurred drilling of horizontal hydraulically fractured wells (Mogensen et al., 2012).

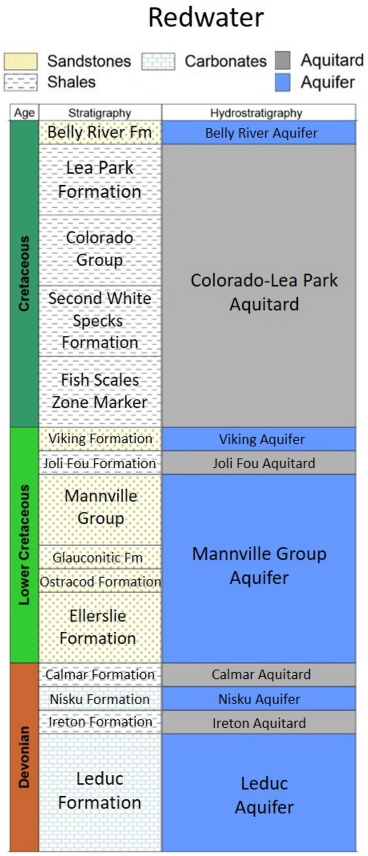


Figure 2.3: Generalized lithostratigraphy and hydrostrigraphy of the Redwater area (after Brydie et al., 2011).

## 1.7 Saskatchewan Case Study Background (SE Saskatchewan)

The Saskatchewan case study covers a larger area, roughly between 105° W to the Saskatchewan Manitoba border and 51° N to the Saskatchewan - United States border, thus encompassing the northeastern portion of the Williston Basin. A simplified hydrostratigraphic column of the area is depicted in Figure 2.4. The deepest formation of interest in this study area is the Devonian Birdbear Formation. As with the Redwater area, the Saskatchewan case study area is composed of a series of siliciclastic and carbonate formations separated by aquitards in the form of competent evaporite and shale beds. However, in this instance the aquifers and aquitards of greatest interest are the carbonate and evaporite formations, respectively, as oil and gas extraction is largely confined to Devonian and Mississippian aged formations (Palombi, 2008). Production in the SE corner of Saskatchewan began in the early 1950s with an exponential increase in the rate of drilling until 1959 (Stanford Research Institute, 1959). Wells were completed into both the Mississippian and Devonian. The Bakken Formation would not see significant production until much later. Waterflooding began to take place as primary production waned in the 1960's, with $CO_2$ miscible flooding occurring at the start of the 2000s (Burrowes and Gilboy, 2001). The Bakken formation began to see higher rates of production in the early 1990's with the introduction of horizontal well drilling and HF (Iwere et al., 2012). Today, production continues in the Bakken as well as many of the more conventional Devonian and Mississippian aged formations using water flooding and $CO_2$ miscible floods.

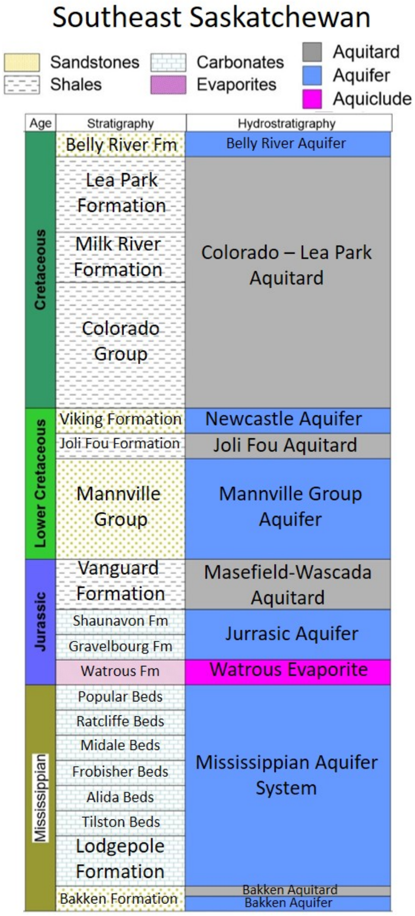


Figure 2.4: Generalized lithostratigraphy and hydrostrigraphy of SE Saskatchewan (after Jensen et al., 2013).

## 1.8 Machine Learning and Random Forest

Machine learning involves the automated detection of patterns in data and can be split into two sub disciplines: supervised and unsupervised learning (Shalev-Shwartz and Ben-David, 2014). Supervised learning involves creating a model using known input and output pairs to predict an unknown output using known inputs, whereas unsupervised learning involves using inputs but no supervising outputs to explore patterns and relationships within the data (James et al., 2017). Unsupervised learning in the context of investigating leaky oil and gas wells could involve, for example, using some clustering analysis method to determine which wells are most similar to each other to aid in generalizing well integrity by specifying different groupings of wells. Supervised learning in the context of this thesis involves predicting the occurrence of well leakage for unmonitored wells using a model trained on a known dataset of well attributes (input) and whether the well has experienced leakage (output) (e.g. Montague et al., 2018). If some knowledge of which inputs are likely to have the most influence on the outcome is available, as is the case with the surface expression of oil and gas well leakage (e.g. Watson and Bachu, 2009; MacDonald, 2016; Bachu, 2017; Wisen et al., 2020), then the goal of the supervised learning is likely predictive accuracy rather than the interpretability of the model.

With supervised learning and high predictive accuracy identified as the best method to achieve the goals of this study the question was how to select the best algorithm with which to model the data. Before this could done some general understanding of the data structure was necessary. The oil and gas industry is data rich and so there are many potential inputs (predictors) that could be used to model the occurrence of well leakage. Some of these predictors will likely be correlated with other predictors (multicollinearity) and may not have a large degree of relevance to predicting the output (weak predictors), thereby introducing noise to the dataset. Predictor relationships with the output may also be highly non-linear. These attributes lend themselves well to machine learning algorithms such as support vector machines, neural networks, and random forest which are all black box type models with higher predictive accuracy at the cost of interpretability (Hastie et al., 2009). In particular, random forest likely has a predictive edge over the other algorithms listed above for this particular application due to its general resistance to highly correlated variables (Kirasich et al., 2018), and its ability to make use of weak predictors (Breiman, 2001). In a study of a small region of Alberta, Montague et al. (2018) used a variety of machine learning models to predict the surface expression of wellbore leakage and in fact found random forest to have the best performance.

Random forest belongs to the ensemble-based machine learning algorithm group (Breiman, 2001). The algorithm utilizes many decision trees, on their own each tree has high variance (Breiman, 2001). Random forest reduces the high variance of these individual decision trees through a process known as bagging. Bagging in the context of random forest involves the algorithm creating N number of decision trees from a subsample of the training data, and then averaging the predictions together (James et al., 2017). Model variance is then further reduced by only considering a subset of the available predictors when constructing each decision tree, effectively resulting in the decorrelation of the decision trees (James et al., 2017). Splits in the decision tree nodes are determined using the Gini index, which is an approximation of entropy

(Menze et al., 2009). A split that results in the most homogenous grouping of one class, for example all wells in the grouping either leak or do not leak, is chosen over splits that result in a more heterogeneous partitioning of the output classes. This is a top down greedy approach known as recursive binary splitting whereby the best split is made for the current step and does not consider whether a different split could lead to more globally optimal splits later down the tree (James et al., 2017). The original algorithm by Breiman (2001) has been altered in a number of ways to produce other versions of random forest (e.g. Geurts et al., 2006, Hothorn et al., 2006, Deng and Runger, 2013, and Wright and Zeigler, 2016). These alternate versions of random forest employ methods that typically have trade offs such as having higher performance for specific types of datasets at the cost of decreased performance for other dataset types (e.g. Geurts et al., 2006), or have increased performance at the cost of increased computation time (e.g. Strobl et al., 2007). Algorithms are available that can assist in selecting the algorithm most likely to have the best performance based on the various algorithms performance on benchmark datasets (Brazdil and Giraud-Carrier, 2018), a process otherwise known as meta-learning, but such an algorithm could not be found that included many of the different iterations of the random forest algorithm. In lieu of an applicable meta-learning algorithm trial and error can be used to determine the best performing machine learning algorithm.

## 1.9 Summary

Several modes of failure exist for well barriers with the most critical barrier element being the cement sheath around a well casing. Cement sheaths can fail either due to the use of poor materials or emplacement techniques, through changes in pressure or temperature, or likely through the interactions of the two. In the two case study locations there are substantial numbers of old abandoned wells located within conventional reservoirs that are experiencing repressurization due to EOR or waste injection activities. These same wells also intersect or are in close proximity to formations that are currently being hydraulically fractured. It appears that within the case study boundaries there is an intersection between the location of older wells of likely poor integrity and the potential for modern subsurface development to affect these older wells. Closer scrutiny of the spatial relationships between modern and historic subsurface activities are warranted given the risks to water resources.

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# AQUIFER COMMINGLING IN ABANDONED BOREHOLES: SPATIAL DISTRIBUTION OF A HIDDEN LIABILITY

## 1.11 Preface:

This chapter was completed in collaboration with Chris Perra, Dr. Jennifer McIntosh, Theresa Watson, and Dr. Grant Ferguson. Chris Perra wrote, analyzed the data, and produced the figures for the thesis. Dr. Jennifer McIntosh and Dr. Grant Ferguson conceptualized and planned the project, as well as providing project oversight. Theresa Watson provided well regulation and construction timelines for the province of Alberta, insight into Alberta oil and gas well integrity issues, assistance with interpreting well tour reports, and insight on study site selection.

## 1.12 Summary:

The interactions between old abandoned wellbores with suspect integrity and HF, EOR, SWD operations can result in upward leakage of deep fluids into overlying aquifers. This risk is largely unquantified as monitoring abandoned wells is rarely done, and leakage may go unnoticed especially when into deeper aquifers. As a first step to estimating this risk, this study performs a proximity analysis between old abandoned wells and HF, EOR, and SWD wells, and identifies comingled formations in old abandoned wellbores to identify the locations with the greatest potential hazard at three study sites in the WCSB. This analysis indicates that at all three study sites there is overlap between old abandoned wells and HF, EOR, or SWD operations. Much of this overlap occurs in formations above typically-produced hydrocarbon reservoirs but below potable aquifers, otherwise known as the intermediate zone, which is often commingled 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.

## 1.13 Introduction

Upward leakage of deep fluids through wellbores can result in the contamination of aquifers (Thamke and Smith, 2014), 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). These hazards pervade many 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 conventional formations (Zou et al., 2015). As early as the late nineteenth century, some of the initially produced conventional hydrocarbon reservoirs were depleted and EOR methods such as waterflooding were used to continue production (Fettke, 1938; Satter et al., 2008). More recently, in locations with lower reservoir permeability, high volume 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 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 (Birdsell et al., 2015; Dockrill and Shipton, 2010; Flewelling et al., 2013). 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 (Darrah et al., 2014; Digiulio and Jackson, 2016; Jacobs, 2009; Pollack et al., 2020; Sherwood et al., 2016).

The potential that an inadequately sealed wellbore could result in the cross-formational flow of fluids predicated many of the early oil and gas well construction regulations in the United States and Canada (Gass et al., 1977; Pettyjohn, 1971). Over time, knowledge gained about the causes of pollution led to improvement in well construction regulations, while better well construction practices also reduced the hazard and probability of oil and gas well integrity failure (King and King, 2013). Modern oil and gas wells may have less risk of leaking, however hundreds of thousands of older oil and gas wells in the United States and Canada were previously constructed and abandoned under less rigorous regulatory oversight and using inferior well construction practices (Richter et al., 1991). Recent studies on the integrity of old abandoned oil and gas wells have largely been based upon risk assessments for carbon sequestration, and hazard and probability assessments for HF (e.g. Carroll et al., 2016; Dilmore et al., 2015; Watson, 2009; Watson and Bachu, 2008). Risks to potable and brackish aquifers from 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 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 into brackish aquifers 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). While brackish aquifers are not widely utilized outside of the oil and gas industry in Alberta and Saskatchewan, in some locations there are concerns about the availability of freshwater to meet demand (Pernitsky and Guy, 2010; Tanzeeba and Gan, 2012), potentially leading to wider utilization of brackish aquifers in the future (e.g. Stanton et al., 2017). This unknown potential occurrence of leakage at depth requires investigation.

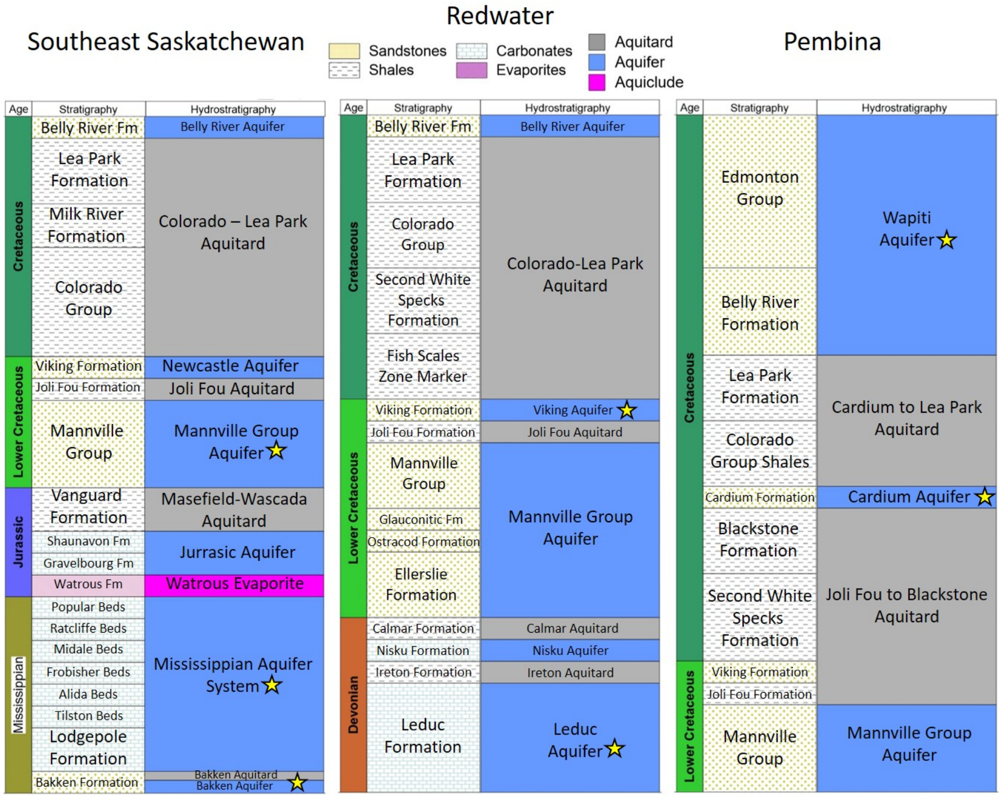
In order to investigate the occurrence of abandoned wells leaking at depth, the locations with the highest probability of leakage occurring must first be identified. Many sedimentary basins around the world have old abandoned wells and ongoing oil and gas production that could be investigated; however the 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 risks posed to brackish and potable aquifers by pre-1960s legacy oil and gas wells. Here, this study aims to: 1) assess the potential for upward migration of brines and hydrocarbons through legacy oil and gas wells due to the pressure produced from nearby HF and EOR activities; 2) explore the likelihood that such 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 commingled wellbores may reduce the effective permeability of intervening aquitards. The probability of hazards 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). Insights gained will improve the understanding of risks posed to brackish and potable aquifers by legacy abandoned wells, identify some locations where the hazards may be greatest, and help determine whether current regulations are adequately managing these risks as they relate to HF and EOR/SWD operations.

## 1.14 Geologic Setting

The WCSB is encompasses two sedimentary basins: the intercratonic Williston Basin in the southeast corner and the northwest trending Alberta Basin along the western edge (Figure 3.1). The Alberta Basin is a structural, retroarc foreland, monocline shaped basin and is filled with a wedge of Phanerozoic strata above Precambrian Bedrock adjacent to the Cordilleran Fold and Thrust Belt. The basin began to form in response to the rise of the Rocky Mountains during the Devonian Period (415 to 360 million years ago). The Alberta Basin ranges in thickness from 0 m at the Canadian Shield to a maximum approximate thickness of 6,000 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 4,875 m (Gerhard et al., 1982). The origin of the Williston Basin is thought to be in response to a combination of mechanisms that resulted in cratonic subsidence (Kent and Christopher, 1994). 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 (Bachu et al., 2011; Schoenfeld et al., 2010). 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 of greatest interest to this study are starred in Figure 3.2.

Figure 3.1: 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.



| Age | Stratigraphy | Hydrostratigraphy |
|---|---|---|
| Cretaceous | Belly River Fm | Belly River Aquifer |
| | Lea Park Formation | Colorado – Lea Park Aquitard |
| | Milk River Formation | |
| | Colorado Group | |
| Lower Cretaceous | Viking Formation | Newcastle Aquifer |
| | Joli Fou Formation | Joli Fou Aquitard |
| | Mannville Group | Mannville Group Aquifer ☆ |
| Jurassic | Vanguard Formation | Masefield-Wascada Aquitard |
| | Shaunavon Fm | Jurrasic Aquifer |
| | Gravelbourg Fm | |
| | Watrous Fm | Watrous Evaporite |
| Mississippian | Popular Beds | Mississippian Aquifer System ☆ |
| | Ratcliffe Beds | |
| | Midale Beds | |
| | Frobisher Beds | |
| | Alida Beds | |
| | Tilston Beds | |
| | Lodgepole Formation | |
| | Bakken Formation | Bakken Aquitard<br>Bakken Aquifer ☆ |

| Age | Stratigraphy | Hydrostratigraphy |
|---|---|---|
| Cretaceous | Belly River Fm | Belly River Aquifer |
| | Lea Park Formation | Colorado-Lea Park Aquitard |
| | Colorado Group | |
| | Second White Specks Formation | |
| | Fish Scales Zone Marker | |
| Lower Cretaceous | Viking Formation | Viking Aquifer ☆ |
| | Joli Fou Formation | Joli Fou Aquitard |
| | Mannville Group | Mannville Group Aquifer |
| | Glauconitic Fm | |
| | Ostracod Formation | |
| | Ellerslie Formation | |
| Devonian | Calmar Formation | Calmar Aquitard |
| | Nisku Formation | Nisku Aquifer |
| | Ireton Formation | Ireton Aquitard |
| | Leduc Formation | Leduc Aquifer ☆ |

| Age | Stratigraphy | Hydrostratigraphy |
|---|---|---|
| Cretaceous | Edmonton Group | Wapiti Aquifer ☆ |
| | Belly River Formation | |
| | Lea Park Formation | Cardium to Lea Park Aquitard |
| | Colorado Group Shales | |
| | Cardium Formation | Cardium Aquifer ☆ |
| | Blackstone Formation | Joli Fou to Blackstone Aquitard |
| | Second White Specks Formation | |
| Lower Cretaceous | Viking Formation | |
| | Joli Fou Formation | |
| | Mannville Group | Mannville Group Aquifer |

Figure 3.2: Simplified stratigraphic and hydrostratigraphic columns for the Southeast Saskatchewan, Redwater, and Pembina study areas. The columns are modified from Jensen et al. (2012), Brydie et al. (2011), and Dashtgard et al. (2008) for the Saskatchewan, Redwater, and Pembina study areas, respectively.

## 1.15 Abandoned Well Integrity and Upward Hydraulic Gradients:

Reviewing the history of well regulations and well construction technology can provide an estimate for a date before which wells abandoned would likely have appreciably worse integrity than wells abandoned after. A thorough review of 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 A1 of Appendix A in the Supporting Information. This review concluded that old wells abandoned before 1960 in the WCSB could be expected to have worse integrity than those abandoned after potentially leading to commingling of aquifers over large sections of the borehole. However, in order for failed integrity to present a hazard 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 result in the transport of injected fluids as well. Further, North America has seen a ten-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 that present the greatest hazard 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) and Pennsylvania (e.g. Dilmore et al., 2015; Montague and Pinder, 2015), but in Canada such studies have mainly focused on risks posed by geologic carbon sequestration (e.g. Celia et al., 2011). Further, these studies on oil and gas production activities contemplated the potential for frac hits 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 commingled within the wellbore. Information regarding formation commingling in old 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.

## 1.16 Methods

### *1.16.1 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 3.1) 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 pre-processing 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 HF wells, the HF formations included in the analysis are the Bakken, Cardium, and Viking formations (Figure 3.2) for the Southeast Saskatchewan, Pembina, and Redwater study areas, respectively. For the HF analysis, abandoned well's were further categorized into four different hazard ratings depending on the abandoned wells 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). The four abandoned well groups are:

- Hazard 1: drilled into or below the HF Formation;
- Hazard 2: drilled to within 150 m above the HF Formation;
- Hazard 3: drilled to within 350 m above the HF Formation;
- Minimal or no risk: drilled to a depth that is greater than 350 m above the Formation

The HF formations studied here are the Bakken, Cardium, and Viking formations (Figure 3.2) 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 ModelBuilder (ESRI, 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; Alberta Energy Regulator, 2016; Bommer et al., 2017; Lefebvre, 2017; Watson, 2013). 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 being that 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 (Appendix A, Table A.2). Further information on data preprocessing, and the spatial analysis between HF, EOR/SWD, and old abandoned wells is available in Appendix A, Sections A2.1-A2.3, respectively.

### *1.16.2 Review of Abandonment Reports*

To better understand the vulnerability of old abandoned wells to inter-borehole flow, tour and completion reports were reviewed for a subset of abandoned wells that were identified as being located near an EOR/SWD well. Tour reports were reviewed to identify which aquifer units were left open and connected between plugs (commingled), and behind uncemented casing (Supporting Information, Section A2.4). Inter-borehole flow could be expected to occur where commingled wells are located near HF or EOR/SWD, which would create strong vertical hydraulic gradients between adjacent aquifer units in most cases. 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 cement sheath, 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 A.3 in Appendix A; 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 ($k_l$) is described by a formula developed by Rayleigh (Rayleigh, 1892) and presented by Pietrak and Wisniewski (Pietrak and Wiśniewski, 2015):

$$k_e = k_m[1 + (k_l - k_m)/k_m)\phi] \qquad [3.1]$$

where $\phi$ is the fraction 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 A.3 in Supporting Information). The case of a rigid open hole with an incompressible fluid is also considered by using the Hagen-Poiseuille equation to estimate $k_l$:

$$k_l = r^2/8 \qquad [3.2]$$

Where $r$ is the radius of the wellbore. 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 ($\phi$) present within the three study sites are also examined.

## 1.17 Results and Discussion

### *1.17.1 Oil and Gas Well Data Overview*

Each study area has substantial differences in the number and type of oil and gas-related wells present (Table A.4 in Appendix A). Total well counts for each study area range from 41,747 for Southeast Saskatchewan to 5,223 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 A.5 in Appendix A lists the number of wells for the three well types used in the spatial analysis: wells fractured after 2000, wells that were injecting any time after 2000, and wells abandoned before 1960. The Pembina study area has over three times the amount 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 ten 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 3.2) 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 (Bachu et al., 2011; Singhal, 2009). 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.

### *1.17.2 Abandoned Wells Near EOR/SWD Wells*

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 3.3) 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. 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 inverse 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.

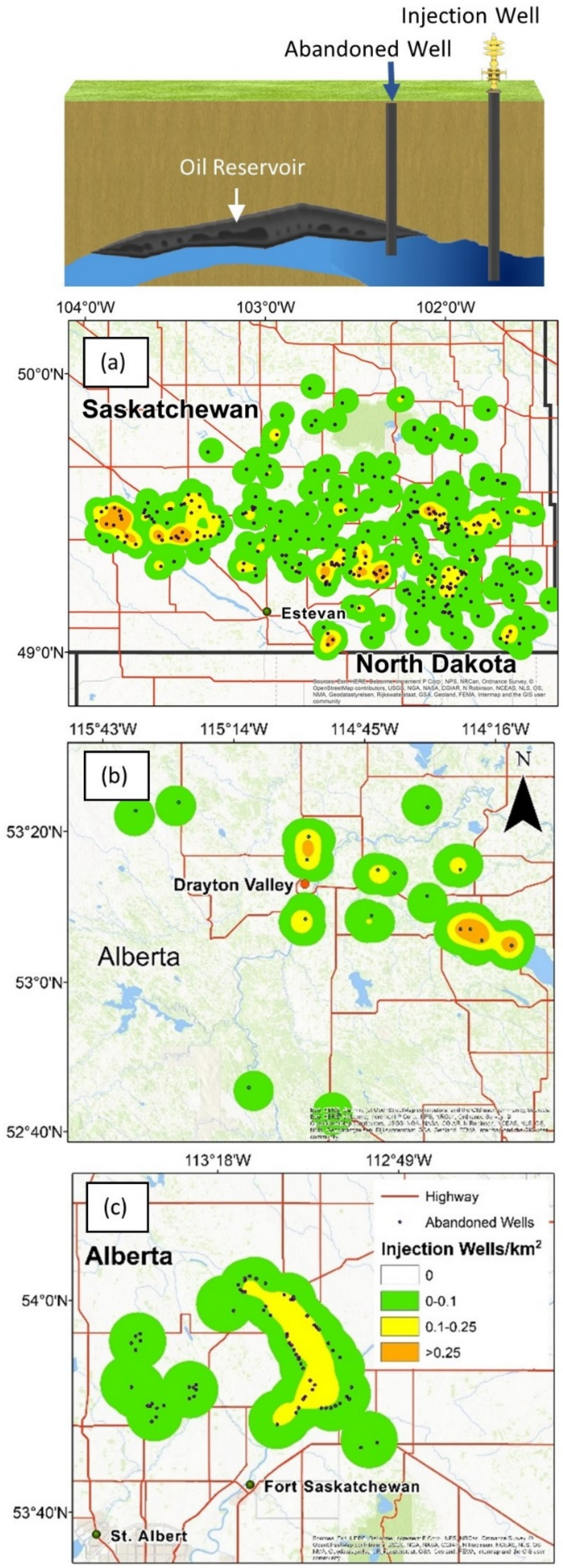


Figure 3.3: Density of EOR/SWD wells that are located nearby (within 2 km of) old abandoned wells for (a) Southeast Saskatchewan, (b) Pembina Field, and (c) Redwater.

### *1.17.3 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 hazard groups depicts distinct differences amongst the three case study areas (Figure 3.4). The Southeast Saskatchewan study area has 55 HF and 39 abandoned wells spread out amongst 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 near five abandoned wells classified as hazard 1. By contrast, the majority of the identified abandoned wells at the other two study areas (Pembina and Redwater) are classified as hazard 1, which indicates that the abandoned well either passes through or is completed into the formation that has been HF by 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 112 HF wells located near 34 abandoned wells, which indicates that each abandoned well can be near multiple HF wells.

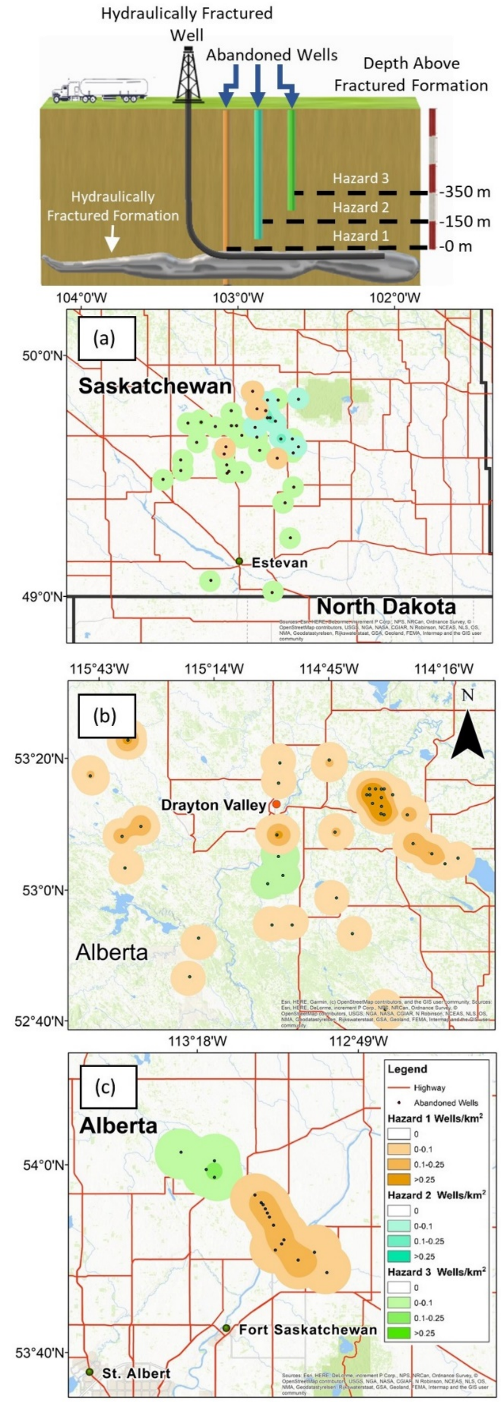


Figure 3.4: Density of HF wells that are located near old abandoned wells for (a) Southeast Saskatchewan, (b) Pembina Field, and (c) Redwater. The bottom right panel depicts the three risk levels.

### *1.17.4 Early Well Abandonment Practices: Open Hole*

Abandonment plug placement locations within abandoned wells were generally similar amongst 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 3.5). 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. 22 out of the 25 open hole abandonments were uncased (except for surface casing), and the three with casing had the 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", or otherwise detected by the drill stem, which indicates that the plug may not have been successfully placed (Watson, 2009). 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 can 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 3.2).

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 3.6). The Viking and Belly River aquifers appear to be commingled in only 1 of the 7 wells reviewed. This is consistent with the tour reports for open hole well abandonments prior to 1960 presented by Watson (2009). For the Pembina area, the open hole abandonments reviewed do not display a strong propensity for one formation to be plugged over another (Figure 3.7). Three aquifer units that appear to be at risk of commingling within uncased abandoned boreholes for the Pembina area are the Cardium, Belly River, and Horseshoe Canyon aquifers. It is likely that for each study area there is a chance of aquifer comingling in some portion of the abandoned open holes, with greater probability occurring in the Pembina and Southeast Saskatchewan study areas, and lesser probability in the Redwater study area.

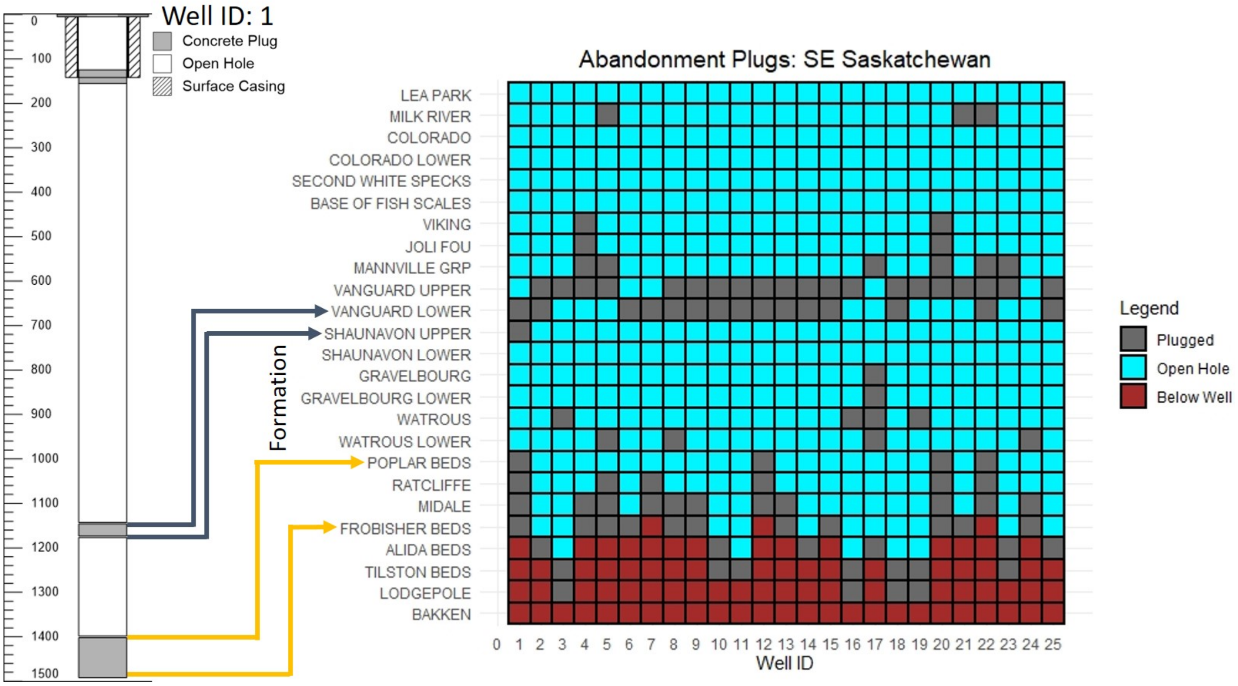
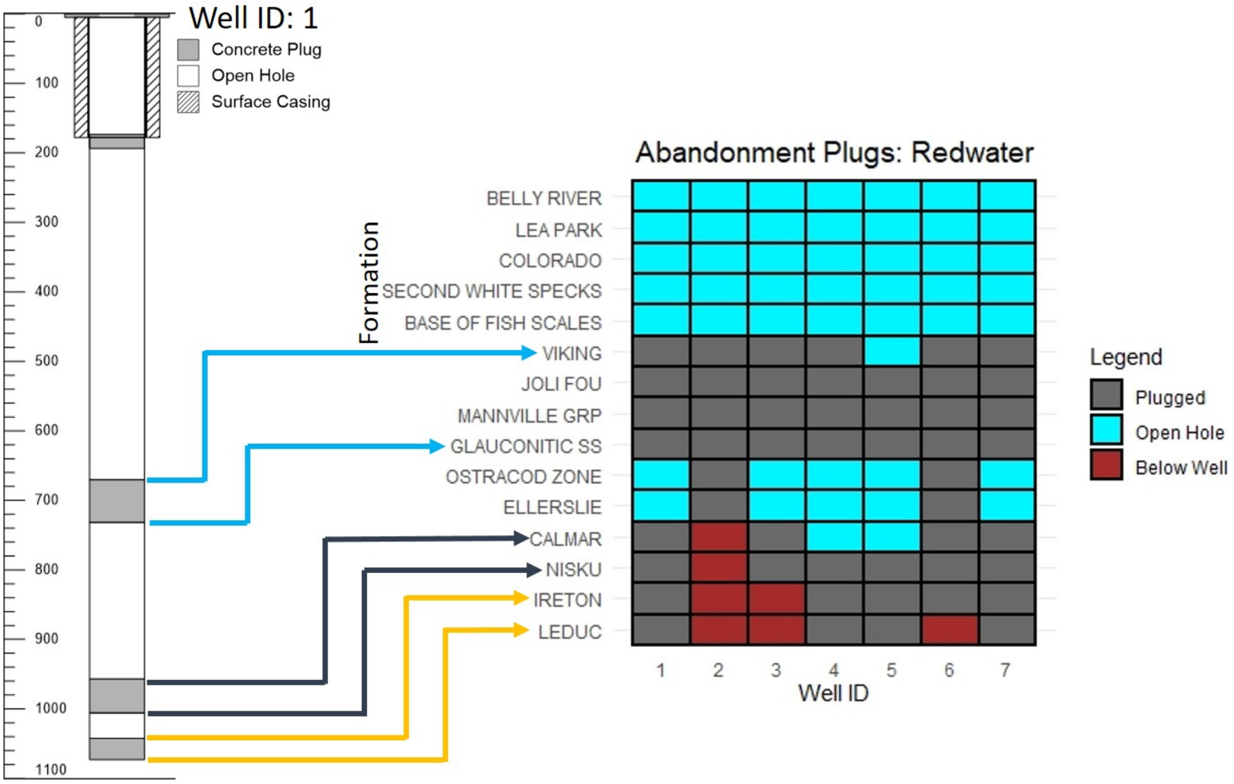
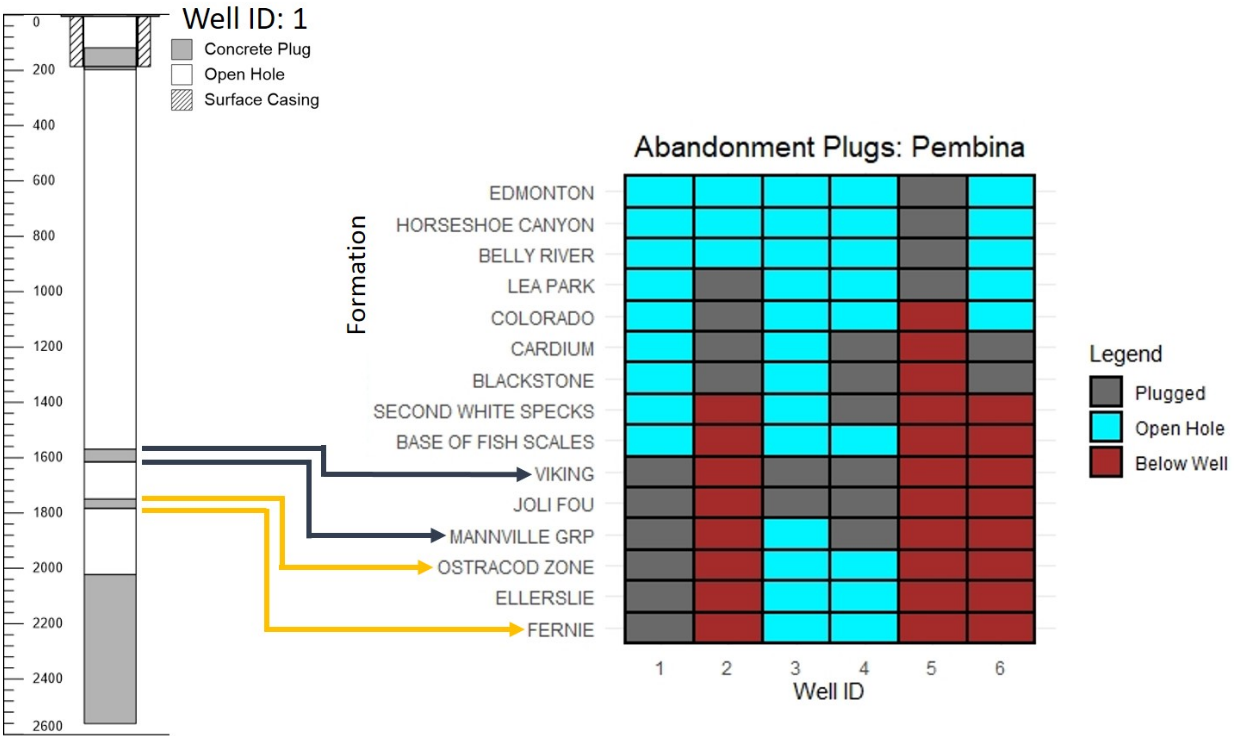


Figure 3.5: An example of a typical well abandonment schematic for a drilled and abandoned well on the left with plug placements in old abandoned wells on the right for the Southeast Saskatchewan study area.



| Formation | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| BELLY RIVER | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole |
| LEA PARK | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole |
| COLORADO | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole |
| SECOND WHITE SPECKS | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole |
| BASE OF FISH SCALES | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole | Open Hole |
| VIKING | Plugged | Plugged | Plugged | Plugged | Open Hole | Plugged | Plugged |
| JOLI FOU | Plugged | Plugged | Plugged | Plugged | Plugged | Plugged | Plugged |
| MANNVILLE GRP | Plugged | Plugged | Plugged | Plugged | Plugged | Plugged | Plugged |
| GLAUCONITIC SS | Plugged | Plugged | Plugged | Plugged | Plugged | Plugged | Plugged |
| OSTRACOD ZONE | Open Hole | Plugged | Open Hole | Open Hole | Open Hole | Plugged | Open Hole |
| ELLERSLIE | Open Hole | Plugged | Open Hole | Open Hole | Open Hole | Plugged | Open Hole |
| CALMAR | Plugged | Below Well | Plugged | Open Hole | Open Hole | Plugged | Plugged |
| NISKU | Plugged | Below Well | Plugged | Plugged | Plugged | Plugged | Plugged |
| IRETON | Plugged | Below Well | Below Well | Plugged | Plugged | Plugged | Plugged |
| LEDUC | Plugged | Below Well | Below Well | Plugged | Plugged | Below Well | Plugged |

Figure 3.6: 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.



Legend: ⬛ Plugged, 🟦 Open Hole, 🟥 Below Well

| Formation | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| EDMONTON | 🟦 | 🟦 | 🟦 | 🟦 | ⬛ | 🟦 |
| HORSESHOE CANYON | 🟦 | 🟦 | 🟦 | 🟦 | ⬛ | 🟦 |
| BELLY RIVER | 🟦 | 🟦 | 🟦 | 🟦 | ⬛ | 🟦 |
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| CARDIUM | 🟦 | ⬛ | 🟦 | ⬛ | 🟥 | ⬛ |
| BLACKSTONE | 🟦 | ⬛ | 🟦 | ⬛ | 🟥 | ⬛ |
| SECOND WHITE SPECKS | 🟦 | 🟥 | 🟦 | ⬛ | 🟥 | 🟥 |
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Figure 3.7: 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.

### *1.17.5 Early Well Abandonment Practices: Cased Wells*

Cased well abandonments have generally been identified as being at greater risk 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 a cement sheath (Figure A.9 in Appendix A). However, while a cement sheath 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 an intervening plug below the top of the cement sheath between the bridge plug near the base of the well and the surface casing shoe, then some or all of the aquifers along the wellbore may become commingled. 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 cement sheath. In general, cased well abandonments reviewed here have a greater number of aquifer units potentially commingled than within open hole well abandonments if casing and cement sheath are considered to be inadequate for horizontal hydraulic isolation.

### *1.17.6 Calculated Changes to Effective Vertical Permeability*

In order to calculate the potential effect abandoned leaky and open wellbores may have on an aquitard's effective permeability using Equation 3.1 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 A.10-A.12 in Appendix A). 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 3.1 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 A.13 in Appendix A). The highest reported field measurements of wellbore permeability results in a two orders of magnitude increase in the aquitard's permeability from $10^{-20}$ 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.

The effect that open or open sections of wellbores can have on effective aquitard permeability by contrast is more striking. Using Equation 3.2, a 177.8 mm diameter open 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 open 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 A.14 in Appendix A). 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 x $10^{-11}$ m$^2$ (Figure A.14 in Appendix A). While leaky wellbores can increase the effective permeability of highly impermeable shales and clays, the impact of open boreholes even at low densities on aquitard effective permeability is significant.

## 1.18 Implications

All three study areas display potential for HF and EOR/SWD to impact wellbores abandoned before 1960, which have an increased probability 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 old abandoned wells common between all study sites. In the Southeast Saskatchewan study area the stratigraphic 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 beneath the older typical target formations (Figure 3.4a). 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 (Figures 3.4b and 3.4c). These findings seem to suggest that when the stratigraphic position of HF and/or EOR/SWD is above that of historical oil and gas targets one would expect greater interactions between the two then in locations where the opposite is the case.

While the population of wells abandoned pre 1960 identified for this study is likely at greater risk of well integrity failure, some unknown number of these wells could maintain their integrity. For the wells that maintain integrity, abandonment plugs may still leave large portions of the wellbore open leading to commingling between aquifer units. 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 operations. Commingled abandoned wells that are located nearby HF or EOR/SWD wells add hazard and probability to those operations that unanticipated cross-formational flow of fluids may occur. Such a hazard exits for EOR/SWD into the Mannville for the Southeast Saskatchewan study area (Figure 3.5), while there is also added hazard for EOR/SWD into the Belly River and Cardium as well as HF in the Cardium (Figure 3.7). 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 open hole abandonments. These boreholes with commingled aquifers could further allow for deep 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, open 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, 2016, 2013). 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 (ER, 2016, 2012). 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 at-risk abandoned well populations. Saskatchewan does not require brine injection well operators to search for and assess offset abandoned wells (ER, 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 (produced water and saline waters) injection wells (Alberta Energy Regulator, 2020, 1994). Alberta's requirement for an area of review for class II 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. Further, there is ambiguity as to how to determine if an abandoned well could allow for migration of injected fluids 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 presents a risk 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. Isherwood, 1980; Upp, 1966; 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. Little information is often 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 (Taylor et al., 2000; 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 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 (Cahill et al., 2019; Davies et al., 2014; Jackson et al., 2013; McIntosh and Ferguson, 2019; Wisen et al., 2020).

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# PREDICTING THE SURFACE EXPRESSION OF WELLBORE LEAKAGE ACROSS ALBERTA

## 1.20 Introduction

Wellbore leakage can result in any one of many adverse environmental consequences such as the release of greenhouse gases (Wisen et al., 2020), pollution of groundwater (Pettyjohn, 1971; Gas et al., 1977), and in rare cases pose an explosive hazard (Chilingar and Endres, 2005). The surface expression of this leakage manifests either as surface casing vent flow (SCVF) or gas migration (GM). SCVF occurs when a well has an inadequate seal across a permeable formation that either has sufficient pressure to drive dense brines to the surface or contains buoyant fluids such as methane (Figure 4.1). In Canada and some portions of the United States the annulus between the surface casing and next string of casing is left open with the surface casing vented to the atmosphere (Lackey et al., 2017). This allows gas to be released to the atmosphere rather than causing pressure to be built up within the surface casing annulus as would occur if the surface casing vent were sealed (Figure 4.1). When surface casing vents are closed as they are in other portions of the United States, pressure buildup in the surface casing annulus can cause damage to the surface casing through sustained casing pressure (SCP). SCP can result in gas leakage into formations located below the surface casing shoe, or cause gas to rise up micro annuli along the cement sheath outside of the surface casing. These two pathways, along with leakage from thin gas bearing zones above the surface casing shoe (Figure 4.1), typically result in the migration of gas through porous media and sometimes to the atmosphere, through a process known as gas migration (GM) (Bachu, 2017).

The rate of wells experiencing well barrier and/or well integrity failure, which can lead to SCVF and GM, has been reported to range widely from 1.9% to 75% depending on location and type of study (Davies et al., 2014). For example, a mobile methane measurement survey of active wells in British Columbia found 46% to be leaking methane (Atherton et al., 2017); however, some of the 46% could be attributable to leakage from other associated infrastructure such as gathering lines, and may not be indicative of SCVF and/or GM. Alberta and British Columbia are some of the few locations where testing of SCVF is mandated after a well is drilled and before it is abandoned. Alberta and Saskatchewan have reported rates of SCVF and GM occurrence over the lifetime of a well of 4.6% and 10.8%, respectively, of their total provincial well population

(Watson and Bachu, 2009; Wisen et al., 2020). However, what is not known with great precision in Alberta, and to some extent British Columbia, is how many wells may currently be leaking between when a well is constructed and when a well is abandoned.

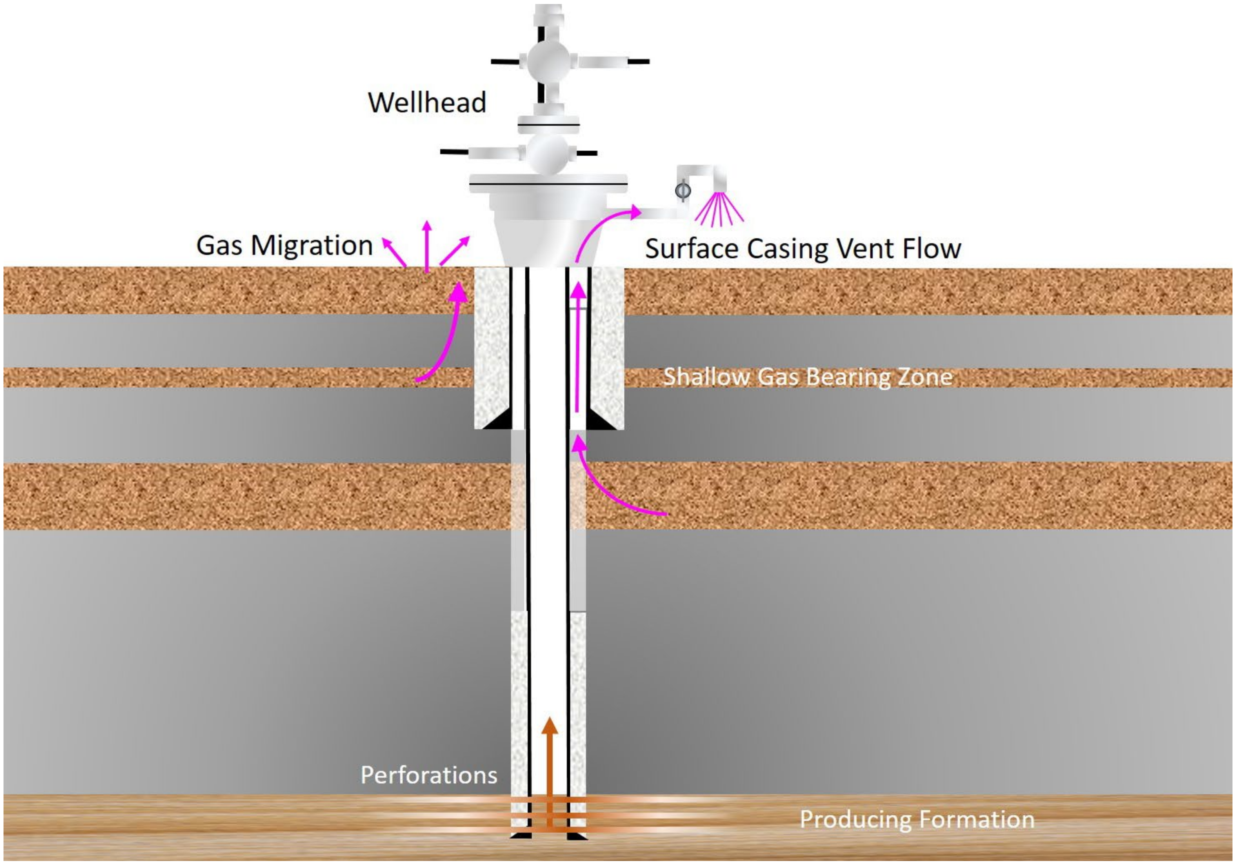

Figure 4.1: Well schematic of a producing well indicating possible pathways of SCVF and GM (after Watson and Bachu, 2008).

The occurrence of SCVF and GM has long been a recognized problem for the oil and gas industry since at least the early 1900s (e.g. Rose and Alexander, 1945). Research into identifying leakage sources within the well, and the best ways to repair or seal the well at the leakage source has been ongoing ever since. More recently, attempts have been made at identifying well populations most at risk of SCVF, GM, and SCP through analysis of large datasets containing information on the occurrence of SCVF, GM, and SCP as well as a large number of various well attributes (Watson and Bachu, 2009; MacDonald, 2016; Bachu, 2017; Lackey et al., 2017; Wisen et al., 2019). The findings of these studies suggest that many predictors are needed to model the occurrence of SCVF and GM (response variables). The relationships between these predictors and the response variable are complex, and often nonlinear. Modeling of high dimensional, nonparametric data with the aim of achieving the highest accuracy possible is often best achieved through the use of 'black-box' type machine learning algorithms. Montague et al. (2018) has previously modeled the occurrence of SCVF and GM in a small area of Alberta, using a variety of machine learning algorithms, identifying the random forest algorithm as having or resulting in the best performance. This study aimed to build on the work of Montague et al. (2018) by first reviewing the well attributes thought to be most important to predicting SCVF and GM, creating a dataset that covers all of Alberta, and then reviewing the performance of five different random forest algorithms. It was expected that the model would perform worse than Montague et al. (2018) given the greater variety of geologic settings covered, and reduction in available predictors for modeling a larger well population. Even with reduced performance, the model will still prove useful to identifying wells at greater risk of SCVF and GM.

### 1.21 Well Attributes that Influence SCVF/GM Occurrence

Wells with SCVF or GM typically produce buoyant fluids such as methane. In a 2020 study in British Columbia, 97.2 % of wells with reported SCVF or GM discharged gas while only 2.8 % of wells with SCVF discharged a liquid (Wisen et al., 2020). The released methane falls into two categories; thermogenic methane and biogenic methane. Biogenic methane is produced by bacteria through methanogensis in reduced environments at up to 80° Celsius (C) (Head et al., 2003), while thermogenic methane is produced by the cracking of source rocks with high organic content at high temperature and pressure. While thermogenic methane can be roughly identified by gas composition, as microbes typically do not produce significant hydrocarbons other then methane and can note produce higher alkanes than methane, such analyses can be deceiving due to a 'chromatographic' effect as thermogenic gases travel through organic rich shales or clays (Martini et al., 2003). Other moderately more accurate methods used to differentiate between thermogenic and biogenic methane include evaluating gas isotope signatures of hydrocarbons through the use of diagrams such as the "Bernard" and "Schoell" diagrams (Mcintosh et al., 2018). It is these methods along with an isotopic source depth profile that are typically used to calculate the source depth of leaking hydrocarbons (Rowe and Muehlenbachs, 1999; Szatkowski et al., 2002; Tilley and Muehlenbachs, 2012). In the WCSB, within which Alberta is located, the source of gases from SCVF and GM have been typically identified as originating in formations below potable groundwater but above target hydrocarbon reservoirs, a region otherwise known as the intermediate zone (Rowe and Muehlenbachs, 1999; Szatkowski et al., 2002; Tilley and Muehlenbachs, 2012; Bachu, 2017). It is worth noting that these isotopic depth profiles of hydrocarbon gases do have their limitations as microbial and thermogenic gas regions can overlap, gas sources can be mixed, and isotopic signatures of hydrocarbons can be altered during migration and microbial oxidation (Mcintosh et al., 2018; Humez et al., 2019). Generally these depth profiles do not provide information on the potential pathway that the gas has utilized to cause SCVF/GM. However, they do provide general information on where the leakage originated, generally identified as within the intermediate zone. This information provides an important starting point to identifying potential predictors to use in a random forest model.

Alberta and British Columbia are unique regulatory jurisdictions in that they both require testing of SCVF within 90 days after well construction and prior to well abandonment. This testing information has been tabulated into extensive databases containing information on SCVF and GM occurrences since the implementation of the 1995 testing regulations which began requiring testing of wells prior rig release and abandonment in British Columbia and Alberta. In 2010, British Columbia began to also require testing during well construction, recompletions, or maintenance (Wisen et al., 2020). Previous researchers have reviewed this data and used descriptive and inferential statistics to identify well attributes that influence or are related to the occurrence of SCVF and/or GM (Watson and Bachu, 2009; MacDonald, 2016; Bachu, 2017; Wisen et al., 2020). The available research is most extensive with regards to the Alberta Energy Regulator (AER) SCVF/GM dataset.

In Alberta the factors that were shown to have the greatest effect on SCVF/GM are wellbore deviation, geographic area, and well construction date (spud date), with the most important factor being the length of uncemented interval above the top of the intermediate casing cement sheath and the bottom of the surface casing shoe (Watson and Bachu, 2009; MacDonald, 2016; and Bachu, 2017). Well depth was also found to have some effect due to its association with length of uncemented interval as deeper wells typically have longer uncemented intervals (Watson and Bachu, 2009). Given that most SCVF/GM has largely been identified to originate in the intermediate zone, it would make sense that wells with a large uncemented interval across the intermediate zone would be at greatest risk from SCVF/GM over wells that are cemented to the surface.

While the well attributes identified as being the most likely to influence the occurrence of SCVF/GM are expected to improve the performance of any machine learning model, random forest can also derive ‘learning’ from other very weak predictors as long as the correlation between them is low (Breiman, 2001). Furthermore, random forest algorithms are generally resistant to the effects of highly correlated variables, unlike many other machine learning algorithms, although such correlation will reduce the usefulness of weak predictors (Kirasich et al., 2018). Random forest is best described as an ensemble-based learning algorithm that utilizes decision trees (Breiman, 2001). Random forest creates N number of decision trees from a subsample of the training data, and then all the predictions are averaged reducing the variance of the model predictions through a process known as bagging (James et al., 2017). Random forest further reduces model variance by only considering a subset of the available predictors when constructing each decision tree, which results in the decorrelation of the individual decision trees (James et al., 2017). The algorithm performs well on high dimensional datasets due to its implicit feature selection by making greater use of strong predictors over weak predictors in decision tree splits by selecting those predictors that provide the greatest decrease in Gini index, which is an approximation of entropy (Menze et al., 2009). This allows many predictors, weak or strong, to be added to the model without a significant penalty on model performance. This property of the random forest algorithm allows for the use of predictors such as well spud date (Figure 4.2a, and Figure 4.2b), operational mode, and well depth that have been previously identified as being poorly or weakly correlated with SCVF/GM through bivariate statistical methods (Watson and Bachu, 2009; MacDonald, 2016; and Bachu, 2017). However, increasing the dataset dimensionality does come at a cost of also increasing the computation time of running the model (Wright and Zeigler, 2016).

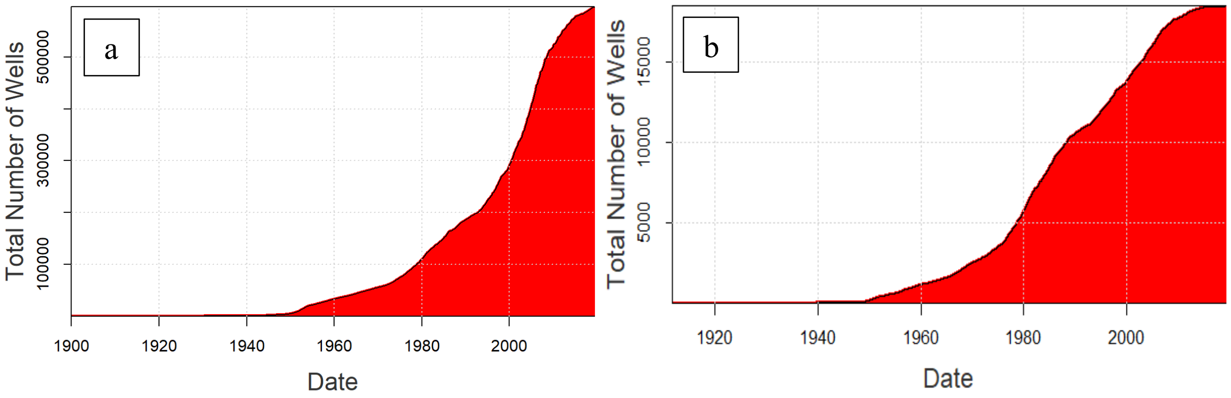

Figure 4.2: Figure (a) is a cumulative plot of wells constructed in Alberta by spud date, while figure (b) is a cumulative plot of wells known to have experienced SCVF/GM by the wells spud date.

### 1.22 Methods

Data on SCVF and GM was queried by AER in May 2019 and includes all reported occurrences of SCVF and GM up to that date. AER provided this data in the form of a database report. Well attributes for all wells in Alberta were downloaded from Accumap V29.05 (IHS Energy, 2019) and includes well attribute information also up to May 2019. The AER SCVF and GM dataset for each well has information such as the well's unique well ID (UWI), the date that the offending incident was reported, what type of leakage occurred (SCVF or GM), the amount of fluid that leaked, along with other attributes. One limitation of the AER dataset is that it only reports UWIs down to the nearest legal subdivision (40 acres). The Accumap (Alberta wells) dataset contains 33 columns of well attributes including UWI, Spud Date, Well Depth, etc. for a total of around 630,000 wells in Alberta, a total which includes applications for yet to be drilled wells (Appendix B). In order to manipulate, process, and analyze such large datasets the statistical software R was used (R Core Team, 2020). All methods described herein can be found in an R markdown document in Appendix B along with the scripts used to produce all figures except Figure 4.1.

Several data manipulations and quality control steps were needed before a final dataset combining the chosen well attributes and the known occurrence of SCVF and GM could be input into a random forest algorithm. These steps included deleting duplicate well entries, identifying errors/inconsistencies in the SCVF and GM and Alberta wells datasets, removing all wells that are located in a legal subdivision with more then one well, and finally merging the Alberta wells dataset of well attributes to the wells contained in the SCVF and GM dataset using UWI for matching wells together. In both the SCVF and GM dataset and the Alberta wells dataset there were numerous duplicate entries for each well. For the SCVF and GM dataset this was due to a separate entry being created each time a given well experienced SCVF and GM while the Alberta wells dataset sometimes had multiple entries for wells that had commingled production or had been recompleted into a new formation. The errors/inconsistencies identified in the Alberta wells dataset included wells that indicate production began after the recorded last production dates, wells without spud dates, and abandonment dates that occur greater than five years before a recorded SCVF and GM incident. The wells with these errors/inconsistencies were removed from the Alberta wells dataset. For the SCVF and GM dataset, while recording of SCVF and GM occurrences had been required since 1995, with some voluntary entries before this date, the early entries in the dataset may not be as reliable before 2003. This is because electronic submission of data was not required until 2003 when Interim Directive 2003-01 was implemented (AER, 2003). Therefore, only occurrences of SCVF and GM after 2003 were used, leaving a total of 11975 wells within the AER dataset. Due to the AER dataset only reporting UWIs down to the nearest legal subdivision all wells located within legal subdivisions with more then one well also had to be removed in order to ensure that wells were correctly identified when matching UWIs between the two datasets. After these adjustments to the Alberta wells dataset and the AER wells dataset, respectively, the two lists were merged using UWI as a common identifier.

With a comprehensive dataset of SCVF and GM occurrences, a dataset of wells known not to have either SCVF or GM was still needed before a complete training/testing dataset could be created. Such wells were identified as those abandoned after 2003, and did not have their UWI listed in the original unedited SCVF and GM dataset indicating that the well experienced SCVF and/or GM. The total number of wells identified with no known SCVF or GM was 94,416, while the dataset of known SCVF and GM occurrences totaled 11,975 wells, showing 82,441 fewer wells. When random forest is trained on an unbalanced dataset it will minimize the overall error rate at the cost of accurately predicting the minority class. However, adjustment of the class weighting can counteract this tendency and provide an easy cost-efficient improvement in accuracy for the prediction of the minority class (Chen et al., 2004). In order to force the algorithm to weight the two response variables more equally, the majority class was undersampled by making a random selection of wells equal to that of the SCVF and GM dataset (minority class) from the dataset of wells known not to have experienced SCVF and/or GM (majority class). The wells known to have experienced and the wells known not to have experienced SCVF and/or GM were combined into one testing/training dataset. The testing/training dataset was then reduced to only the predictors to be used in the random forest algorithms (Table 4.1) and the known outcomes. Notably, the previously identified most important predictor to determining SCVF and GM, the length of the uncemented interval, is not used here as it is not contained in the AccuMap database. The predictors that were factors, basin, play, play type, fluid, and license type, had any entries that were blank or listed as NA changed to the factor NONE, such that the wells associated with such entries could still be included in the testing/training dataset. For all other numeric predictors listed in Table 4.1, wells with entries that were blank or listed as NA were removed leaving a total of 23,949 wells, or one less well then before, in the testing/training dataset.

Table 4.1: List of predictors used to model SCVF and GM.

| PREDICTOR | ACRONYM |
|---:|:---:|
| Days the well has been on production | ProD |
| True vertical depth | True_Vert_Depth |
| Spud date | Spud_Date |
| How many days it took to drill the well | D_Drilled |
| Type of fluid produced | X.Fluid |
| Which basin the well is located in | X.Basin |
| Type of well license | License_Type |
| Type of well (vertical, horizontal, deviated) | X.Type |
| Which play the well is located in | X.Play |
| Type of play (oil, gas, ect.) | Play_Type |
| Days the well has been on injection | InjD |

The caret R package (Kuhn, 2008) was used for all further preprocessing and for running the random forest models. The five random forests models to be considered were chosen by selecting the most downloaded random forest packages on the Comprehensive R Archive Network that were available for use through the caret R package (Table 4.2). Using the caret package 10% of the training/testing dataset was partitioned into a dataset consisting of 2,396 wells, to train the random forest models. This training/testing dataset was then split further using 10 fold cross-validation. Although this step is not necessary to evaluate random forest models due to the algorithm’s inclusion of bagging (James et al., 2017), 10 fold cross-validation was used here to allow for the creation of confidence intervals for model performance. The five random forest models were run using the caret and caretEnsemble (Deane-Mayer and Knowles, 2019) package’s wrappers so that each model used the same training/testing and validation, datasets making the results directly comparable. Models were evaluated using both the overall classification accuracy of the predictions and using the Cohen’s Kappa statistic. Accuracy is calculated as the total of True Positives and True Negatives divided by the total number of observations, while Cohen’s Kappa statistic is related to classification accuracy but is normalized to the baseline of random chance for the given dataset (Ferri et al., 2009). The importance of each predictor was determined using the best performing model by calculating the mean reduction in Gini index over splits using a given predictor based on the methods originally described by Breiman (2001). Finally, a receiver operator curve was produced using the ROCR package (Sing et al., 2005) to evaluate the effect of using different cutoff values depending on the potential desired outcome of the prediction by a regulatory agency or oil and gas operator.

Table 4.2: Random forest algorithms used to model SCVF/GM.

| ACRONYM | FULL NAME | PACKAGE | ORIGINAL PUBLICATION |
|---|---|---|---|
| ranger | Random Forest Generator | ranger | Wright and Zeigler, 2016 |
| cforest | Conditional Inference Forest | party | Hothorn et al., 2006 |
| rf | Random Forest | randomForest | Breiman, 2001 |
| RRF | Regularized Random Forest | RRF | Deng and Runger, 2013 |
| extratrees | Extremely Randomized Trees | extraTrees | Geurts et al., 2006 |

## 1.23 Results and Discussion

It was not possible to include all of the predictors identified by previous researchers as being the most likely to influence the occurrence of SCVF and GM. The most important predictor, amount of uncemented casing between the surface casing shoe and the top of the cement sheath around intermediate casing, can only be estimated using well tour reports or applicable well logs. Compiling a large dataset of the amount of uncemented casing could be cost prohibitive in the case of reviewing well tour reports purchased through the AER, and is likely time prohibitive using either or both methods. However, some other available predictors may be correlated with some of the previously mentioned missing important predictors and may also work to approximate some of them in the algorithm. One predictor identified as being important, well location (Figure 4.3a and Figure 4.3b), was approximated using the basin and play that each well was located within. Another potentially important predictor, whether a well was drilled and abandoned before use, or completed and cased was approximated using the number of days the well produced. If a well did not produce any oil and gas it is more likely to have been drilled and abandoned. Ultimately the exclusion of identified important predictors likely results in a model with reduced model performance over one that was able to include all the predictors of SCVF/GM that are thought to most impact its occurrence.

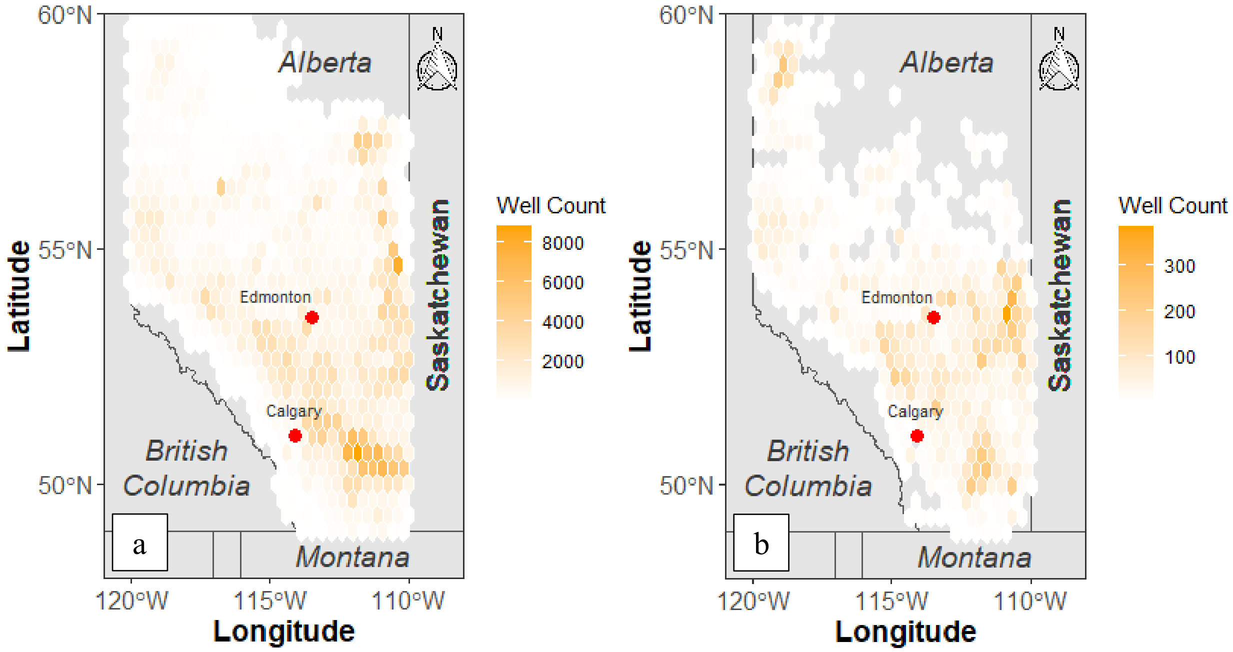

Figure 4.3: (a) Map of the distribution of all wells in Alberta; (b) map of the distribution of all wells known to have experienced SCVF/GM.

The performances of the five different random forest algorithms were very similar (Figure 4.4 and Figure 4.5). The cforest algorithm performed the best out of the five with the extra trees performing the worst. This is as expected as it has been found that the cforest algorithm commonly provides the best performance as it does not favor predictors with a greater number of classes, or a larger scale of measurement as does the original random forest algorithm (Strobl et al., 2007). The supposed performance of cforest comes at great computational cost, whereas the next best performing algorithm, the ranger package, is designed to be computationally efficient (Wright and Ziegler, 2017). Comparing the other algorithms using Spearmans rank correlation (Table 4.3) suggests that the algorithms generally produce similar predictions for a given well, with worst performing algorithm, extraTrees having the lowest correlation between the different algorithms. The poor performance of the extraTrees algorithm could be due to the algorithm's greater reliance on tuning parameters, particularly that of K, in the presence of noisy predictors (Geurts et al., 2006). If the extraTrees tuning parameters were to be optimized using a grid search, it is possible that the algorithm may perform similar to the other random forest algorithms. The other algorithms may also see slight increases in performance if a grid search was used to select the optimal tuning parameters.

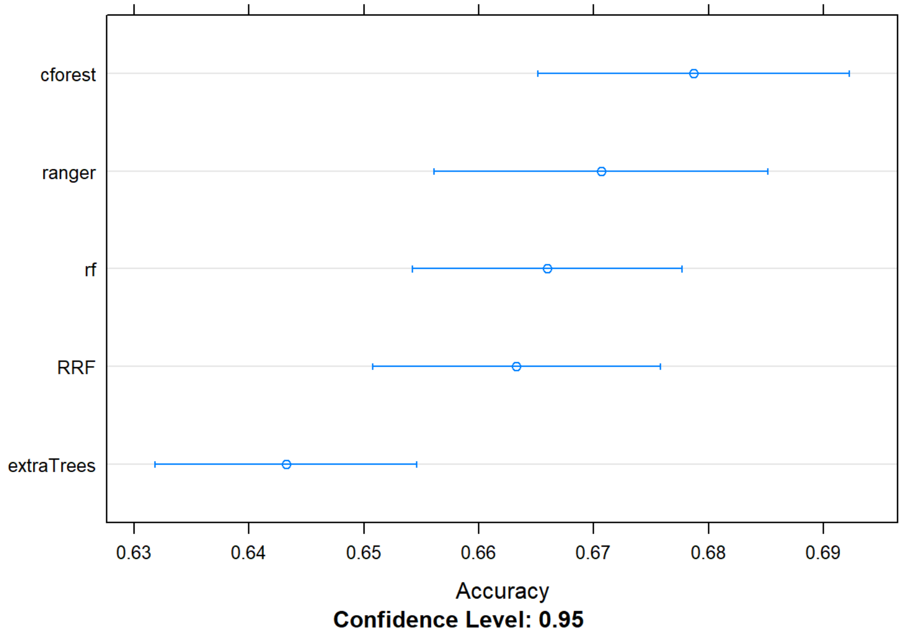

Figure 4.4: The average accuracy of each random forest algorithm within 95% confidence intervals.

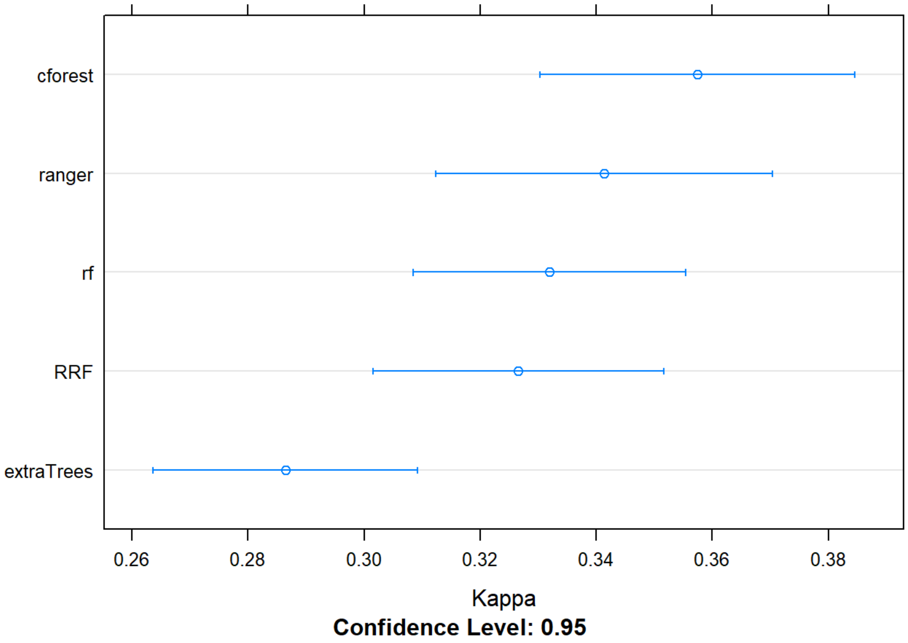

Figure 4.5: The average Cohen's Kappa of each random forest algorithm within 95% confidence intervals.

Table 4.3: Comparison of model predictions between each other model using spearman's rank correlation.

| ALGORITHM | rf | Ranger | RRF | Cforest | Extratrees |
|---|---|---|---|---|---|
| rf | 1.000 | 0.304 | 0.856 | 0.745 | 0.580 |
| Ranger | 0.304 | 1.000 | 0.324 | 0.488 | -0.262 |
| RRF | 0.856 | 0.324 | 1.000 | 0.914 | 0.295 |
| Cforest | 0.745 | 0.488 | 0.914 | 1.000 | -0.001 |
| Extratrees | 0.580 | -0.262 | 0.295 | -0.001 | 1.000 |

The importance of each predictor can provide some additional insight into and support for the previously defined mechanisms and causes behind the occurrence of SCVF and GM: However, any unexpected importance measures should be verified carefully using other methods (Zhao and Hastie, 2019). Predictor importance was calculated for the best performing random forest algorithm, ranger (Figure 4.6). Unsurprisingly the number of days that a well has been on production provides the greatest mean decrease in Gini index. The number of days that a well has been on production likely acts as an approximation for whether a well has been drilled and abandoned or drilled, completed, and cased, the latter of which has been identified as being far more susceptible to SCVF and GM then the former. It is also possible that the number of days on production could be correlated with the amount of wear and tear on the wellbore caused by production activities due to changes in pressure, and temperature (Dusseault et al., 2000; King and King, 2013). The high ranking of the true vertical depth of wells may also be due to the predictor being correlated with the amount of uncemented casing within a given well (Watson and Bachu, 2009).

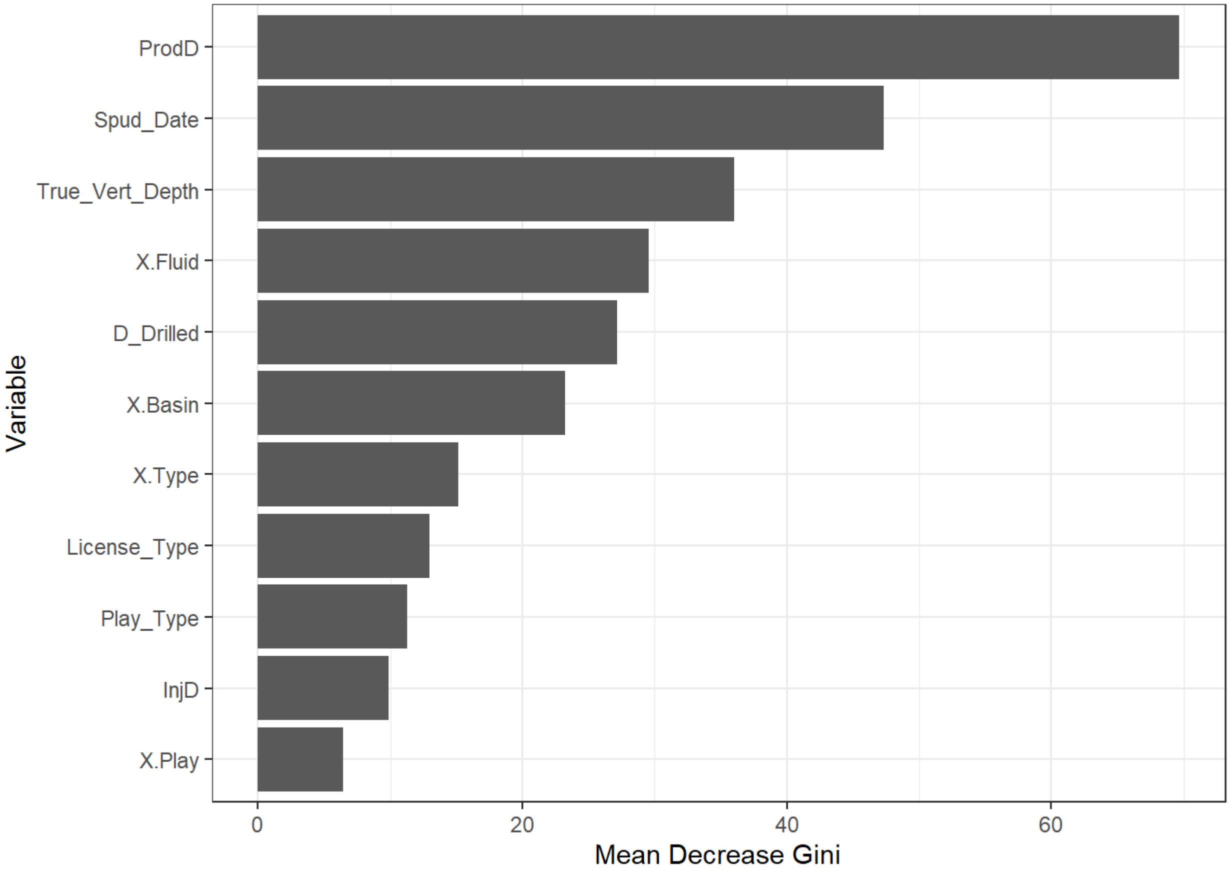

Figure 4.6: Bar graph of predictor importance rankings as determined by the mean decrease in Gini index of the given predictor.

When predictions are made on the remaining 90% of the training/testing dataset not used in training the random forest models the performance of the models is greater than that calculated for the out of bag data during model training. The ranking of the individual models generally remained the same, with cforest remaining the best performer with 72.4% accuracy and extratrees the worst with 70.2% accuracy. While the accuracy of the model gives us a metric on which to assess model performance it does not provide detail on the performance of the model for the two individual outcome classes, occurrence of SCVF and GM, and no occurrence of SCVF and GM.

A receiver operating characteristic (ROC) curve instead provides context on the performance of the model on the two outcome classes allowing for the results from multiple models to be displayed on one graph. The curve provides information on how changing the threshold used to determine whether the model identifies a well as having SCVF and GM or not may impact the accuracy of the model for predicting whether a well has SCVF and/or GM. The five random forest algorithms have similar ROC curves (Figure 4.7). If a regulator were interested in identifying the vast majority of wells with SCVF and/or GM (true positive) at the expense of misclassifying some wells without SCVF or GM as having SCVF and/or GM (false positive) the cut off threshold could be adjusted such that about 85% of wells with SCVF and/or GM are correctly identified at the expense of misclassifying about 50% of wells without SCVF or GM as having SCVF and/or GM. Conversely if an oil and gas operator was interested in identifying SCVF and/or GM wells without many false positives, the cutoff threshold could be adjusted such that 50% of wells have a true positive rate while only 10% of wells are given a false positive.

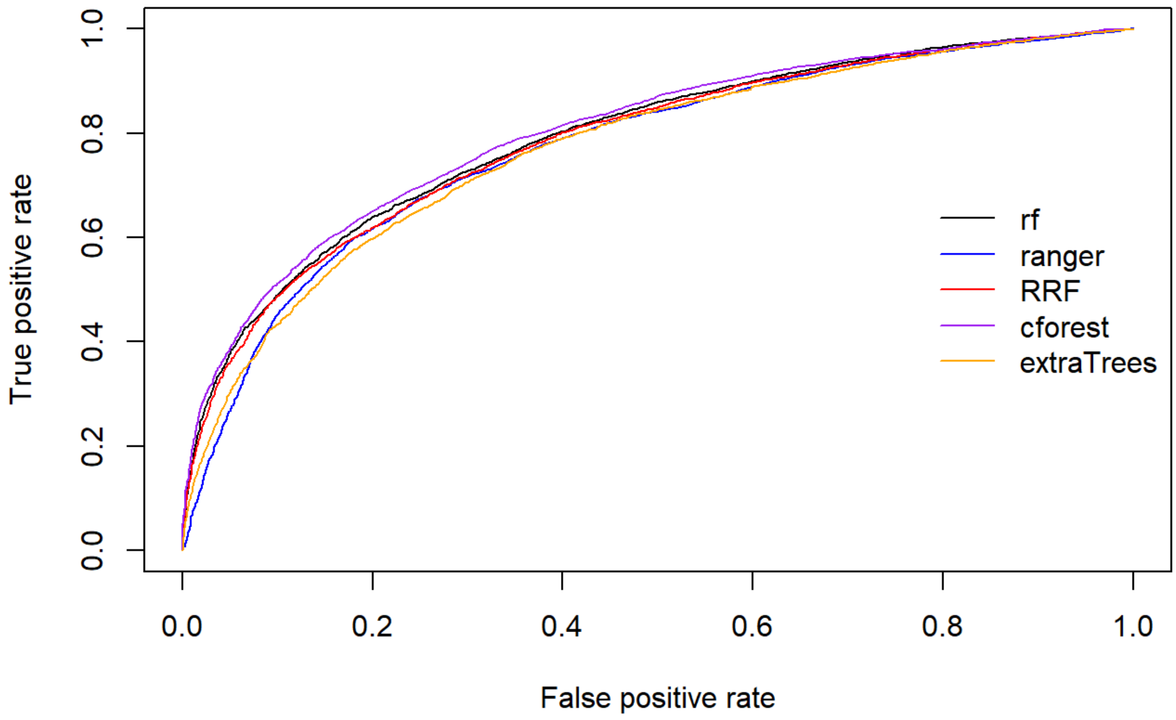

Figure 4.7: ROC curves for the five random forest algorithms produced from using the trained models on the test dataset.

## 1.24 Conclusions

The random forest models presented here perform reasonably well at predicting the occurrence of SCVF and GM with the cforest algorithm providing the best average performance. While the performance of the random forest models are modest, they could still provide a first approximation of how many wells may have experienced SCVF and/or GM between when it was constructed and when it was abandoned in Alberta. If a regulator or oil and gas well operator has a strong interest in correctly identifying one outcome class over another, an ROC curve (Figure 4.7) could assist in choosing the appropriate cut off threshold. Model performance could be improved by including more predictors identified as having a more significant impact on the occurrence of SCVF and/or GM. Minor improvement may also be gained by using a grid search to identify optimal tuning parameter values for each algorithm. While model performance can likely be improved, there may be an upper limit on model performance due to the accuracy of the AER SCVF/GM dataset, namely that the dataset may not have identified all instances of SCVF and GM in the province after well construction and before well abandonment (false negative). Independent field sampling of wells may be needed to verify the accuracy of the AER SCVF/GM dataset. Further research could include investigating whether it is possible to maintain or improve upon the modest model performance achieved here while only using predictors based on well construction. If modest model performance could be achieved, the results of the model may be applicable outside of the geographic area used to produce the training dataset (outside of Alberta). If possible, such a model could be applied to a jurisdiction such as Saskatchewan, where the amount of wells with SCVF/GM between well construction and abandonment is unknown and the available data may not be sufficient or is too unreliable to adequately train a random forest model.

## 1.25 References

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# CONCLUSIONS AND FUTURE WORK

This thesis investigated the potential for leakage, including deep leakage, from old abandoned wells in Chapter 3 and the surface expression of well leakage from unabandoned wells, which typically has a shallow source (Rowe and Muehlenbachs, 1999; Szatkowski et al., 2002; Tilley and Muehlenbachs, 2012; Bachu, 2017), in Chapter 4. In Chapter 3, the locations with the highest probability of leakage from old abandoned wells were identified across three study areas: the Pembina study area, the Redwater study area, and the Southeast Saskatchewan study area (Figure 3.1). Areas of enhanced hazard were identified across all study areas for abandoned wells located near both HF and EOR/SWD wells. Stratigraphic position between historical and current production targets was identified as a strong control on the amount of interaction between HF and EOR/SWD wells, with shallower HF and EOR/SWD activities typically having a greater likelihood of encountering old abandoned wells within the study areas. Not all of the abandoned wells identified in this study will experience well integrity failure, but even for those that do not experience well integrity failure many formations within the abandoned wellbore may still be commingled. These commingled formations have been identified to be typically located within the intermediate zone, and inter-borehole flow between these formations would likely be enhanced in the presence of increased vertical gradients created by HF and/or EOR/SWD. Current regulations on HF and EOR/SWD in Alberta and Saskatchewan may not be adequate to fully mitigate the potential for HW and EOR/SWD to interact negatively with nearby old abandoned wells. Although the potential for inter-borehole flow to leak into potable aquifers through old abandoned wells is mitigated by the presence of surface casing in almost all abandoned wells, and lower intervening aquifers siphoning pressure (Nordbotten et al., 2004) the potential for adverse effects on water resources still exists.

In Chapter 4, the surface expression of wellbore leakage was modeled using several different implementations of the random forest algorithm. These models were trained and tested on a known dataset that covered all of Alberta based on industry reported data from the AER, and well attribute information from Accumap. The best performing model was able to accurately predict whether an active wellbore would experience the surface expression of well leakage or not 76.9% of the time. This result is comparable to that of Montague et al. (2018) for their random forest model that was trained and evaluated using their full well dataset covering a small region of

Eastern Alberta. With the modest predictive accuracy achieved here, regulators and oil and gas operators could likely make use of the model results by modifying the output cut off thresholds using the ROC curve displayed in Figure 4.7 to fit their desired outcome.

The conclusions from Chapter 3 on the interactions between old abandoned wells and their proximity to HF and EOR/SWD wells identifies the intermediate zone as being uniquely susceptible to negative interactions between the two. Not only do old abandoned wells leave many intermediate zone aquifers commingled between abandonment plugs, there are also more abandoned wells that are completed into or pass through the intermediate zone then there are for deeper formations. The intermediate zone is also the formation from which the stray gas responsible for SCVF and GM studied in Chapter 4 originates. For both Chapter 3 and Chapter 4 more study, and in particular field study, on the intermediate zone is needed in order to improve and build upon the respective study's conclusions. For Chapter 3 such field studies should include large studies on the condition of re-entered abandoned wellbores to determine the degree to which aquifers may be commingled within the well, and investigating the potential for leaky or discontinuous confining units between intermediate zone aquifers and any potential potable aquifers above. Chapter 4 would also derive some benefit from the above field studies but in particular, predictive accuracy of the random forest algorithm could be improved by including more predictors already known to be associated with leaky wellbores, and by conducting further field studies of leaky wells in order to identify additional yet to be identified predictors.

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# APPENDIX A. SUPPORTING INFORMATION FOR AQUIFER COMMINGLING IN ABANDONED BOREHOLES: SPATIAL DISTRIBUTION OF A HIDDEN LIABILITY

## A1 Historical Well Regulations

Federal regulation of oil and gas wells in Canada began in 1887 (Thompson, 1966). At the time, well abandonment regulations only specified that a well be plugged with sand, clay, or other material. More prescriptive regulations were implemented in 1919, including the ability of the government to recoup costs from abandoning derelict wells; however, substantial hostility from the general public and oil companies towards the enforcement of these regulations muted the impact of their implementation (Breen, 1993). In 1930, control of natural resources in both Alberta and Saskatchewan was passed from the federal government to the provinces (Breen, 1993). Alberta passed the first Oil and Gas Act in 1931 (S. A., 1931), while Saskatchewan passed its first substantive well construction regulations with the Oil and Gas Act of 1936 (R. S. S., 1940). This provincial legislation introduced more prescriptive well construction and abandonment regulations, such as requiring metal casing and the sealing of aquifer units, although Saskatchewan's regulations would lag behind Alberta's for years to come. These first provincial regulations would only see small incremental changes (Alberta Provincial Government, 1945, 1939, 1931; Saskatchewan Provincial Government, 1949, 1946) until the passage of the Oil and Gas Resources Conservation Act of 1950 for Alberta (S. A., 1950) and the Oil and Gas Conservation Act of 1953 for Saskatchewan (R. S. S., 1953). During the 1950s, Saskatchewan would continue to have some weaknesses in its regulations, especially in relation to dry holes and abandoned wells, such as explicit sanctioning of the complete removal of casing from abandoned wells (Saskatchewan Provincial Government, 1957, 1953, n.d.). Alberta, by contrast, established a regulatory framework with the Oil and Gas Act that encapsulated several of the tenants of modern regulations (Alberta Provincial Government, 1950).

While the regulatory requirements for well construction and abandonment don't appear to have changed dramatically during the 1930-1950s, substantial political events and technological advancements had a marked effect. The Great Depression and court decisions limited the effectiveness of the earliest regulations (Breen, 1993), while World War II led to well casing variances due to a shortage of steel (Gow, 2005). Saskatchewan's government in the late 1940s faced significant pressure from the public, industry, and bondholders to increase oil and gas development in the province. This pressure forced the government to adapt oil and gas policies similar to that of neighbouring Alberta (Emery and Kneebone, 2008). This period also saw changes in well drilling technologies, particularly the transition from cable tool to rotary drilling. Other improvements included better Portland based cement mixtures, high pressure pumps fed by high volume cement mixers, and the introduction of centralizers to keep holes straight and scratchers to clean the wellbore prior to cementing to Alberta in 1949 (Breen, 1993; Gow, 2005). Cementing practices saw improvement from being standardized by the American Petroleum Institute in 1952 (King and King, 2013). Although changes to regulations and world events likely had an impact on well integrity with time, the most impactful changes occurred due to improvements in well drilling and construction technologies.

Even with the major technological advancements that occurred, construction techniques and regulations still had several shortcomings. Before the 1960s, leaks from casing couplings were common (Kerr, 1965) and methods used to cement surface casing did not adequately consider cold temperatures near the surface during winter (Thorvaldson, 1962). Additionally, the cement bond log, an important wireline tool that allowed for the pinpointing of poor cement quality, was not invented until 1959 (Grosmangin et al., 1961; Nelson, 1990). Further, best practices for well construction were not always followed as evidenced by a 1952 survey of well drillers in North America by the American Petroleum Institute that recorded 40% of drillers did not use scratchers during cement plug emplacement, amongst other discrepancies (Anderson et al., 1955). Well abandonment may have been particularly prone to substandard practices with the abandonment of wells being completed as cheaply as possible (Herndon and Smith, 1976). Drilled and abandoned wells, which are abandoned without production casing, were not closely scrutinized by regulators at the time (Breen, 1993) and cased wells abandoned with bridge plugs were commonly capped with only small amounts of cement resulting in an estimated failure rate of 10% over long periods of time (Watson and Bachu, 2009). In the state of Michigan, some early studies of reentered wells have found missing abandonment plugs or that the well had not been abandoned despite plugs being recorded in the wells' tour reports (Isherwood, 1980; Upp, 1966). A later study of reentered abandoned wells in Alberta completed in 2004 of 15 wells abandoned in 1975 or later found several instances of abandonment regulations at the time not being met, although notably plug integrity was found to be intact (Watson, 2005). King and King (2013) suggest that oil and gas wells constructed prior to the 1960s have a moderate potential to cause pollution due to leakage, although they did not specifically address abandonment methods in this assessment. The situation in the WCSB is in agreement with King and King's (2013) finding that wells constructed prior to the 1960s have a moderate potential for pollution but is more specific to abandoned wells. We expect that old wells abandoned before 1960 in the WCSB could be expected to have worse integrity than those abandoned after potentially leading to commingling of aquifers over large sections of the borehole.

The effect of a singular commingled well with large vertical hydraulic gradients emanating from a contaminated or saline aquifer can be a significant point source of pollution to any less brackish or potable aquifers also connected within the wellbore (e.g. Jacobs, 2009). However, where the concentration of commingled wellbores is high and there are large differences in hydraulic gradients between aquifers, commingling of aquifers through wellbores has been shown to have the potential to cause considerable alterations to the water budgets of confined aquifers used for irrigation and municipal supply (e.g. Burns et al., 2012; Eger et al., 1989; Landon et al., 2008), and allow for widespread contamination (e.g. Gailey, 2018; Mejía et al., 2012; Viers et al., 2012). In one study in Nebraska modeling suggested that 25% of flow across a confining unit was through commingled wellbores within the study area (Landon et al., 2008). Such short circuiting of flow through confining units can result in orders of magnitude changes in the effective permeability of confining units (Hart et al., 2006). The occurrence of intra-borehole flow of groundwater through commingled wells for irrigation, municipal, and domestic supply are thought to be common leading to significant aggregated effects (Gailey, 2017; Jasechko and Perrone, 2017). While such aggregated effects have not been widely documented in the deeper subsurface, monitoring of the deeper subsurface, especially aquifers located below potable groundwater but above oil and gas reservoirs, is often limited.

The history of well regulations and well construction technology provides an estimated cut off date for well integrity, but in order for failed integrity to present a hazard 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. Further, North America has seen a ten-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 that present the greatest hazard can be identified. Similar spatial proximity studies between a vulnerable well population and oil and gas production activity have been completed in the United States (Jasechko and Perrone, 2017) and in particular Texas (Brownlow et al., 2017) and Pennsylvania (Dilmore et al., 2015; Montague and Pinder, 2015), but in Canada such studies have mainly focused on risks posed by carbon sequestration (e.g. Celia et al., 2011). Further, these studies on oil and gas production activities contemplated the potential for frac hits 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 commingled within the wellbore. Information regarding formation commingling in old wellbores is not readily available in Canada, but this information can help identify formations that are susceptible to cross-formational flow within the wellbore.

## A2 Spatial Analysis

### A2.1 Data Preprocessing

To investigate the spatial relationships between wells abandoned before 1960 and wells that have been HF or used for EOR/SWD after 2000, data pre-processing was required to classify wells first by type and then by the formations they were completed into or passed through. For each study area, the wells were first split into three categories: wells abandoned before 1960, wells that were injecting at any point after 2000, and wells that had been HF after 2000. All other wells were discarded from the dataset. The wells abandoned before 1960 represent the well population with the greatest probability of experiencing well integrity failure, while the other two groups represent production activities that can create pressure increases that may cause cross-formational flow in a well with failed integrity. The two well populations for HF and EOR/SWD wells capture a period of substantial technological advancement that led to the increased adoption of horizontal drilling and multistage, high volume HF (Lucas et al., 2014) and subsequent increase in produced/flowback water from unconventional fields that has occurred since 2000 (Scanlon et al., 2017, 2016; Shrestha et al., 2017). A discrepancy was observed in the database for wells abandoned before 1960, whereby drilled and abandoned wells did not have an abandonment date listed. Therefore, drilled and abandoned wells that were abandoned before 1960 were identified using a custom query that selected all wells drilled prior to 1960 that were listed as abandoned and also lacked an associated last production or injection date. A subsample of these wells were verified as having actually been drilled and abandoned by referencing tour reports of drilling operations available from Accumap for both provinces. Additionally, a few production wells were also identified as being abandoned before 1960 without an abandonment date listed. These abandoned previously producing wells were selected by querying for wells identified as abandoned with a final production date before 1960.

### A2.2 Hydraulic Fracturing

Abandoned wells were further categorized based on depth and the last formation that the well was drilled into in order to discern whether a given abandoned well passed through or was completed into a HF formation. The HF formations are the Bakken, Cardium, and Viking formations (Figure 3.2) for the Southeast Saskatchewan, Pembina, and Redwater study areas, respectively. This categorizing process differed between Alberta and Saskatchewan due to the accessibility of a publicly available geologic model for Saskatchewan from which the elevation of the formation tops for the Bakken Formation could be derived (TGI Williston Basin Working Group, 2009) if a given abandoned well was not drilled into or through the Bakken. For Saskatchewan, a spatial analysis using ArcGIS V10.6 (ESRI, 2018) was performed to estimate the depth of the Bakken Formation top by overlaying a raster of Bakken Formation tops with the abandoned wells database, then extracting the raster cell values to the abandoned wells. The abandoned wells were then subdivided into four groups based on the difference in depth between the estimated Bakken Formation tops and the well. 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. The highest vertical separation cutoff was selected based on Davies et al. (2012) finding that less than 1% of hydraulic fractures propagate above 350 m, suggesting that a frac hit above this vertical separation would be unlikely. The 150 m vertical separation cutoff was selected to be the boundary below which most hydraulic fractures will be contained, with Davies et al. (2012) finding that 80% of hydraulic fractures attain a height of less than about 150m. The four abandoned well groups are:

- Hazard 1: drilled into or below the Bakken Formation;
- Hazard 2: drilled to within 150 m above the Formation;
- Hazard 3: drilled to within 350 m above the Formation;
- Minimal or no risk: drilled to a depth that is greater then 350 m above the Formation

In Alberta, a publicly accessible geologic model was not available. If a well was shallow and was not recorded as being drilled into or through either the target HF Viking or Cardium formations for the Redwater and Pembina study areas respectively, then the depth was estimated by calculating the average depth of the formation top within the respective study area. As with the Saskatchewan study area, the abandoned wells were then subdivided into four groups based on the difference in depth between the estimated depth of the formation tops and the depth of the well.

The evaluation of whether a HF well may impact an old abandoned well was completed using the ArcGIS 10 ModelBuilder (ESRI, 2018). HF wells that were horizontal or directional were mapped as lines using bottom and surface hole locations. A proximity analysis was completed between each abandoned well grouping and the HF wells for a study area. An abandoned well and HF well were selected using a proximity distance that was based on an approximated potential length of the fracture network horizontally from the wellbore (fracture half-length), which varied depending on the study area. Given that the physical processes underlying HF are difficult to accurately model (Dahi Taleghani et al., 2016), predictions of fracture half-length are usually based off observation such as the extent of microseismic data from nearby wells (Yu and Aguilera, 2012), or through evidence of communication between HF wellbores (Loveless et al., 2019). Another estimate of the fracture half-length that is more specific to the study areas can be made by measuring the spacing between stimulated wells. Considering the detrimental impact that frac hits can have on producing wells (King et al., 2017; Wisen et al., 2019), it can be assumed that operators attempt to space their HF stimulated wells to limit the occurrence of such events, while still maximizing production. For the Redwater area, a rough estimate of average spacing between wells is 350 m, for the Pembina this is around 625 m, and for Southeast Saskatchewan it is around

700 m. These values are double the estimated half length, and are assumed to be upper thresholds. These values are within the range of reported values from studies documenting frac hits to offset producers (Ajani and Kelkar, 2012; Alberta Energy Regulator, 2016; Bommer et al., 2017; Lefebvre, 2017; Watson, 2013).

### A2.3 EOR/SWD

To evaluate whether an EOR/SWD well may impact an old abandoned well, old abandoned and EOR/SWD wells for each study area were first grouped based on the last formation a well was drilled or injected into, respectively, using ArcGIS 10 ModelBuilder. Not all formation groups were used, with selection based on whether an individual formation had more than 20 wells listed as being the last formation the well was drilled into, or injecting into it. If the cutoff value of 20 wells did not represent greater than 80% of the total well population of either abandoned or injecting wells, then a lower cutoff value of 5 wells for a given formation was used. A list of the formations used for each study area is depicted in Figures A.1-A.6. The abandoned well groups were subsequently arranged into whether or not they penetrated one of the formations where EOR/SWD was taking place. For all abandoned wells that were drilled through or completed into a formation where EOR/SWD was taking place, a proximity analysis was performed between those wells and the EOR/SWD wells of a given formation. An abandoned well and EOR/SWD well were both identified if they were within two kilometers of each other.

Table A.1: Formation code key for formation codes used in Figures A.1-A.6.

| SOUTHEAST SASKATCHEWAN | |
|---|---|
| ACRONYM | FULL NAME |
| ALIDABD | Alida Beds |
| BAKKEN | Bakken Formation |
| BAKKENM | Middle Bakken Formation |
| BAKKENU | Upper Bakken Formation |
| BIRDBER | Birdbear Formation |
| FROBBD | Frobisher Beds |
| LODGEPOL | Lodgepole Formation |
| MANN | Mannville Group |
| MIDALE | Midale Beds |
| MIDALEEV | Midale Evaporite |
| MISSNCYN | Mission Canyon Formation |
| RATCLIFF | Ratcliffe Beds |
| SOURSVL | Souris Valley Beds |
| TILSTNBD | Tilston Beds |
| TORQUAY | Torquay Formation |

| PEMBINA | |
|---|---|
| ACRONYM | FULL NAME |
| BANFF | Banff Formation |
| BEAVERHL | Beaverhill Lake Formation |
| BELLYRV | Belly River Formation |
| BLACKSTN | Blackstone Formation |
| CARDSD | Cardium Formation |
| EDMNTN | Edmonton Group |
| MANN | Manville Group |
| NISKU | Nisku Formation |
| OSTCZ | Ostracod Formation |
| VIK | Viking Formation |
| WABAMUN | Wabamun Formation |

| REDWATER | |
|---|---|
| ACRONYM | FULL NAME |
| BEAVERHL | Beaverhill Lake Formation |
| COOKLK | Cooking Lake Formation |
| ELLERSL | Ellerslie Member |
| IRETON | Ireton Formation |
| LEDUC | Leduc Formation |
| NISKU | Nisku Formation |
| VIK | Viking Formation |
| VIKSS | Viking Formation |

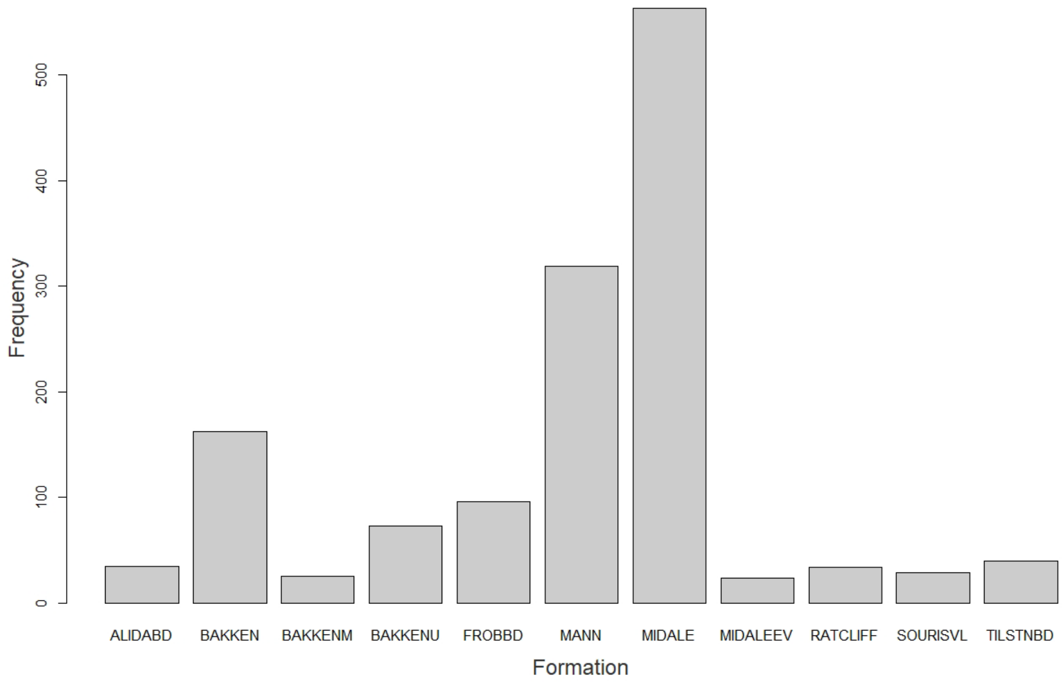


Figure A.1: Frequency count of the number of wells injecting into formations with greater than 20 wells injecting into them in the Southeast Saskatchewan study area.

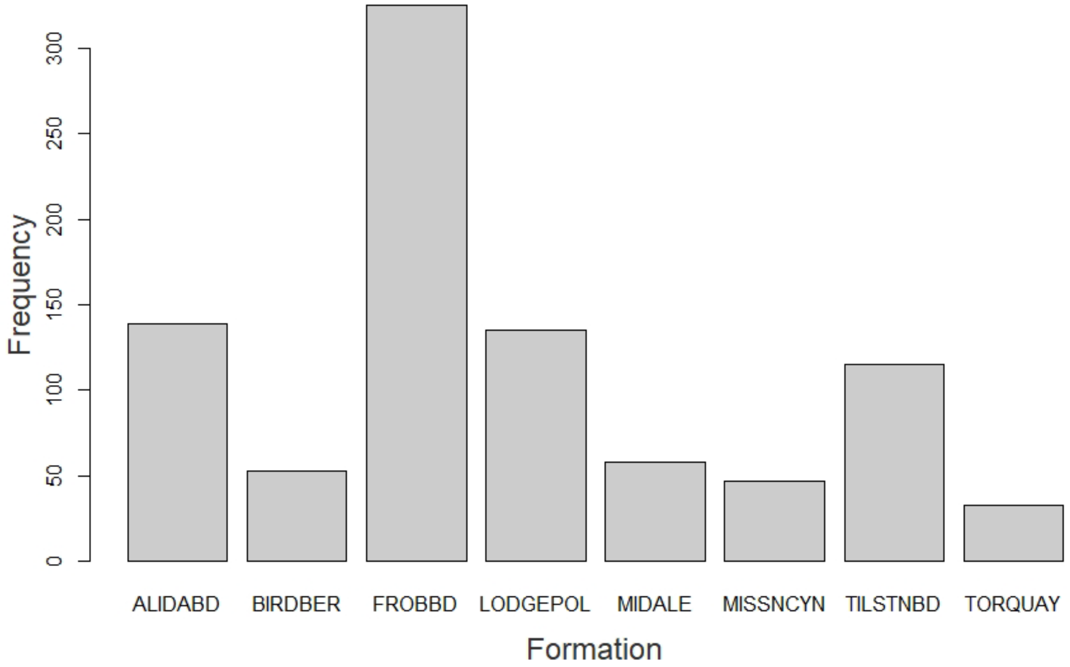


Figure A.2: Frequency count of the last formation drilled into for wells abandoned before 1960 in the Southeast Saskatchewan study area for formations with greater than 20 wells.

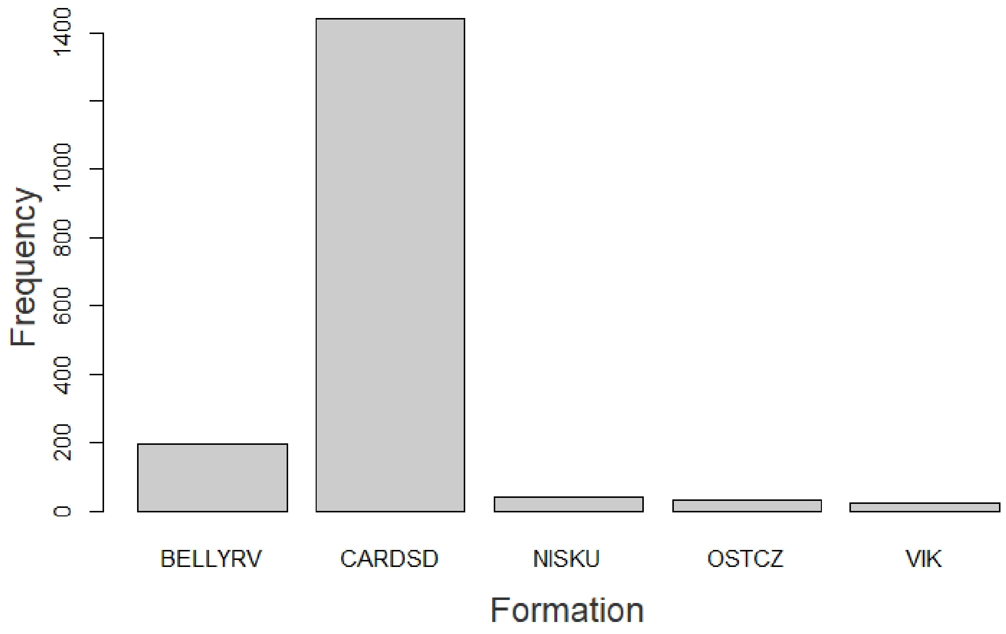


Figure A.3: Frequency count of the number of wells injecting into formations with greater than 20 wells injecting into them in the Pembina study area for formations with greater than 20 wells.

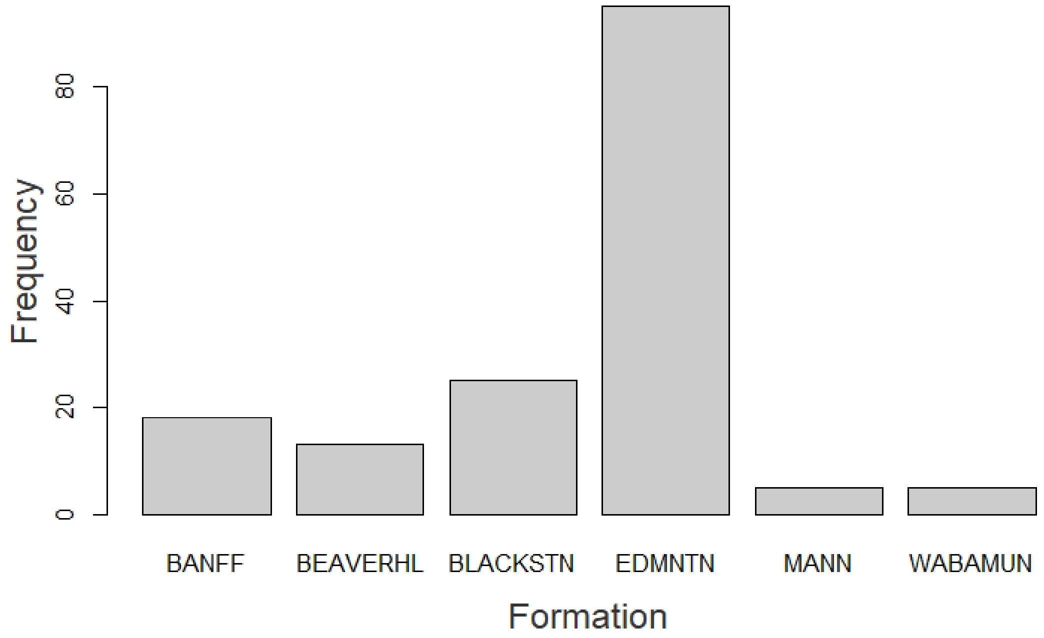


Figure A.4: Frequency count of the last formation drilled into for wells abandoned before 1960 in the Pembina study area for formations with greater than 5 wells.

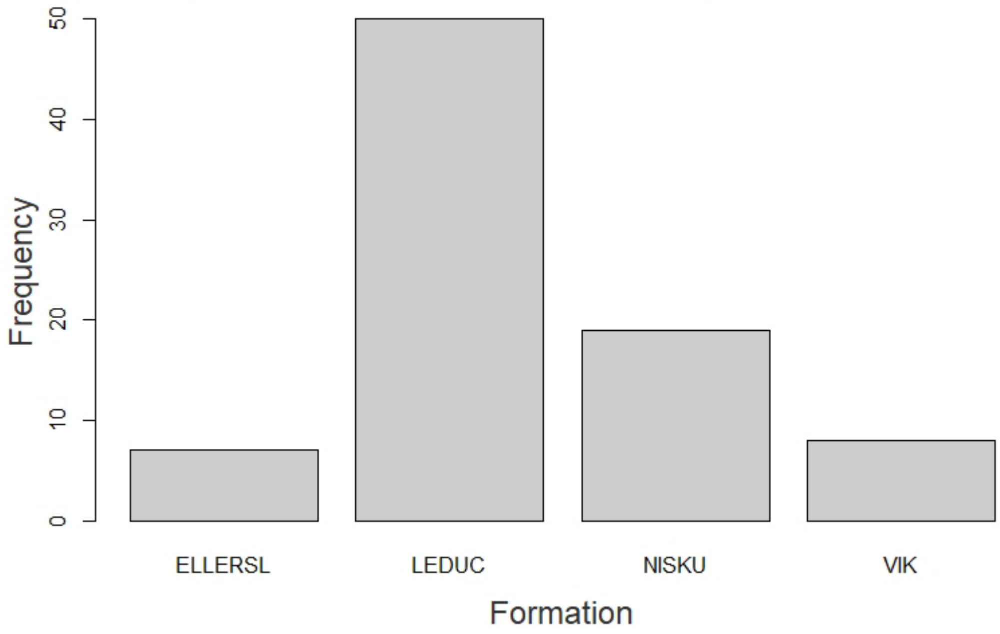


Figure A.5: Frequency count of the number of wells injecting into formations with greater than 5 wells injecting into them in the Redwater study area.

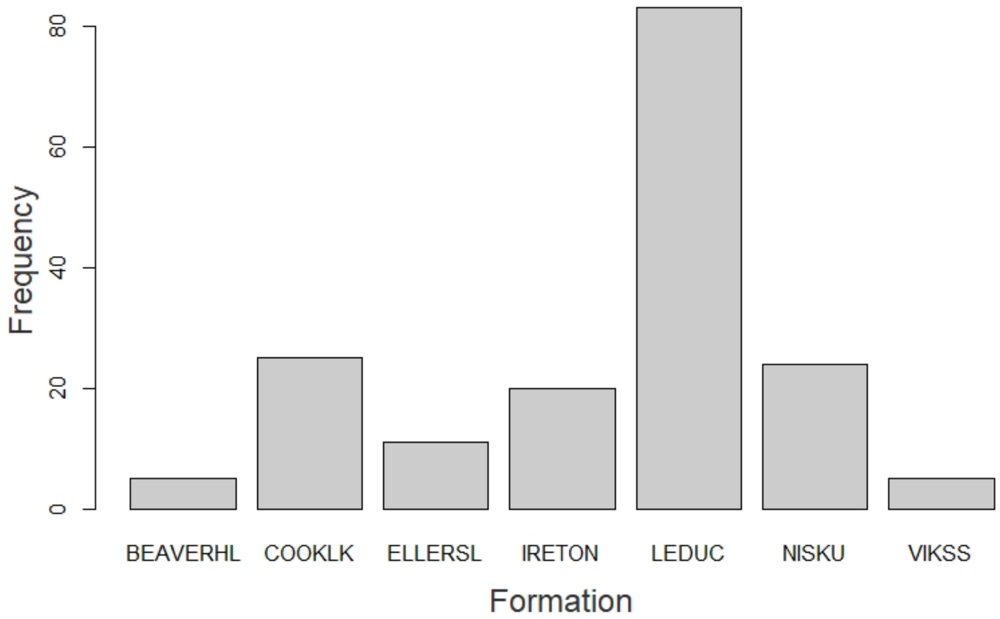


Figure A.6: Frequency count of the last formation drilled into for wells abandoned before 1960 in the Redwater study area for formations with greater than 5 wells.

The search distance used in the proximity analyses between old abandoned wells, and HF, EOR, SWD wells was determined using the Cooper Jacob Approximation (Cooper and Jacob, 1946):

$$s = \frac{2.303Q}{4\pi T}\log(\frac{2.25Tt}{r^2S}) \qquad [A.1]$$

Where S is drawdown, Q is pumping rate, T is transmissivity, t is time, r is radial distance from the pumping well, and S is storativity. The proximity analysis investigates EOR/SWD in several different aquifers that have different thicknesses, and permeabilities. For example the Leduc Formation (Redwater Reef) in the Redwater study area has an average thickness and permeability of 245 m and $10^{-13}$ $m^2$ respectively (Kuznetsov and Zhuravleva, 2018), but the permeability has a large range from $10^{-17}$ to $10^{-12}$ $m^2$ (Sodagar and Lawton, 2010) with injection likely taking place into the more permeable portions of the formation. By contrast the Lower Midale Formation, a part of the Mississippian Aquifer System, in the Southeast Saskatchewan study area has an approximate average thickness of 20 m and a permeability of around $10^{-14}$ $m^2$ respectively (Burrowes and Gilboy, 2001; Kent et al., 2004). The difference in aquifer thickness is reflected in typical injection rates for these two formations, 27700 and 100 $m^3$/d for the Redwater and Southeast Saskatchewan study areas respectively. These average injection rates were calculated using Accumap data for all wells injecting into the respective formations between 2000 and 2019 using mean monthly injection rates (IHS Energy, 2019). When the change in head over distance (upconing curve) is roughly approximated using the Cooper Jacob Approximation over 10 years it is apparent that the shape of the curve created from the two scenarios are similar (Figures A.7 and A.8). This can be explained by considering Equation A.1 in its simplified form of y=a*log(b). Changes in a move the curve up or down, while changes in b change the slope/shape of the curve. Changes in permeability and thickness both change the transmissivity term of Equation A.1, which is located in both terms a and b. However, changes in transmissivity cause large changes in a but small changes in b when time is large, such as here where timescales on the order of decades is considered. Another of the terms in the Cooper Jacob Approximation, injection rate, is expected in many cases to be at rates that result in wellhead pressures that approach the maximum allowable by regulation, which in Alberta is 90% of the formation fracture pressure (Alberta Energy Regulator, 1994).

Table A.2: Parameters used in the Cooper Jacob Approximations for injection into the Leduc and Midale Formations of the Redwater and Southeast Saskatchewan study areas respectively.

| Study Area | Redwater | Southeast Saskatchewan |
|---|---|---|
| Pumping Rate (Q) | 27700 $m^3/d$ | 100 $m^3/d$ |
| Storativity (S) | $10^{-5}$ | $10^{-5}$ |
| Duration of Continuous Injection (t) | 10 Years | 10 Years |
| Radial Distance from Injection Well to Observation Point (r) | Variable | Variable |
| Aquifer Thickness | 245 m | 20 m |
| Aquifer Permeability | $2 * 10^{-13}$ $m^2$ | $2 * 10^{-14}$ $m^2$ |
| Density of the Fluid | 1080 $kg/m^3$ | 1080 $kg/m^3$ |
| Coefficient of Gravity | 9.81 $m/s^2$ | 9.81 $m/s^2$ |
| Dynamic Viscosity | $5.80 * 10^{-5}$ kg/(m*s) | $5.80 * 10^{-5}$ kg/(m*s) |

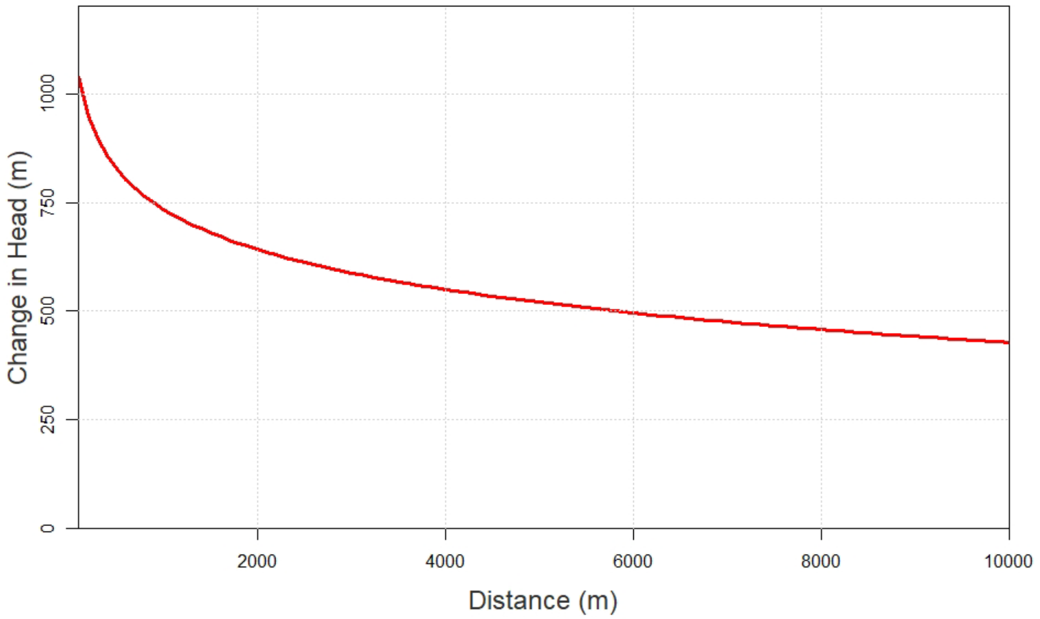


Figure A.7: Upconing curve produced using the Cooper Jacob Approximation for the Redwater study area scenario of injection into the Leduc Formation. Parameters used are detailed in Table 3.1.

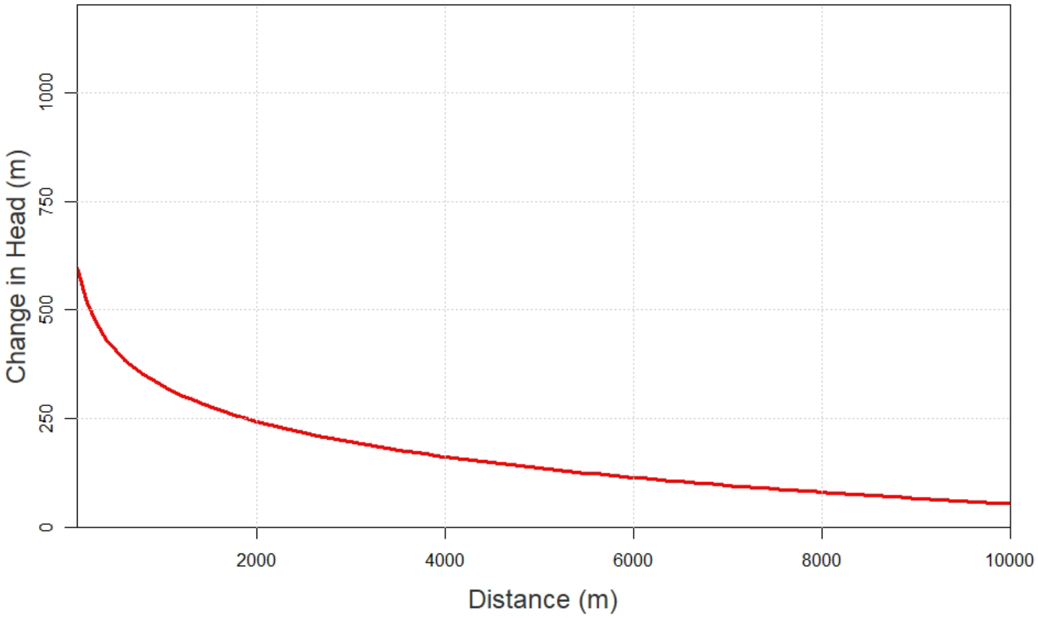


Figure A.8: Upconing curve produced using the Cooper Jacob Approximation for the Saskatchewan study area scenario of injection into the Midale Formation. Parameters used are detailed in Table 3.1.

In almost all cases considered here such wellhead pressures should result in significant vertical hydraulic gradients between adjacent aquifers. If it is assumed that the other aquifer parameters that don't impact transmissivity remain constant then the greatest changes in head are captured by using a search distance of two km for the proximity analysis of EOR/SWD and abandoned wells. This distance is expected to be a conservative lower bound due to the likely presence of superimposed cones of increased pressure from EOR/SWD wells, and the likelihood that preferential fluid flow in the direction of fracture orientation causes increases in pressure at greater distances than that predicted by an analytical method that assumes isotropy such as the Cooper-Jacob approximation (Heffer, 2002). The two kilometer search distance could become too large in locations where drawdown cones from pumping wells are significant.

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). For this analysis, all wells were displayed as points. For horizontal wells, the mapped line connecting the surface and bottom hole locations was transformed into a single point located halfway along the mapped line. In ArcGIS, the kernel density method creates a circular area for each of the selected well points that is defined by a kernel function within which there is a smooth and continuous density surface with the highest value at the center and diminishing to zero beyond the specified bandwidth, otherwise known as the search distance, which in this case was defined as five kilometers (Brownlow et al., 2017). The sum of the overlapping density surfaces was taken at each cell in a raster grid with a cell size of 25 m. The resulting continuous surface was then split into four categories: high, medium, low, and none. These categories represent > 0.25, 0.1 to 0.25, >0 but < 0.1, and no wells present per km$^2$ respectively.

### A2.4 Review of Abandonment Reports

To gain further insight into construction and abandonment practices at the study sites for wells prior to 1960, tour and completion reports were reviewed for a subset of abandoned wells that were identified as being located near an EOR/SWD well. The reports were queried from Alberta and Saskatchewan regulatory agencies. Reports were reviewed primarily to identify whether casing was present or absent, presence of cement sheath, and abandonment plug locations. For wells identified as being abandoned open hole (i.e. without casing), which includes both drilled and abandoned wells and wells that had been cased but had their casing pulled during abandonment, information regarding cement plugs was tabulated into a queryable database. Plug locations within the open hole wellbores were cross referenced with corresponding formations of the same depth to identify which formations were plugged or left open to the wellbore. Formations that were identified as plugged could be partially or fully covered by a cement abandonment plug, whereas formations identified as open are wholly uncovered. Information on open hole abandonment plug locations was tabulated into a matrix format and presented as a raster grid.

Table A.3: Measured permeability of wellbores and wellbore cement barrier elements for five field studies.

| **STUDY** | **PERMEABILITY (m$^2$)** |
|---|---|
| Kang et al., 2015 | $10^{-21}$ to $10^{-13}$ |
| Tao and Bryant, 2014 | $10^{-17}$ to $10^{-14}$ |
| Hawkes and Gardner, 2014 | $10^{-19}$ to $10^{-18}$ |
| Gasda et al., 2013 | $10^{-15}$ to $10^{-13}$ |
| Duguid et al., 2013 | $10^{-19}$ to $10^{-11}$ |

## A3 Figures and Tables for Results and Discussion

Table A.4: Well type and count for the three study areas as of December 31st, 2018.

| | **SOUTHWEST SASKATCHEWAN** | **REDWATER** | **PEMBINA** |
|---|---|---|---|
| *WELL TYPE* | *WELL COUNT* | | |
| Directional/deviated | 777 | 456 | 3,815 |
| Horizontal | 19,317 | 1,264 | 4,260 |
| Vertical | 21,652 | 3,502 | 18,760 |
| Abandoned | 11,952 | 1,745 | 5,876 |
| Disposal | 597 | 5 | 5 |
| Injection | 1,772 | 11 | 1,196 |
| Producing | 13,632 | 1,106 | 4,817 |
| Suspended | 6,857 | 731 | 8,131 |
| Fractured | 891 | 946 | 8,662 |
| **TOTAL COUNT** | 41,747 | 5,223 | 26,836 |

Table A.5: Well types and counts for the three study areas as utilized in the spatial analysis.

| | **SOUTHWEST SASKATCHEWAN** | **REDWATER** | **PEMIBINA** |
|---|---|---|---|
| *WELL TYPE* | *WELL COUNT* | | |
| Fractured after 2000 | 889 | 741 | 3,265 |
| EOR/SWD after 2000 | 1,528 | 86 | 1,809 |
| Abandoned before 1960 | 1,038 | 441 | 408 |

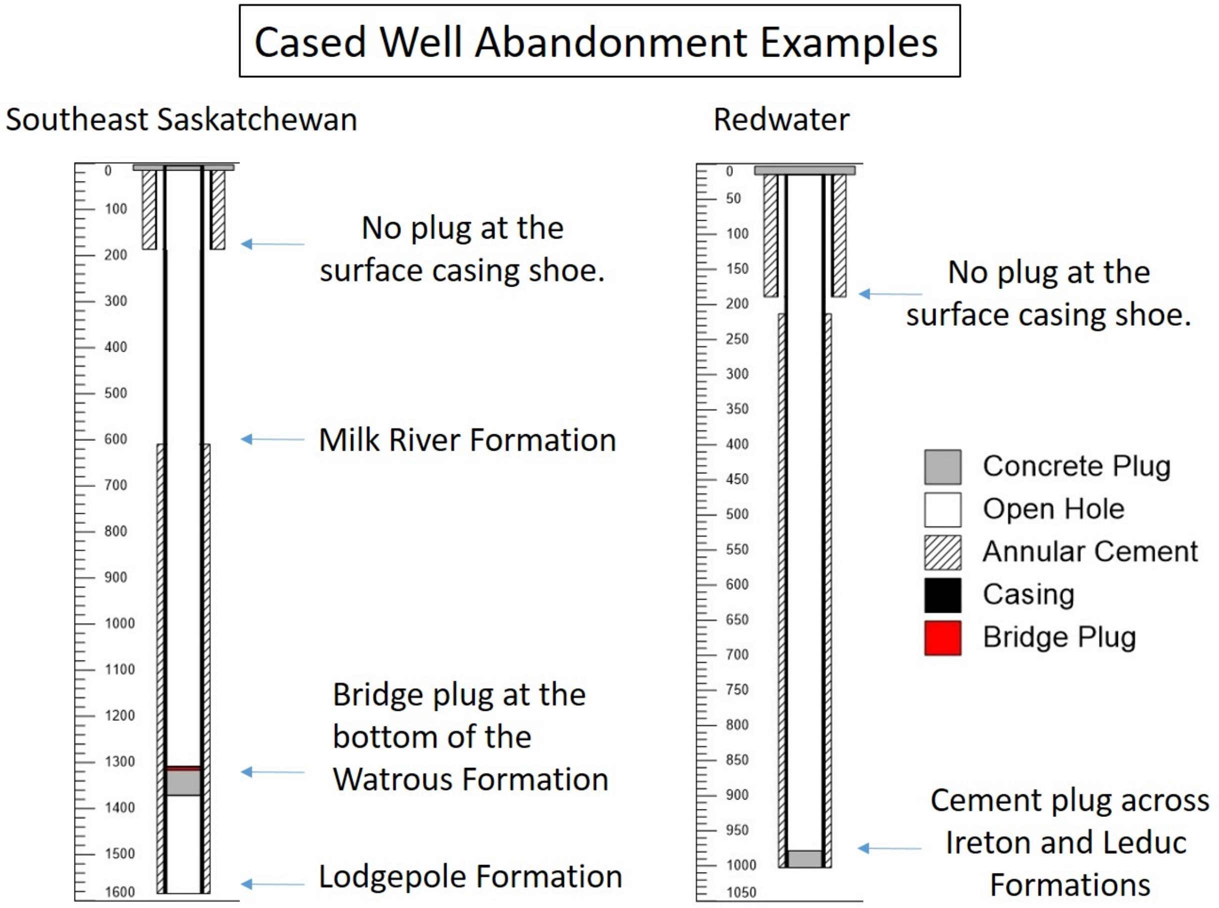


Figure A.9: Cased well abandonment examples for the Southeast Saskatchewan and Redwater study areas (cement sheath estimated from borehole dimensions and amount of cement used, perforations not depicted).

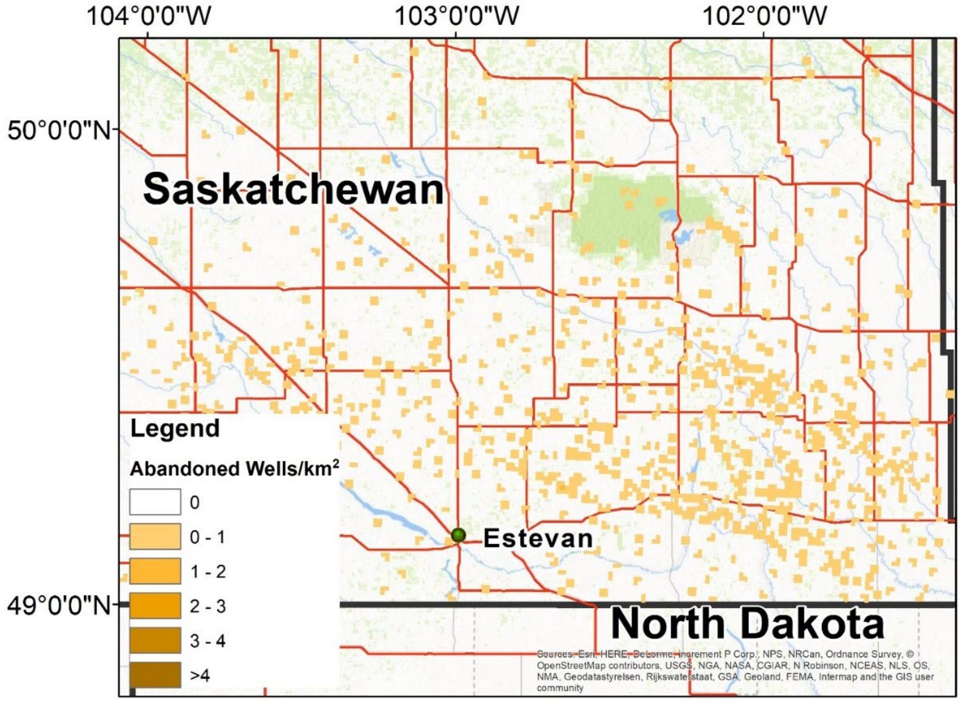


Figure A.10: Density of pre 1960 abandoned wellbores in the Southeast Saskatchewan study area.

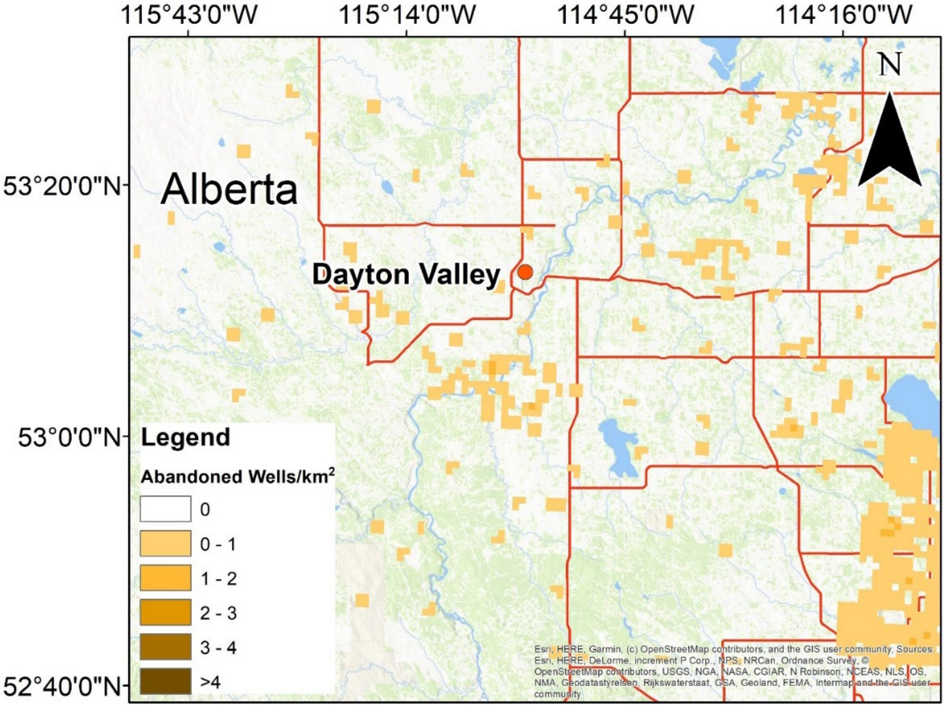
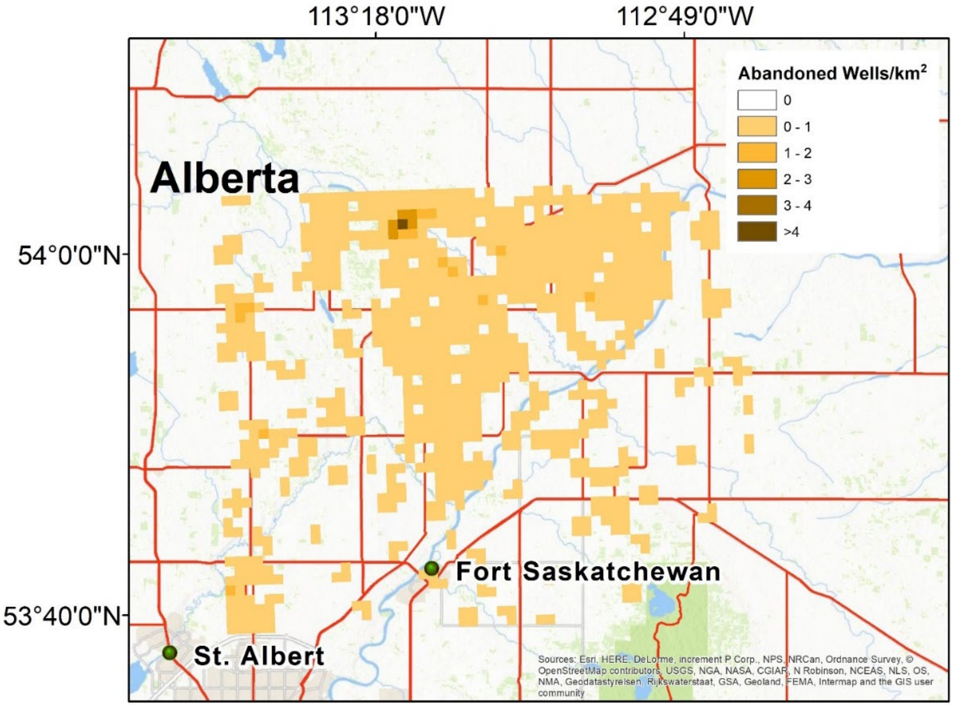


Figure A.11: Density of pre 1960 abandoned wellbores in the Pembina study area.



Sources: Esri, HERE, DeLorme, increment P Corp., NPS, NRCan, Ordnance Survey, © OpenStreetMap contributors, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community

Figure A.12: Density of pre 1960 abandoned wellbores in the Redwater study area.

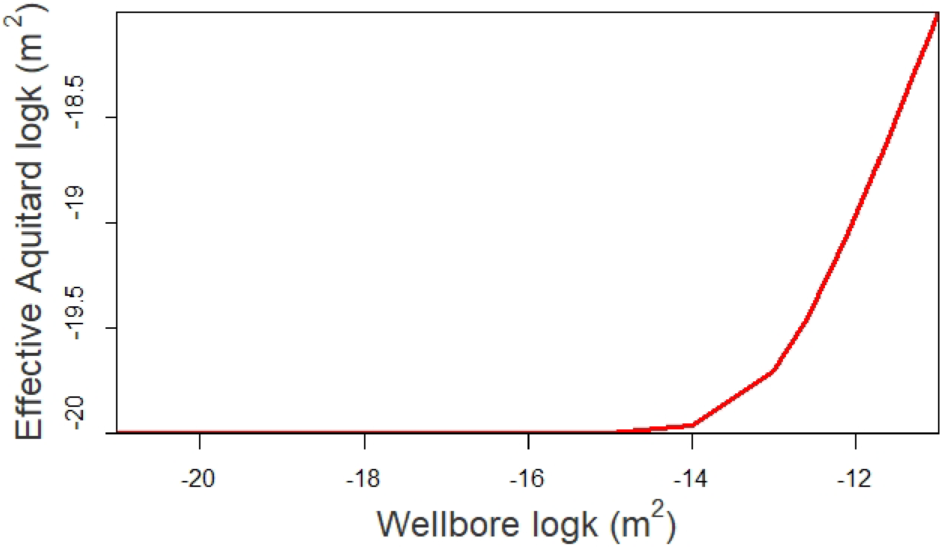


Figure A.13: Change in aquitard permeability due to a density of one leaky well across the aquitard per km$^2$ for an aquitard with a permeability of $10^{-20}$ m$^2$.

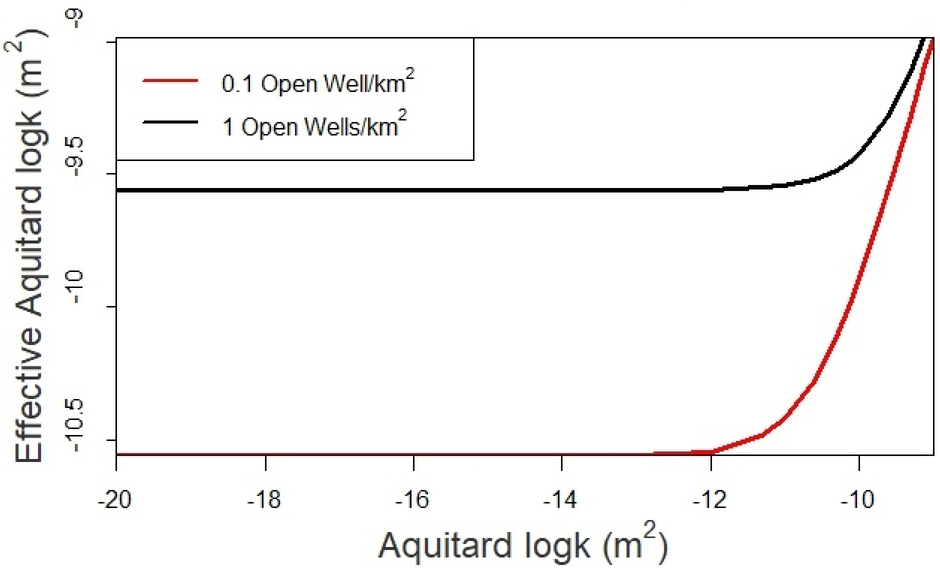


Figure A.14: Change in aquitard permeability due to a density of one leaky well and 0.1 leaky wells across the aquitard per km$^2$ for varying aquitard permeabilities.

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# APPENDIX B. SUPPORTING INFORMATION FOR PREDICTING THE SURFACE EXPRESSION OF WELLBORE LEAKAGE IN ALBERTA