Developing a risk assessment model using fuzzy logic to assess groundwater contamination from hydraulic fracturing

Submitted by

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to the University of Exeter as a thesis for the degree of
Doctor of Philosophy in Water Informatics Engineering

November 2019

I certify that all material in this thesis which is not my own work has been identified and that any material that has previously been submitted and approved for the award of a degree by this or any other University has been acknowledged.

(Signature) . . . .

ABSTRACT

Technological advances in directional drilling has led to rapid exploitation of onshore unconventional hydrocarbons using a technique known as hydraulic fracturing. This process took off initially in the US, with Canada following closely behind, but brought with it controversial debates over environmental protection, particularly in relation to groundwater contamination and well integrity failure. Prospective shale gas regions lie across areas in Europe but countries such as the UK are facing public and government turmoil surrounding their potential exploitation. This extent of energy development requires detailed risk analysis to eliminate or mitigate damage to the natural environment.

Subsurface energy activities involve complex processes and uncertain data, making comprehensive, quantitative risk assessments a challenge to develop. A new, alternative methodology was applied to onshore hydraulic fracturing to assess the risk of groundwater contamination during well injection and production. The techniques used deterministic models to construct failure scenarios with respect to groundwater contamination, stochastic approaches to determine component failures of a well, and fuzzy logic to address insufficiency or complexity in data.

The framework was successfully developed using available data and regulations in British Columbia (BC), Canada. Fuzzy Fault Tree Analysis (FFTA) was demonstrated as a more robust technique compared with conventional Fault Tree Analysis (FTA) and implemented successfully to quantify cement failure. A collection of known risk analysis methods such as Event Tree Analysis (ETA), Time at Risk Failure (TRF) and Mean Time To Failure (MTTF) models were successfully applied to well integrity failure during injection, with the novel addition of quantifying cement failures. An analytical model for Surface Casing Pressure (SCP) during well production highlighted data gaps on well constructions so a fuzzy logic model was built to a 93% accuracy to determine the location of cement in a well. This novel application of fuzzy logic allowed the calculation of gas flow rate into an annulus and hence the probability of well integrity failure during production using ETA.

The framework quantified several risk pathways across multiple stages of a well using site-specific data, but was successfully applied to a UK case study where there existed significant differences in geology, well construction and regulations. The application required little extra work and demonstrated the success and limitations of the model and where future work could improve model development.

This research indicated that risks to groundwater from hydraulic fracturing differ substantially depending on well construction. Weighing up the risk to groundwater compared with financial gain for well construction will be essential for decision-makers and policy. To reduce the social anxiety of hydraulic fracturing in the UK, decision-makers who

face criticism must ensure information is disseminated properly to the public with a well-defined risk analysis which can be interpreted easily without prerequisite knowledge. Finally, although this research is based on onshore hydraulic fracturing, the risk assessment techniques are generic enough to allow application of this research to other subsurface activities such as CO_2 sequestration, waste injection disposal and geothermal energy.

"The moment of victory is much too short to live for that and nothing else."

– Martina Navratilova

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ACKNOWLEDGEMENTS

The production of this thesis would certainly not have been possible without the endless support and guidance from many people over the past four, challenging years. I would firstly like to thank my supervisor Prof. Akbar Javadi for his continuous patience, encouragement and faith in my ability to reach the end. I would also like to thank Prof. Zoran Kapelan for his support, guidance and feedback during the project and the WISE CDT, in particular cohort 2, for such a wonderful first year and for being there after, despite living in different cities. Special thanks go to my examiners, Prof. Guangtao Fu and Dr Majid Sedighi for their insights and recommendations to improve this work.

To all those at the University of British Columbia, Canada, especially Dr Aaron Cahill, Laurie Welch and Elyse Sandl and those in the Energy and Environment Research Initiative (EERI) team. This project would have not been possible without you and I am eternally grateful for all the effort you put in to support my 3 month stay and make me feel welcome. To Lily and Zack, who gave me such a wonderful home during my stay and shared the highs and lows of PhD life; you both really encouraged me to keep going, for which I am forever grateful.

To those outside my academic life, I would not be where I am today without you all. To my parents, Andrew and Stephanie for passing on all your knowledge to encourage my engagement in science and for believing in me, even when I could not myself. To my sister, Catherine and to my closest friends, Veronica and Dilly. Thank you for always being at the other end of my distressed messages or phone calls when I needed you. You have all been more help than you realise and I owe you all so much. To all my extended friends and family, those I met during my time at Exeter and older friends from Durham and my childhood, I appreciate all your patience and I am sorry for not being around as much over the past few years.

Finally, my eternal gratitude goes to Martin who has sat by me and supported me unconditionally, even through my darkest times. Thank you for sharing all your wisdom, knowledge and insightful inputs on my research, from discussions over cooking the dinner, to your help in everything programming or maths related. I am so grateful for you taking the time out of your busy work schedule to read every chapter and for listening to my endless ramblings about energy, fracking and the struggles of research. I do not know if I would have completed this thesis without your endless encouragement and 'look to the future' attitude. Your support and understanding has meant the world.

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
BC	British Columbia
BCOGC	British Columbia Oil and Gas Commission
BGS	British Geological Survey
BOP	Blowout Preventer
BORA	Barrier and Operational Risk Analysis
DECC	Department of Energy and Climate Change
EA	Environment Agency
EIA	Environmental Impact Assessments
EPA	Environmental Protection Agency
ERA	Environmental Risk Assessment
ETA	Event Tree Analysis
FTA	Fault Tree Analysis
FAHP	Fuzzy Analytical Hierarchy Process
FETA	Fuzzy Event Tree Analysis
FFTA	Fuzzy Fault Tree Analysis
FIS	Fuzzy Inference System
FLS	Fuzzy Logic Systems
FPS	Fuzzy Possibility Score
FST	Fuzzy Set Theory
FVIM	Fussell-Vesely Importance Measure
FWI	Fuzzy Weighted Index
GHG	Greenhouse Gas
GIS	Geographical Information Systems
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HOF	Human and Organizational Factor
HSE	Health and Safety Executive
IQR	Interquartile Range
LQ	Lower Quartile
MCS	Minimal Cut-sets
MTTF	Mean Time To Failure
MD	Measured Depth
MLE	Maximum Likelihood Estimation
NEBC	Northeastern British Columbia
NOAV	Notice of Alleged Violations

NORM   Naturally Occurring Radioactive Material
NOV   Notice of Violations
OAT   One-factor-at-a-time
OGA   Oil and Gas Authority
PADEP   Pennsylvania Department of Environmental Protection
PEDL   Petroleum and Exploration Development License
QRA   Quantitative Risk Assessment
SAM   Similarity Aggregation Method
SCP   Surface Casing Pressure
SCVF   Surface Casing Vent Flow
SPR   Source-Pathway-Receptor
SPZ   Source Protection Zone
TCF   Trillion Cubic Feet
TDS   Total Dissolved Solids
TRF   Time at Risk Failure
TVD   Total Vertical Depth
UBC   University of British Columbia
UKCS   UK Continental Shelf
UQ   Upper Quartile
USDOE   US Department of Energy
US EIA US Energy Information Administration
WFD   World Framework Directive

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND RATIONALE

Dwindling energy resources in parallel with a highly demanding growing population is no doubt a concern. For the last 100 years, the world has relied on oil and gas from conventional sources (Arthur and Cole, 2014) and with the environmental push towards net zero carbon emissions, renewable energy is a potential target for improved energy security (CIWEM, 2014). However, renewable energy is still in its infancy and there is still a requirement, at least in the medium term, for gas to heat homes particularly in the northern hemisphere (CIWEM, 2014). Therefore, alternative sources of energy are being sought after with unconventional resources demonstrating successful oil and gas production in a significant portion of the globe.

The US took the centre stage on unconventional resource production and have been commercially successful since the late-1990's with record low energy prices from the 21st century (Trembath et al., 2012) and the popularity of natural gas projected to increase throughout the coming decades (Figure 1.1). Canada have also followed suit, commercialising shale hydrocarbon production from 2005, albeit on a slightly lower scale compared with the US (Rivard et al., 2014). The US shale gas boom allowing for rapid self-sufficiency and domestic energy success encouraged other regions such as Europe, Argentina and China to explore for potential unconventional resources (Stephenson, 2015b). However, onshore development is an unfamiliar territory, particularly for Europe where the majority of energy exploits are imports from the North Sea and Russia (Stephenson, 2015b). Additionally, prospective shale regions across Europe often underlie densely populated areas and the size of the countries often means onshore well pads will never be too far from civilisation (Figure 1.2). The size of the US and Canada and expansive unpopulated regions reduces this problem.
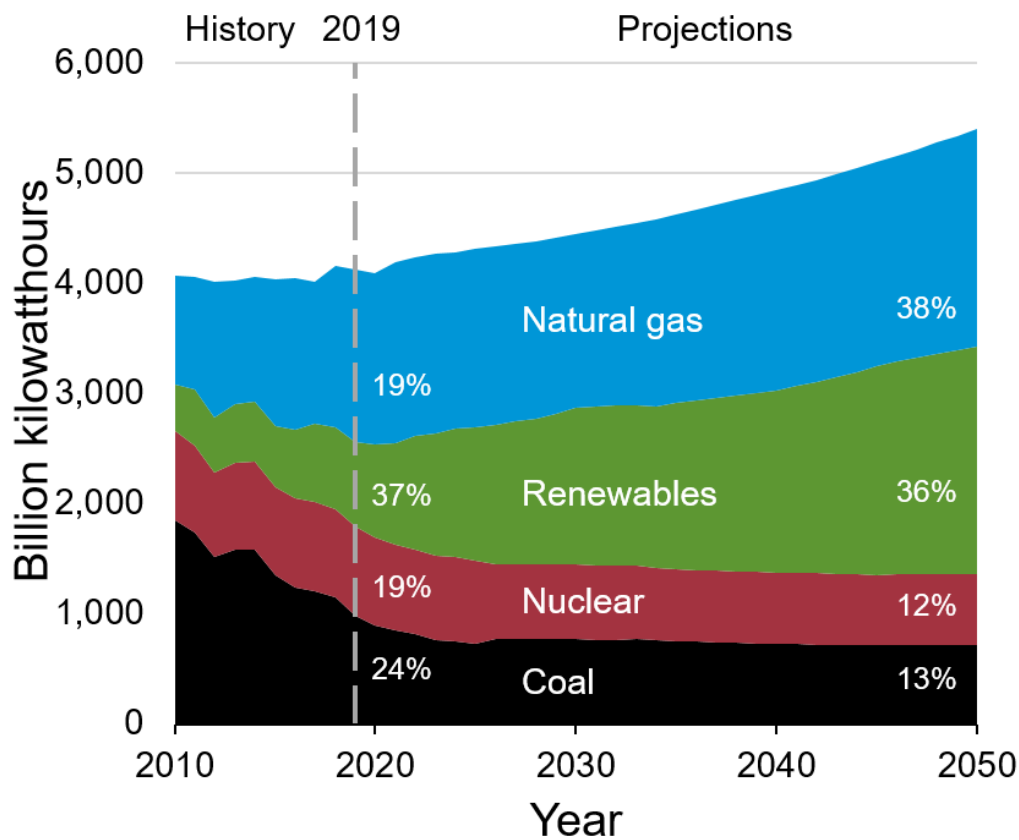
FIGURE 1.1: Past history and future energy projections for the US (US Energy Information Administration, 2019).

Although the rapid development of the US shale gas industry has brought economic prosperity and independence, it has simultaneously caused environmental degradation, perhaps one of the most challenging and controversial issues facing the onshore hydraulic fracturing industry (Arthur and Cole, 2014). Despite continuous success in the US, countries within Europe such as the UK, France, Poland and Romania have faced public scrutiny and stagnant policy decisions over industry development (Bomberg, 2017). Although a number of issues underlie the reasons for poor unconventional exploitation outside of North America, environmental issues such as water availability, induced seismicity, groundwater contamination and air quality (to name a few) are some of the key problems in hydraulic fracturing. As such, a focus of this research has been on the issues surrounding groundwater contamination from onshore hydraulic fracturing.

The technical and scientific understanding of hydraulic fracturing is well developed within the oil and gas industry and there is a general consensus on the qualitative environmental impacts and behaviour of contaminants in the sub-surface of the complex, onshore operation. However, sufficient quantification of the risks surrounding these impacts is lacking,
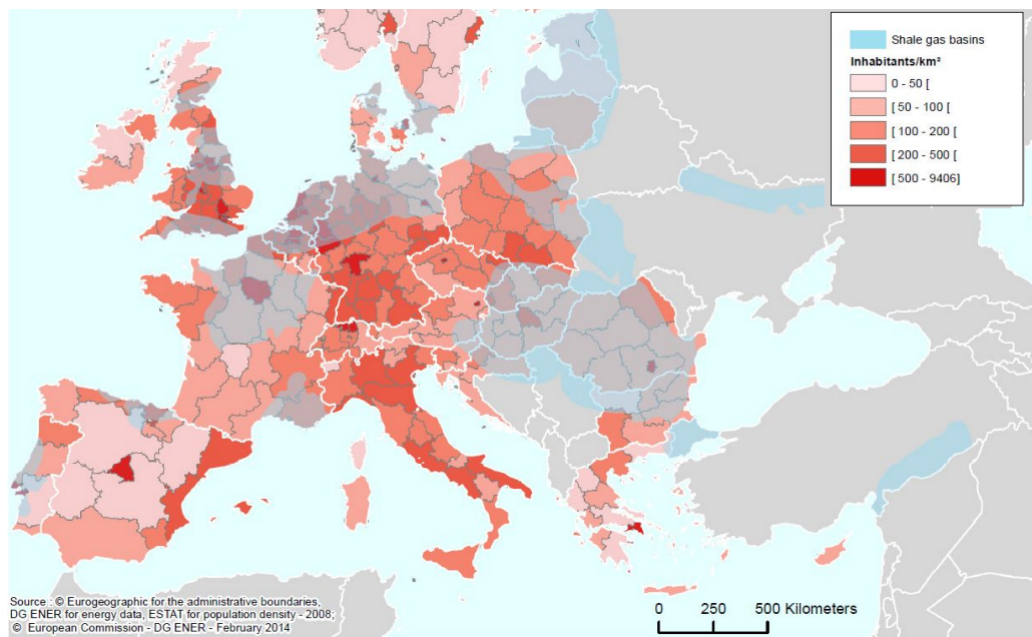
FIGURE 1.2: Shale gas basins in Europe and the population density surrounding the basins (Schuetz, 2014).

particularly with respect to the water environment (Davies, 2011; Molofsky et al., 2011; Schon, 2011; Warner et al., 2012; US Environmental Protection Agency, 2016a). If risks towards groundwater contamination (and other receptors) can be highlighted and quantified across different regions, more scientific evidence without bias towards or against the industry might reduce the anxiety and concerns facing public perception and government decisions (Kirkman et al., 2017).

Risk assessment is the technical process of quantifying the probability and consequence of an event or hazard (Modarres, 2006; Fjeld et al., 2007). It is used across many engineering industries and has become a particularly important area for countries fluctuating in uncertainty over exploiting potential unconventional gas reserves. Risk assessment studies focusing on hydraulic fracturing have recently increased in the literature, addressing a selection of environmental issues. In the UK, the Environment Agency (EA) produced a qualitative document on many risks associated with unconventional shale gas operations, a good starting point for risk analysis (Environment Agency, 2013). Across different countries (with a main focus in the US), Rozell and Reaven (2012) looked at the probability of water contamination from the Marcellus shale, Ziemkiewicz et al. (2014) analysed the failure of waste pits, Ingraffea et al. (2014) used historical data to analyse casing and cement failure in conventional and unconventional wells, Hu et al. (2018) looked at a method to assess the hazards associated with the chemicals used during well injection and Jabbari et al. (2017) assessed groundwater contamination from the perspective of well casing failure. However, these studies focused on one risk pathway with high uncertainty in the results. Where case studies are applied, the outcome can only be discussed with

respect to a particular area which does not encourage other countries with vastly different geology and regulations to trust site-specific decisions.

Zoback et al. (2010), Dethlefs and Chastain (2012) and Considine et al. (2013) present general knowledge on environmental risks associated with well integrity scenarios with outputs used for industry best practises and government regulations and Li et al. (2017) discusses a selection of risks to groundwater and highlights the importance of well integrity on reducing risk to groundwater contamination. These studies introduce useful qualitative information and some specific modelling studies to understand the movement of gas through fractured systems. However, significant gas migration is common along well annuli and this is poorly quantified in the literature, particularly with respect to cement failure. Within this research, fuzzy logic has been a useful tool for handling gas migration pathways which are not easily quantifiable.

Fuzzy logic is a form of artificial intelligence but is more of a knowledge representation model involving human reasoning and judgement as opposed to machine learning which requires well-defined examples and data to train a concept. Fuzzy logic can be more appropriate for systems where binary logic is not as well-defined but there exists a vagueness between 0 and 1. In complex systems such as subsurface environments, not all events occurring are known or are only known to a certain extent. Fuzzy logic enables decisions to be made or a better understanding of a system even when not all events can be observed or there exists ambiguity in the observations. Within hydraulic fracturing, very often data might be sparse or events of gas migration are poorly correlated with available data. In these circumstances, an improved understanding of these events using fuzzy logic can be tackled using a combination of human reasoning, expert judgement, linguistic descriptors (such as 'very low', 'low', etc.) and numerical data. Using solely numerical data to train a model to understand the reasons behind gas migration is more likely to lead to a wrong or inaccurate outcome, especially as human errors during an engineered operation can not be as easily implemented in machine learning compared with fuzzy logic.

To summarise, the gaps in the literature which are tackled in this research are listed below:

- New subsurface energy industries such as the UK have substantially different requirements compared with the historic industries such as Canada and the US. The impact hydraulic fracturing has on groundwater in the UK compared with North America is significantly different due to the implications gas migration has on densely populated areas with highly vulnerable groundwater aquifers. This comparison has not been made in research, to date.

- Generic risk assessments which can be applied to different case studies and subsurface environments have not been executed in the past.

- Where quantification does exist for assessing certain failure pathways, there are always high levels of uncertainty so alternative methods are required to reduce this uncertainty.

- Current research cannot be successfully applied to a new industry for predicting future multiple contamination pathways.

- Well integrity failure is a well-known issue in subsurface engineering but the focus has not been on groundwater as the receptor, especially in more highly densely populated groundwater areas.

- Well integrity failure in conventional versus unconventional is expected to be different as increased pressures, particularly during injection, makes hydraulic fracturing more susceptible to well failures. The two techniques are often not comparable.

The frequent discussions on the importance of well integrity for groundwater protection and a lack of quantitative analysis across different regions in the world has encouraged the focus of this research to be on assessing the risk of groundwater contamination from well integrity failure across several stages of an onshore hydraulic fracturing well and its applicability to the UK, currently challenged by social perceptions (Andersson-Hudson et al., 2019; Acquah-Andoh et al., 2019).

This research is developed based on onshore hydraulic fracturing but the risk assessment techniques used are generic enough to allow application of this research to other subsurface activities such as CO_2 sequestration, waste injection disposal and geothermal energy.

1.2   AIMS AND OBJECTIVES

The aim of this research is to develop a risk assessment framework for the onshore hydraulic fracturing UK industry to quantify the probability of groundwater contamination from well integrity failure during the injection and production stages of a well, incorporating data uncertainty methods due to insufficiency, complexity and subjectivity of failure mechanisms.

To achieve this aim, eight objectives are defined and explained below which contribute to the research:

1. Identify the risks to environmental receptors facing the onshore hydraulic fracturing industry globally and its future in the UK.

   (a) Identify, define and explain the techniques for hydraulic fracturing.

   (b) Develop a conceptual model for groundwater contamination globally.

(c) Explain the concept behind well integrity failure to determine its position in environmental degradation from hydraulic fracturing.

(d) Develop an understanding of the hydraulic fracturing industry from a UK perspective and the challenges it faces.

2. Identify the gaps in knowledge by evaluating the current literature surrounding risk assessment approaches in the oil and gas industry.

    (a) To highlight the scope of the work, define the concept of risk and the risk assessment process.

    (b) Identify the current limitations in existing qualitative and quantitative risk assessment methodologies, particularly in reference to oil and gas industry methods.

    (c) To fill the gaps in knowledge, evaluate the suitability of the chosen methodology for developing a risk assessment framework for onshore hydraulic fracturing.

3. Demonstrate the suitability of using fuzzy logic theory to fill literature gaps and handle data uncertainty in the hydraulic fracturing industry.

    (a) To ensure the validity in the framework, describe fuzzy logic theory and the development of fuzzy logic systems.

    (b) Identify the limitations and opportunities for improvements in the existing fuzzy logic risk assessment methodologies to apply to this research.

    (c) Identify and explain the application of the chosen risk assessment approach to fuzzy logic theory.

4. Identify a suitable case study for model development and application.

    (a) Develop collaborative engagement with an external academic or industry institution where data collection is possible and the case study area is appropriate for model development.

    (b) Identify important groundwater contamination and well integrity issues within the case study area.

    (c) Collect data where possible, identifying areas of high uncertainty.

    (d) Introduce the applicability and limitations to the UK industry.

5. Assess the risk to groundwater contamination from well integrity failure during the well injection and production stages of an onshore hydraulically fractured well.

    (a) To apply the risk assessment methodologies to a new case study area, design the risk assessment framework and risk analysis methods for an injection and production well.

(b) Identify the failure scenarios and apply event and fault tree analysis to construct the framework.

(c) To produce the risk assessment results, apply the quantification methods using case study data where possible.

6. To test the accuracy of the implemented framework, evaluate and validate the fuzzy logic risk assessment methodologies.

(a) To analyse the success of the model outputs, conduct sensitivity analysis on the injection and production well models.

(b) To assess the risks to groundwater contamination, present the analysis of results on the outputs of injection and production well models.

(c) Validate the model by comparing the outputs of the model with past and current literature.

7. To identify the models utilities and limitations, apply the model to a case study.

(a) To analyse the future and potential risks to an inexperienced industry, apply the model to the UK highlighting important adjustments to the model.

(b) To assess the risks to groundwater contamination in the UK, discuss the outputs of the models.

(c) To reduce uncertainty in the model, present limitations and the requirement for further work.

8. Present recommendations for policy makers for practical application of the framework.

(a) Present the contributions to the research field within risk assessment, fuzzy logic and onshore hydraulic fracturing.

(b) Identify where the framework can be applied in policy decision-making.

(c) Discuss recommendations for policy makers globally and in the UK.

(d) Present suggestions for further research to improve its application.

1.3 THESIS SCOPE AND OUTLINE

Within the scope of this research, two out of three questions are answered focusing on how likely it is groundwater is contaminated by methane gas during the well stimulation (injection) and production stages of unconventional onshore hydraulic fracturing. The first question looks at ''what can go wrong?" which focuses on the potential risk scenarios to groundwater contamination. The second looks at ''how likely is it to occur?" which

focuses on the probability or likelihood the scenario event happens. The final question looks at ''what are the consequences'' which assesses the implications to different receptors if the scenario occurred. This research focused on the first two questions in depth to ensure generic case study applicability to cover some key gaps in the literature. The consequences were not determined in this research but future work can focus on the economic variability between different well constructions during injection and production weighed up against the probability of failure for both constructions. In addition, the environmental costs of groundwater remediation if gas migration does occur based on significantly different groundwater areas.

The limitations of this research have focused on only two stages of the hydraulic fracturing process: injection and production, because these are the two main stages which experience well integrity failure. The risk pathways surrounding site setup and drilling are generally different but well integrity failure is also experienced during post-closure and abandonment, especially long-term. The techniques used in this research can be applied in the exact same way to this stage of hydraulic fracturing but more research is required on the long-term degradation of cement.

The structure of the thesis containing eight chapters is shown in Figure 1.3, connecting the objectives with each chapter. The multidisciplinary nature of the research requires fundamental concepts of hydraulic fracturing, risk assessment and fuzzy logic to be properly reviewed to establish commonalities between each topic. This chapter discussed the background and rationale behind the research, the aims and objectives and outline of the thesis.

Chapter 2 presents background knowledge and techniques on hydraulic fracturing. The environmental pressures facing the industry are discussed, focusing on the development of a conceptual model for groundwater contamination. Well integrity failure is chosen as the main pathway for contamination and the theory and literature reviewed. The chapter concludes with a discussion on the UK perspective to the hydraulic fracturing industry.

Chapter 3 is a literature review on risk assessment and an introduction to fuzzy logic theory, focused on the oil and gas industry. The theory of risk assessment is introduced and the scenario modelling, event and fault tree methodologies used in this research are discussed. Fuzzy logic theory is explained, focusing on the system elements required for model development in this research. Literature is reviewed for both risk assessment and fuzzy logic methodologies.

Chapter 4 presents two case studies discussed in this research, British Columbia (BC) in Canada and the UK (Lancashire). The chapter discusses the reason for using BC as the model development case study and the reason for applying the model to the UK. Both case studies discuss the geology and shale formations, the status of the groundwater, the drilling regulations and well integrity requirements within both study areas.
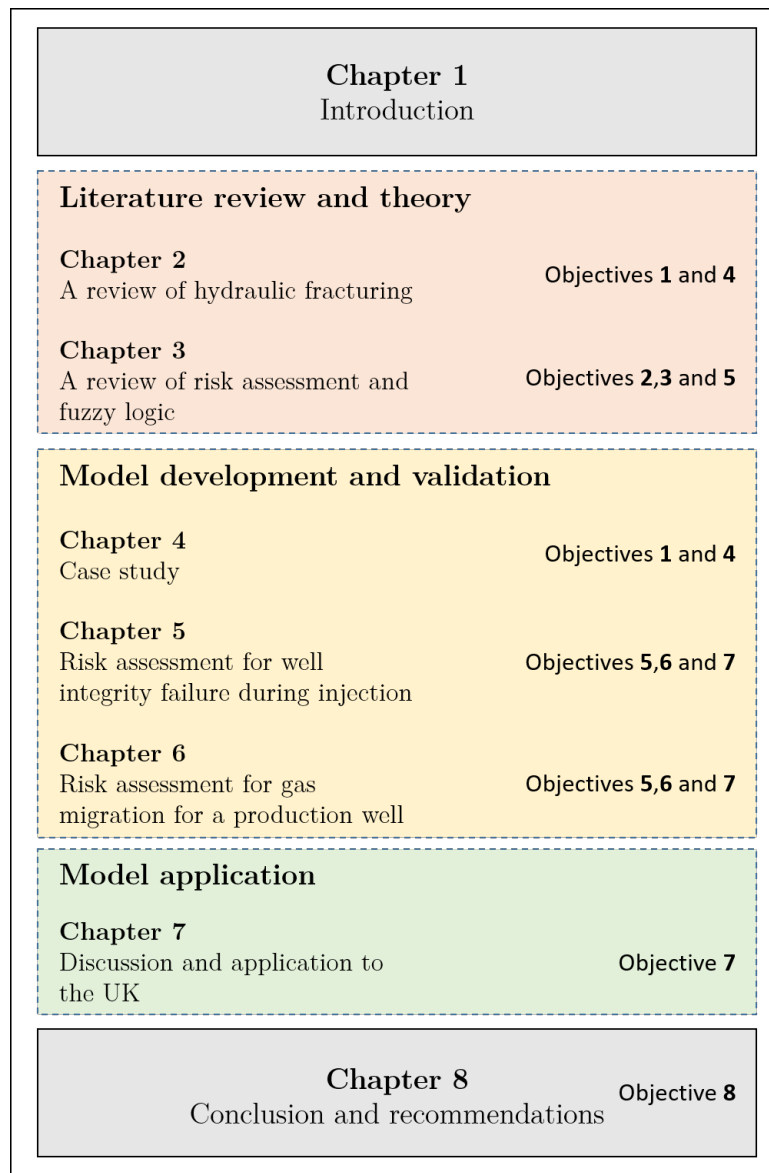
FIGURE 1.3: Thesis structure and objectives.

Chapter 5 is the first model construction and development chapter, focusing on the injection stage of hydraulic fracturing. This chapter focuses largely on quantifying cement failure using fuzzy logic. The framework and conceptual model of the injection well is first introduced, along with the application to the BC case study. The methodology for fuzzy event and fault tree analysis is discussed and results presented from quantifying the event and fault trees. Finally, sensitivity analysis is conducted to test the robustness of the fuzzy model and the outputs discussed.

Chapter 6 is the second model construction and development chapter, focusing on the production stage of hydraulic fracturing. The theory behind gas migration along wellbore annuli and the numerical model for Surface Casing Pressure (SCP) is discussed. The

conceptual model is illustrated and provides the template for event tree development, data collection and application to the BC case study. The fuzzy model and numerical model for gas migration is designed and constructed, and sensitivity analysis is used to test and validate the model. Finally, the results are analysed and discussed with respect to the case study.

Chapter 7 applies the model in Chapters 5 and 6 to the Lancashire well in the UK. Cement failure is discussed focusing on where improvements can be made for more specific application. The Lancashire well site and conceptual model is introduced and the available data for model application. This case study is then applied to the well injection model and well production model, highlighting any limitations or data gaps.

Chapter 8 summarises the conclusions obtained in the thesis for each objective and highlights the contributions to the research field. Recommendations are suggested for policy specific to the UK as well as globally and the chapter concludes with suggestions for further research.

CHAPTER 2

A REVIEW OF HYDRAULIC FRACTURING

2.1   THE SHALE GAS REVOLUTION

The history of hydraulic fracturing can be traced back to 1866 when a war veteran, Colonel Edward A.L. Roberts was awarded a patent for stimulating shallow, hard rock oil wells in Pennsylvania, New York, Kentucky and West Virginia using detonations (American Oil & Gas Historical Society, 2007). However, it wouldn't be until the late 1940's that the idea of hydraulically fracturing a rock formation to produce oil and gas would come into play. An experiment was conducted in 1947 at Hugoton gas field in Kansas where 1000 gallons of naphthenic acid, palm oil gasoline and sand, followed by a gel breaker, were injected into a 2400 feet deep limestone formation (Smith and Montgomery, 2015). The production of gas was very minimal due to poor deliverability from the well, but it marked the start of commercial hydraulic fracturing. By 1949, J.B. Clark of Stanolind published a paper on a more detailed process which obtained a patent, and a license was granted to the Halliburton Oil Well Cementing Company. Oklahoma and Texas received the first two commercial hydraulic fracturing treatments on 17 March 1949 with 332 wells treated in the first year. During the 1950's, more than 3000 wells a month were fractured, by the 1960's Pan American Petroleum used the technique in Oklahoma and in the 1970's it was used in the Piceance Basin, the San Juan Basin, the Denver Basin and the Green River Basin (Manfreda, 2015). The process has since been used widely across the world (Smith and Montgomery, 2015).

However, modern day hydraulic fracturing only took off in the 1990's when George P. Mitchell (of Mitchell Energy) combined the technique with horizontal drilling, allowing the penetration of tight gas and oil reserves, especially within shales (Trembath et al., 2012). The first shale horizontal well was drilled in 1991 into the Barnett Shale and since then the technology of hydraulic fracturing has improved dramatically (Robbins, 2013). The improvement from conventional to unconventional drilling allowed the well to cover

a much larger area of shale to obtain substantially more gas in locations that might have previously been inaccessible (Robbins, 2013). In addition, it allowed the use of only one vertical well to cover a much larger radius with multiple horizontal wells drilled from just one well, reducing the need to drill excess numbers of vertical wells (The Geological Society of America, 2016).
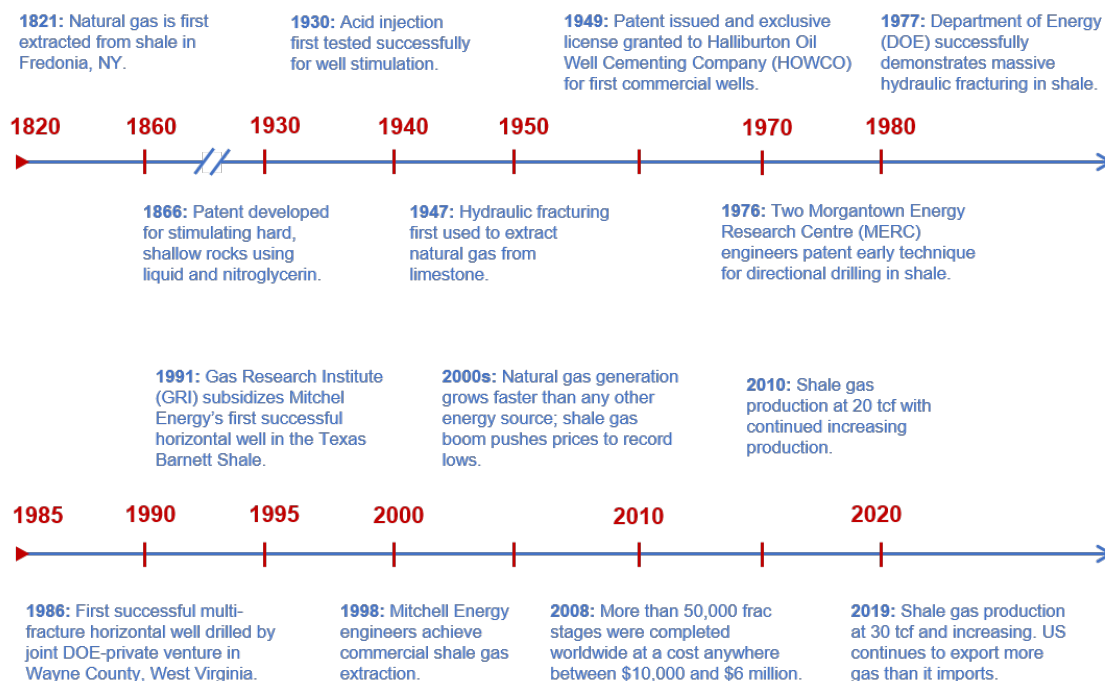
FIGURE 2.1: Timeline representing the development of the US shale gas industry. Adapted from Trembath et al. (2012) and US Energy Information Administration (2019).

The US has the largest shale gas industry in the world and production from unconventional formations has increased substantially over the past 20 years as conventional fossil fuels are being depleted and the requirements for gas have increased (Trembath et al., 2012; Stephenson, 2015b). The US has five main shale plays: Barnett shale, Marcellus shale, Eagle Ford shale, Haynesville shale and Fayetteville shale (Stephenson, 2015b).

Canada has over $500,000$ wells drilled across various provinces with around $375,000$ in just Alberta (Rivard et al., 2014). Oil and gas development started from the mid-1800's although was not commercialized till the late-1800's (Rivard et al., 2014) with recent wells mainly being hydraulically fractured wells on unconventional formations; drilled from about 2005 (Rivard et al., 2014). Canada has two main shale plays: Muskawa (Horn River) shale and the Montney shale.

Onshore unconventional development has been a successful industry in North America which has prompted other countries, such as the UK to seek to exploit their shale gas to improve their own energy production and reduce their need to import (Grafton et al., 2017). In 2013, the British Geological Survey (BGS) started exploring for unconventional

gas reserves and their potential for economical production. The BGS discovered high potential for shale gas extraction from formations such as the Bowland Shale with extensive amounts of gas present. This has driven the UK to strongly consider producing from our shale resources in an attempt to be more self-sufficient and improve the economy.

Within Europe, Poland has also explored its shale gas reserves and had some advancements in shale gas development (Stephenson, 2015b). Its dependency on Russia for gas imports and coal for electricity generation has urged Poland to utilise its domestic resources. However, 33 exploration wells have been drilled and 11 have been hydraulically fractured with substantially mixed results (Grafton et al., 2017). Other prospective areas for shale gas development within Europe consist of the eastern Baltic, north-eastern Ukraine, western Ukraine, the Balkans, northern Germany, southern Norway and Sweden, Netherlands and northern France (Stephenson, 2015b).

2.1.1 Shale gas

Hydraulic fracturing allows the exploitation of unconventional formations which could sit 4 km below the surface (Stephenson, 2015b) containing huge amounts of gas which otherwise could not be accessed due to their extremely low permeability. The permeability and porosity of rock formations has a large impact on the available and recoverable amount of reserves. The porosity of the rock determines the amount of gas the formation can hold and the permeability of the rock determines the flow of the product into the well. Conventional methods tap into permeable formations such as limestone and sandstone whereas unconventional methods utilise rock formations with commercially viable quantities of gas but very low permeability, such as shale (Figure 2.2).
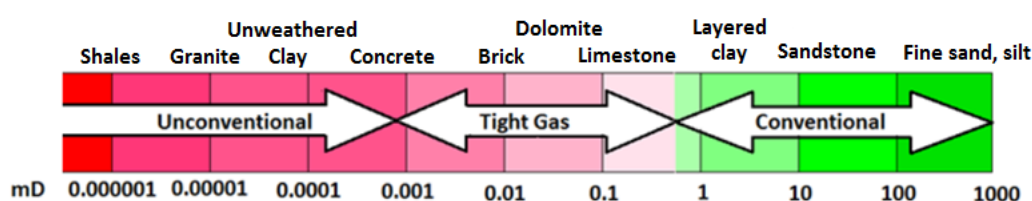
FIGURE 2.2: The permeabilities for various types of rock. Adapted from King (2012) and Bear (1972).

Access to shale gas has been an issue for large scale production due to the lack of natural permeability (Stuart, 2012). However, deep wellbores and the forced creation of fractures opens up pathways in the rock to increase permeability in the shale allowing the flow of gas into the well; this has led to the development of hydraulic fracturing (Jenkins and Boyer, 2008).

2.2 DRILLING AND HYDRAULIC FRACTURING

Hydraulic fracturing drills deep into impermeable shale rock and fractures the rock, allowing gas to migrate into a horizontal production well. A vertical well is drilled down into the shale and then continued horizontally along the target formation. A typical horizontal well (Figure 2.3) can range from 300 m to over 3000 m in length and substantially increases the length of contact a production well has with the shale rock, increasing the volume of gas produced (Arthur et al., 2009; Jackson et al., 2013a). Horizontal wells can replace 3 or 4 vertical wells, reducing production costs which contribute to the economic feasibility of the production of shale gas and reducing the environmental impact associated with construction (Gregory et al., 2011).
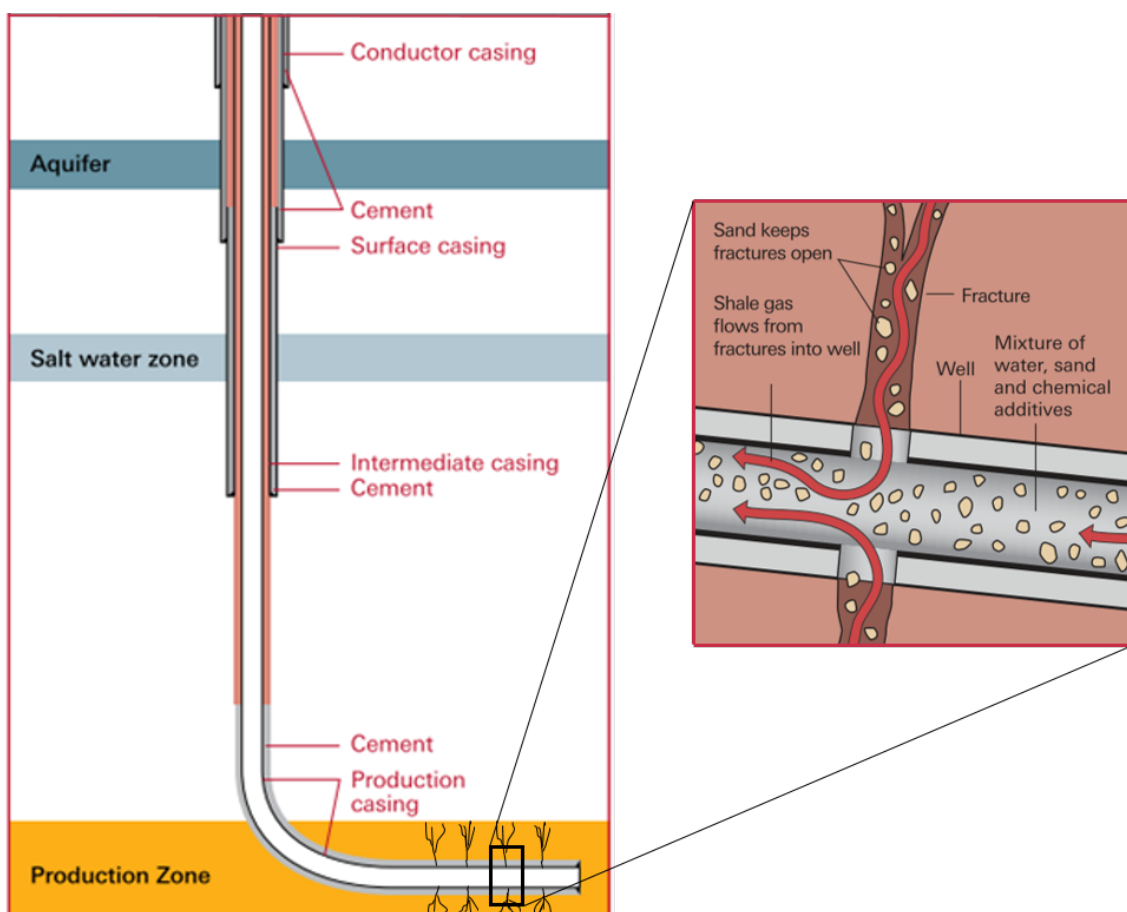
FIGURE 2.3: Diagram showing a typical horizontal well construction and explanation of the well stimulation process. Adapted from The Royal Society (2012).

A well is drilled vertically into the ground and casings are inserted (Figure 2.3) to prevent contamination from the wellbore to the surrounding formation and vice versa. The production casing surrounding the horizontal part of the well is perforated with tiny holes to allow gas to move from the formation into the well. Fracturing fluids consisting of water, proppant and chemicals are injected into the well at high enough pressures

above the formation pressure to create fractures in the target rock (Stuart, 2012; Smith and Montgomery, 2015). In British Columbia (BC), Canada 1,000-70,000 m^3 of fracturing fluid and water can be used for one horizontal well (Johnson and Johnson, 2012). Once the pumping of the fluid into the well has stopped, the direction of flow down the well is reversed which would cause the fractures to close up. Proppant in the fluid remains in the formation between the fractures to hold them open to allow the fluid and gas to return to the surface (Figure 2.3).

The pressure difference between downhole and at the surface allows fluid and gas to return to the surface. The fluid is known as flowback which mainly consists of the fracturing fluid pumped down the well. The amount of fluid returning depends largely on the geological and production conditions (Gregory et al. 2011). According to the US Environmental Protection Agency (2012), 10-70% of the fluid will return to the surface with the rest imbibing in the rock formation (Birdsell et al., 2015). Gas returning up the well signifies a well is in production and can happen over months or years. However the production of gas over time decreases substantially. Table 2.1 refers to the amount of gas obtained from a Marcellus well in New York, US over a period of more than 11 years (Hardy, 2015). Often wells are re-fractured to extend the wells life; this can happen more than once (Hardy, 2015).

TABLE 2.1: Production of gas over the lifetime of a Marcellus well in New York, US (Hardy, 2015)

Year	Initial rate (m^3 d^{-1})	Final rate (m^3 d^{-1})
1	79,000	25,500
2-4	25,500	15,600
5-10	15,600	6,400
11+	6,400	Declining at a rate of 3% per annum

Once gas production begins, produced water will continue to flow to the surface over the lifetime of the well in much smaller volumes compared to the flowback fluid, around 2-8 m^3 d^{-1} (Gregory et al., 2011). Produced water originates from the shale formation containing high concentrations of Total Dissolved Solids (TDS) and could vary in chemical composition from freshwater to brackish to saline or supersaturated brine (GWPC and ALL Consulting, 2009). The water might contain heavy and light petroleum hydrocarbons and Naturally Occurring Radioactive Materials (NORM) (Arthur et al., 2009; Gregory et al., 2011). The variation in chemistry of the produced water depends on the time it has spent in the formation and the geochemical conditions. Over the lifetime of the well it is hard to distinguish between produced water from the fracturing process and natural formation water which has been in the rock for millions of years (GWPC and ALL Consulting, 2009).

2.2.1 Stages of hydraulic fracturing

The lifetime of a gas well exists through different stages, some which last much longer than others. Each stage requires strict regulations and protocol to follow to ensure environmental protection of the surrounding area and off-site locations. The lifetime of a well consists of five stages:

1. Site preparation

    Once a geological area has been chosen as a viable location to produce economically favourable gas, the area must be prepared before drilling can commence. This involves clearing an access road to the site for ease of transportation, levelling the area for the drilling pad, digging reserve pits and impoundments, and pipeline development (Hyne, 2012). This could take a couple of months to develop.

2. Drilling and construction

    The well pad has been constructed, the equipment for drilling has been delivered to the site and access roads have been built to allow movement of infrastructure, equipment, water, chemicals and waste water to be transported to and from the site. Drilling, construction and preparing of the well will use a range of equipment, techniques and chemicals. The most important factor is to ensure groundwater resources are not affected during the drilling process.

3. Well stimulation/high pressure well injection

    The high pressure injection will occur from around 20 minutes to about 4 hours depending on the design of the frac (King, 2012). This process injects high pressure fluids down the well to create the fractures in the target formation and keep them open using proppant. Wells might require re-fracturing or re-stimulation after the initial production of gas to obtain maximum economic output.

4. Production

    This is the longest active stage of the well. Once the rate of flowback fluid and produced water decreases significantly (few weeks to a few months (King, 2012)), gas production will begin returning up the well. Gas wells can be producing from a few years to decades, so wells can be in this stage for a long period of time.

5. Closure and abandonment

    When a well has come to the end of its production life and re-fracturing is completed where possible, the well is shut down. The well is cemented in sections to prevent fugitive gas moving into surrounding water resources or venting at the surface (The Royal Society, 2012). A cap is put on the well at the surface and environmental remediation is undertaken around the well.

6. Waste and waste water management

    During the wells lifetime across all stages, waste is produced either as solid or liquid

form. Management of drilling fluids and mud cuttings require on-site storage and disposal along with chemicals used for well stimulation. Waste water which returns up the well must be disposed of carefully. It can have a very high saline content which is a challenge to treat at standard waste water treatment plants and NORMs are present in produced water which are harmful if they reach the environment and interact with humans, plants and animals.

2.2.2 Environmental concerns

Hydraulic fracturing has been an established technique for gas exploitation for many decades, with North America being the largest and only commercial contributor to shale gas development in the world (Stephenson, 2015b). Other countries throughout Europe and in China (Brinded et al., 2012; Stephenson, 2015b) have utilised the technology and due to its success, this has prompted countries such as the UK to exploit their shale gas and improve their own energy production to reduce their need to import (Grafton et al., 2017). However, fast production with unstable regulations in the US lead to environmental issues (Figure 2.4), opening up a controversial debate which has resonated with the UK. Atmospheric releases and social pressures to protect the environment, climate and water resources has lead to conflicts of interest involving our increasing energy demands (BBC, 2015; Ficenec, 2014).

Hydraulic fracturing brings with it the potential to release methane into the atmosphere over its life cycle, a potent greenhouse gas, effectively offsetting its positive application of producing a cleaner fuel (Rozell and Reaven, 2012). Fugitive gas migration is a common problem with hydraulic fracturing (Osborn et al., 2011; Jackson et al., 2013b; Vengosh et al., 2013; Vidic et al., 2013; Vengosh et al., 2014; Cahill et al., 2019). These gases can reach shallow groundwater contaminating public water supplies or vent at the surface releasing methane into the atmosphere. Fluids injected into the subsurface, NORMs and high saline waters are also a cause for concern in groundwater along migration pathways.

Water quantity required for high pressure, high-volume hydraulic fracturing can deplete water supplies, degrading the quality of surrounding water resources. Additionally, storage and treatment of returning waste waters on-site can lead to contamination of the surrounding area and general environmental degradation.

Seismicity has been a prominent issue in hydraulic fracturing (Davies et al., 2013; Ellsworth, 2013; Clarke et al., 2014; Zecevic et al., 2016). The high pressure injection process causes micro-seismic events and in some cases these seismic events can be felt at the surface or cause destruction.

These environmental concerns potentially experienced due to hydraulic fracturing are poorly quantified, particularly with respect to water resource contamination from fugitive
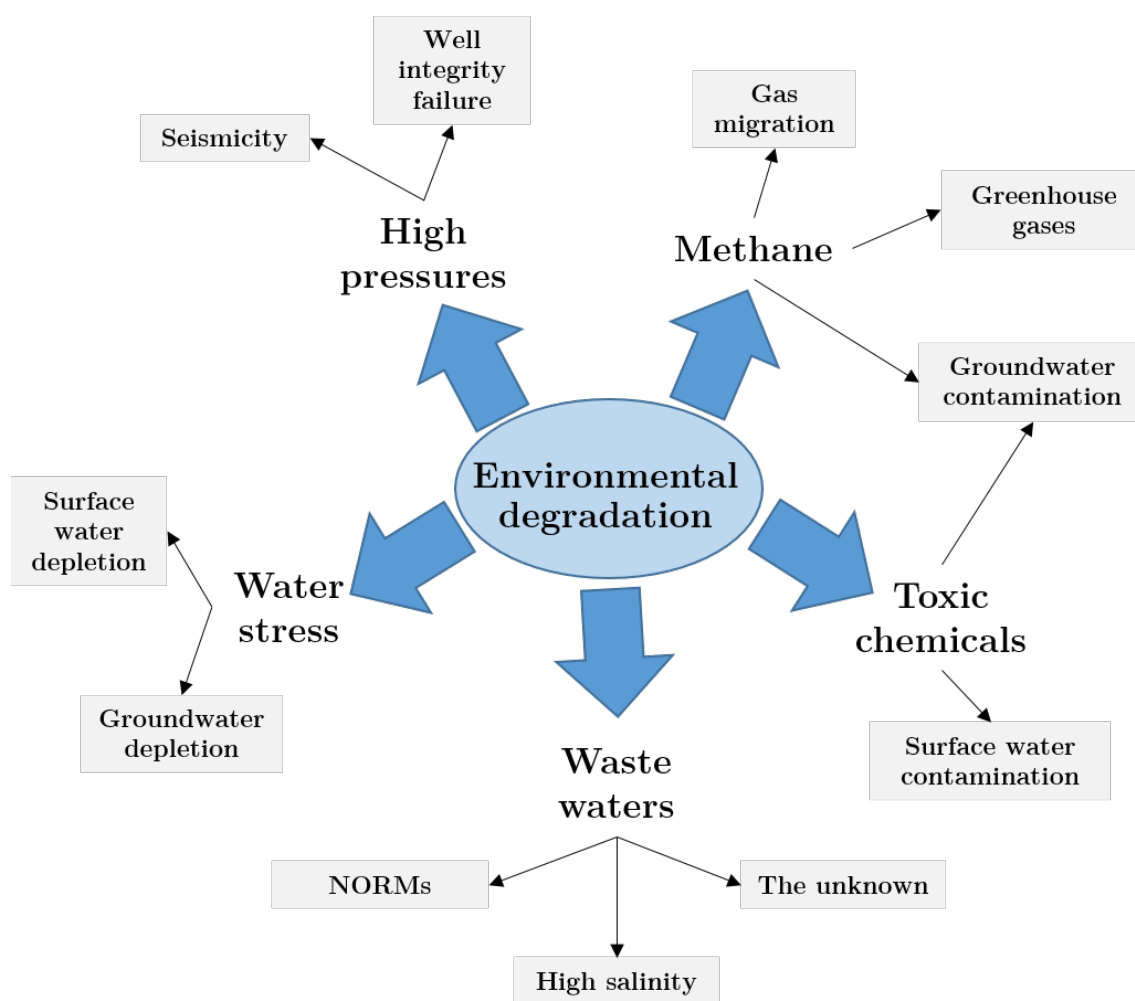
FIGURE 2.4: An overview of the environmental concerns facing the hydraulic fracturing industry.

gas migration (Davies, 2011; Molofsky et al., 2011; Schon, 2011; Warner et al., 2012; US Environmental Protection Agency, 2016a). A lack of baseline monitoring prior to hydraulic fracturing and conflicts in evidence means the fate of water from hydraulic fracturing is still a large unknown (Davies, 2011; Molofsky et al., 2011; Schon, 2011; Molofsky et al., 2013). The contaminants present in the hydraulic fracturing process are generally known but their quantifiable risk to water in varying environmental and geological scenarios throughout the process of hydraulic fracturing is limited (Lavoie et al., 2014), particularly as site-specific risk analysis may not be transferable across different case studies (Prpich et al., 2015). The fate of water resources from hydraulic fracturing can involve changes in quantity and/or quality of surface water and groundwater (Vidic et al., 2013; Gallegos et al., 2015). The vulnerability of water resources is high throughout the life cycle of hydraulic fracturing suggesting many factors must be considered and assessed before exploration and production can begin.

2.3 GROUNDWATER CONTAMINATION

Groundwater is a high risk receptor to contamination from hydraulic fracturing. In the US, hydraulic fracturing has caused issues regarding groundwater contamination from methane (Molofsky et al., 2011; Osborn et al., 2011; Molofsky et al., 2013; Jackson et al., 2013b), flowback (Warner et al., 2012; Haluszczak et al., 2013) and chemicals (Gordalla et al., 2013) via different potential contaminant pathways (Ward et al., 2015). Although hydraulic fracturing occurs at depths of more than 1 km, where an aquifer is present in the geological strata it must be penetrated to reach the underlying shale rock. Aquifers are vital groundwater resources of freshwater for the population and agricultural practises, but the fracturing procedure has elevated concerns over the contamination of these aquifers.

Methane gas from target formations or other gas producing zones and fluids used during hydraulic fracturing are the sources of contamination for groundwater. The pathways which connect these sources with the receptor are often the focus in risk assessments or field studies within the literature (Harrison, 1983; Zoback et al., 2010; Environment Agency, 2013; Stephenson, 2015a; Ward et al., 2015) and are summarised and conceptualised in Figure 2.5. Specific pathways such as well integrity (Dethlefs and Chastain, 2012; Ingraffea et al., 2014; Guan et al., 2015; Jabbari et al., 2017), migration and propagation (Kissinger et al., 2013; Lange et al., 2013) and exposure pathways of waste water (Ziemkiewicz et al., 2014) have been a common target for hydraulic fracturing studies with risk assessments taking qualitative or quantitative approaches.

Several critical reviews have been developed on water quality from hydraulic fracturing (Entrekin et al., 2011; Vidic et al., 2013; Jackson et al., 2013a; Brantley et al., 2014; Jackson et al., 2014; Ryan et al., 2015; US Environmental Protection Agency, 2016a) but have all considered information from the US or Canada due to the commercial industry and published results. In addition, the conclusions often indicate a lack of baseline and historic data to understand potential temporal changes in water quality.

Vidic et al. (2013) reviewed the impacts of shale gas development on water quality of the Marcellus Shale in the Appalachian region. Conclusions indicated the effect of hydraulic fracturing on water quality is still unknown. According to Harrison (1983), methane contamination of water in the Marcellus Shale occurred long before gas exploitation began, challenging the idea that hydraulic fracturing causes water contamination. Organic and inorganic compounds are used in fracturing fluid but some of these compounds potentially present prior to fracturing will naturally migrate over time or are derived from other anthropogenic changes such as waste discharge or salting roads (Brantley et al., 2014). Llewellyn (2014) and Warner et al. (2012) demonstrated evidence and mechanisms for natural brine migration from formations to shallow aquifers, indicating migrating pathways for brine and gas, suggesting not all the blame should fall on hydraulic fracturing.
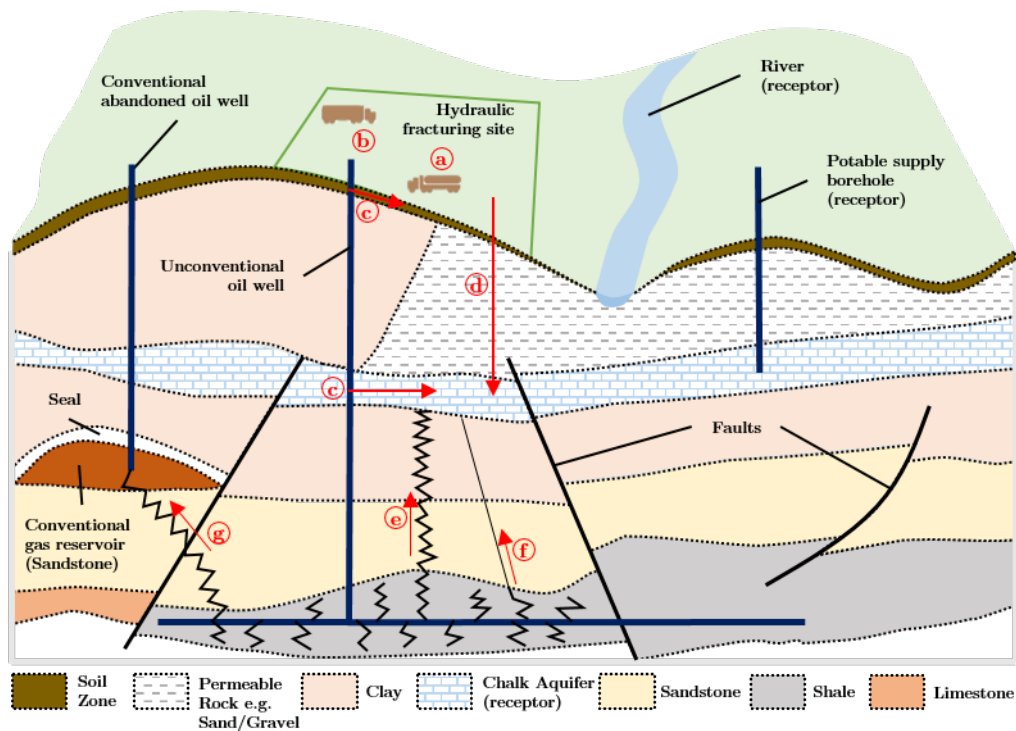
FIGURE 2.5: A conceptual model indicating the main potential contaminant pathways reaching groundwater from a hydraulic fracturing site. The letters correspond to individual contaminant pathways: (a) chemicals spills on-site, (b) returned flowback/produced water spills, (c) well integrity failure, (d) infiltration, (e) fracture propagation, (f) natural fracture connection, (g) connection with old oil wells.

In addition to natural gas migration, contaminants can transport from the rock through fractures to the aquifers either from man-made fractures, connection of man-made fractures with natural faults, or fractures connected to old oil and gas wells (Zoback et al., 2010). Abandoned wells with poor seals could create an easy pathway between the subsurface and aquifers for fast movement of gas and fluids to migrate. Davies et al. (2014) highlighted the problems with oil wells across the world, demonstrating there are many oil wells unknown in the US; around a million were drilled before any regulations were put in place and many are forgotten about. In the US, operators are not required to locate abandoned wells prior to drilling (Brantley et al., 2014). In the UK, 65.2% of wells drilled have no monitoring or records and around 53% of wells have unknown ownership (Davies et al., 2014). However, a connection with a consecutive well would be noticed immediately due to a significant reduction in pressure at the surface and production would be stopped.

Fracture propagation leading to a connection between a gas reservoir and groundwater has been studied in depth, mainly through subsurface modelling studies (Salehi and Ciezobka, 2013; Guo et al., 2015; Reagan et al., 2015; Zhou et al., 2016; Westwood et al., 2017). However as hydraulic fracturing is occurring at depths greater than 1 km, the fractures would have to propagate a considerable distance to reach the aquifer through several layers of rocks with varying physical properties, considerably reducing the chance

to reach aquifers. Davies et al. (2012) examined how far fractures could propagate in five different regions in the US and determined the maximum propagation of vertical fractures would be 588 m and calculated the probability of fractures extending further than 350 m is only 1%, though this still suggests a potential for contamination. In addition, when pumping is stopped in the fracturing process the reversal of pressure will mean contaminants will move from the cracks into the well rather than via the fractures towards the aquifers.

The significant unknowns in subsurface activity and the potential development of gas and fluid migration pathways during hydraulic fracturing operations highlights the need for further research to narrow down these gaps in knowledge. Groundwater is a vital resource which must be protected and is in danger of degrading during hydraulic fracturing. Therefore, this work will focus on this receptor and gas as a source, originating from the target formation or overlying gas producing formations.

2.4   WELL INTEGRITY

As discussed, the contamination of groundwater from gas or chemical compounds is not always traceable to hydraulic fracturing due to a lack of understanding on migration pathways. However, a well-known and documented problem which indicates the origin of contamination is due to poor cementing and drilling practises of the well. Documented data of stray gas contamination of groundwater is very often related to failures of well integrity with this being conclusive in most literature which discusses reductions in water quality from hydraulic fracturing (Szatkowski et al., 2002; Watson and Bachu, 2009; Osborn et al., 2011; Jackson et al., 2013a; Vengosh et al., 2013; Vidic et al., 2013; Darrah et al., 2014; Dusseault and Jackson, 2014). Sufficient well integrity is vital in preventing environmental damage during oil and gas drilling and is therefore considered one of the most significant pathways for gas or fluid migration to groundwater (Arthur and Cole, 2014; Dusseault and Jackson, 2014; Ryan et al., 2015).

To understand the extent to which well integrity failure can occur, Davies et al. (2014) gathered available data sets to quantify well integrity statistics for wells drilled globally. Table 2.2 highlights numerous incidents of well integrity and barrier failure which have occurred across the world through onshore and offshore drilling, where as high as 75% of wells drilled in a certain area have shown gas bubbling to the surface. On the other hand, values as low as only 0.7% of wells drilled in a different area saw integrity failure, indicating a large variability in (1) the data provided, (2) the time period with which the wells were drilled and hence varying technology, (3) unconventional or conventional targeted formations, and (4) geological conditions (Davies et al., 2014).

TABLE 2.2: Statistics on barrier and well integrity failures across the world both onshore and offshore, adapted from Davies et al. (2014).

Location	Onshore/ Offshore	Number of Wells	% of Wells Contaminated	Reason	References
Alberta, Canada	Onshore	316,439	4.6%	SCVF and GM failure.	Davies et al. (2014) andWatson and Bachu (2009)
Alberta, East of Edmonton, Canada	Onshore	20,725	5.7%	GM evidence.	Jackson et al. (2014)
Ann Mag Field, US	Onshore	18	61.0%	Well barrier failures in shale zones.	Yuan et al. (2013)
Bahrain	Onshore	750	13.1%	Failure of surface casing and leaks to surface.	Sivakumar and Janahi (2004)
Daqing Field, China	Onshore	6,860	16.3%	Barrier failure.	Zhongxiao et al. (2000)
Gudaeo Reservoir, China	Onshore	3,461	30.4%	Barrier failure in oil-bearing layer.	Peng et al. (2007)
Gulf of Mexico	—	8,000	2-29%	SCP on outer casing strings.	Bourgoyne et al. (2000)
Gulf of Mexico	Offshore	15,500	43.0%	47.1% production string failure. 26.2% surface casing failure. 16.3% intermediate string failure. 10.4% conductor pipe failure.	Brufatto et al. (2003)
Gunan Reservoir, China	Onshore	132	6.1%	Barrier failure.	Peng et al. (2007)
Hetan Reservoir, China	Onshore	128	5.5%	Barrier failure.	Peng et al. (2007)
Kenli Reservoir, China	Onshore	173	2.9%	Barrier failure.	Peng et al. (2007)

Table 2.2 continued

Location	Onshore/ Offshore	Number of Wells	% of Wells Contaminated	Reason	References
Kenxi Reservoir, China	Onshore	160	31.3%	Well barrier failure.	Peng et al. (2007)
Lloydminster, Canada	Onshore	1,230	23%		Erno and Schmitz (1996)
Malacca Strait, Indonesia	Onshore & Offshore	164	4.3%	Well integrity and barrier failures. Further 41.4% wells identified as high risk of failure.	Calosa et al. (2010)
Marcellus Shale, US	Onshore	8,030	6.3%	Integrity and barrier failure. 1.3% leak to surface.	Davies et al. (2014)
Marcellus Shale, US	Onshore	4,602	4.8%	Integrity and barrier failure.	Ingraffea (2013)
Marcellus Shale, US	Onshore	3,533	2.6%	2.4% cement/ casing failure. 0.1% blowouts. 0.06% gas venting.	Considine et al. (2013)
Nationwide CCS/Natural Gas Storage Facilities, US	Onshore	470	1.9%	Integrity failure; significant gas loss	IPCC (2005)
Nationwide Gas Storage Facilities, US	Onshore	6,953	6.1%	Integrity and barrier failure.	Marlow (1989)
Netherlands	Onshore	31	13.0%	Barrier failure.	Vignes (2011)
Norway	Offshore	193	38.0%	Integrity and barrier failure. 2 wells with leak to surface.	Vignes (2011)
Norway	Offshore	217	25.0%	Integrity and barrier failure. 32% leaks occurred at well head.	Randhol and Carlsen (2007)
Norway	Offshore	711	20.0%	Integrity and barrier failure.	Davies et al. (2014)

Table 2.2 continued

Location	Onshore/ Offshore	Number of Wells	% of Wells Contaminated	Reason	References
Norway	Offshore	406	18.0%	Integrity and barrier failure. 1% had well head failure.	Vignes and Aadnoy (2010)
Pennsylvania, US	Onshore	6,466	3.4%	Integrity and barrier failure. 0.24% leak to surface.	Vidic et al. (2013)
Santa Fe Springs Oilfield, US	Onshore	>50	75.0%	Surface gas bubbles along well casing.	Chilingar and Endres (2005)
Saskatchewan, Canada	Onshore	435	22.0%	Integrity failure. SCVF and GM failure.	Erno and Schmitz (1996)
UK Active Wells	Onshore	143	0.7%	Well integrity failure.	Davies et al. (2014)
UK Continental Shelf	Onshore	6,137	10.0%	Integrity and barrier failure.	Davies et al. (2014)

SCP: Surface casing pressure
SCVF: Surface casing vent flow
GM: Gas migration

2.4.1 Well integrity terminology

The failure of a well generally indicates a pathway has been formed in the cement, casing or both. This failure allows the movement of contaminants along a wellbore either through an annular leak, vertically between casings/cement/rock, or a radial leak, migrating horizontally either out of the well to the surrounding rock formation or into the annuli acting as a conduit for shallower vertical migration (The Royal Society, 2012). However, King and King (2013) improved the definition of well integrity failure by splitting it into two terms, single barrier failure in a multiple barrier well design or full well integrity failure. The rates at which full well integrity failure occurs are two to three orders of magnitude lower than a single barrier failure (King and King, 2013). In a single barrier failure, one or more barriers might fail but if properly constructed this will not lead to a significant risk of contamination. In full well integrity failure, the barriers preventing contamination have been breached and contaminants have escaped to the surroundings.

Pressure tests are conducted on wells to determine if there is a failure in the barrier system. Sustained Casing Pressure (SCP) tests are often used to determine the performance of the well. If SCP is noticed at the surface of the well and rebuilds after being bled down by the operator, it can be assumed there is a gas leak into the annulus due to a barrier failure causing this continuous build-up of pressure (Rocha-Valadez et al., 2014). If SCP is not dealt with or recognised, consistent pressure build-up in the annulus can force fluids out of the wellbore causing well integrity failure. In cases where SCP occurs but a surface casing vent is opened at the surface, the gas can release into the atmosphere to prevent the build-up of pressure and well integrity failure to potential aquifers. This venting is known as Surface Casing Vent Flow (SCVF) and might occur in places such as Canada (Dusseault and Jackson, 2014). However, venting is just moving the problem of gas contamination from aquifers to the atmosphere.

In rare but severe circumstances, blowouts can occur which have drastic impacts on humans and the surrounding environment (Zoback et al., 2010; Skogdalen and Vinnem, 2012; Zulqarnain, 2015). Blowouts can occur during well drilling and are often caused by incorrect drilling mud pressures and unexpected over-pressurised formations. If the drilling mud pressure is less than the formation pore pressure, formation fluids will flow uncontrollably into the wellbore, up the annulus and/or up the drill pipe; this is known as a kick. Modern wells have Blowout Preventers (BOPs) to isolate the problem and regain correct circulation within the well. If not under control, a kick will quickly turn into a blowout when the formation fluids reach the surface and eject the drill string and damage the drilling rig. Flammable oil and/or gas can ignite easily and cause a fire or explosion which can be fatal. However, blowouts are very rare. Considine et al. (2013) calculated only 4 blowouts occurred in 3,533 wells that had been drilled in the Marcellus Shale between 2008 and 2011 and there are several preventative measures which are put in place during the drilling process.

2.4.2 Well construction and migration pathways

The construction of oil and gas wells differ substantially depending on a variety of factors such as location, geological conditions, operator and budget. Figure 2.6 is an ideal well construction for deep wells to ensure enough cement and casings are protecting vital subsurface resources. Surface and production casings are the minimum requirement in the US for well construction as the production casing isolates the produced gas up the well and the surface casing, which must be about 25 m below aquifers, is present to reduce groundwater contamination (The Royal Society, 2012). However, in the UK three casing strings are expected, including an intermediate string to isolate non-freshwater zones which might cause abnormal pressures. The casings should all be cemented to the surface. The conductor casing might be used as a well foundation and prevent soils caving into the wellbore during drilling (The Royal Society, 2012). However poor well construction practises such as too few casing strings for geology and depth requirements, or insufficient cementing which does not extend to the correct heights can significantly increase the risk to gas migration and groundwater contamination (Lackey et al., 2017; Stone et al., 2019).

In addition to poor construction design, pathways for gas migration can develop surrounding the cement, casing and formation. The pathways indicated in Figure 2.6 can develop in the cement or casing through a number of ways such as poor cement or casing installation, degradation or corrosion over time (Dusseault et al., 2000) and well operations (Jackson et al., 2014). Once the pathways begin to develop, the boreholes are perfect conduits for the movement of gas or fluids to the surface and vertical pressure gradients will draw the contaminants along these pathways (Davies et al., 2014). Pressure differences during stages in a wells life and the pressures of surrounding formations will be the most important factor in determining where gas or fluids migrate to if cement or casing failures were to occur (Bonett and Pafitis, 1996). The development of these pathways and therefore a loss of well integrity can occur at any point in the life cycle of a well; drilling and construction, hydraulic fracturing and well stimulation or abandonment.

Brufatto et al. (2003) focused on understanding problems which arose from the construction of a gas well. In Mexico, Brufatto et al. (2003) concluded SCP was observed either due to shallow gas-bearing formations connecting directly with the surface or due to poorly primary cementing opening pathways from the deep gas-bearing formations. In Canada, SCP and gas migration was observed in all types of wells such as shallow gas wells, oil production wells or deep gas wells, however approximately 1% of the wells saw a pressure build-up due to the movement of formation fluids to the surface (Brufatto et al., 2003).

Watson and Bachu (2009) analysed data up to 2004 from 316,500 wells in Alberta, Canada to determine the probability of leakage occurring in wells in this region. This analysis is a start on understanding how wells act in the subsurface and determining quantitatively
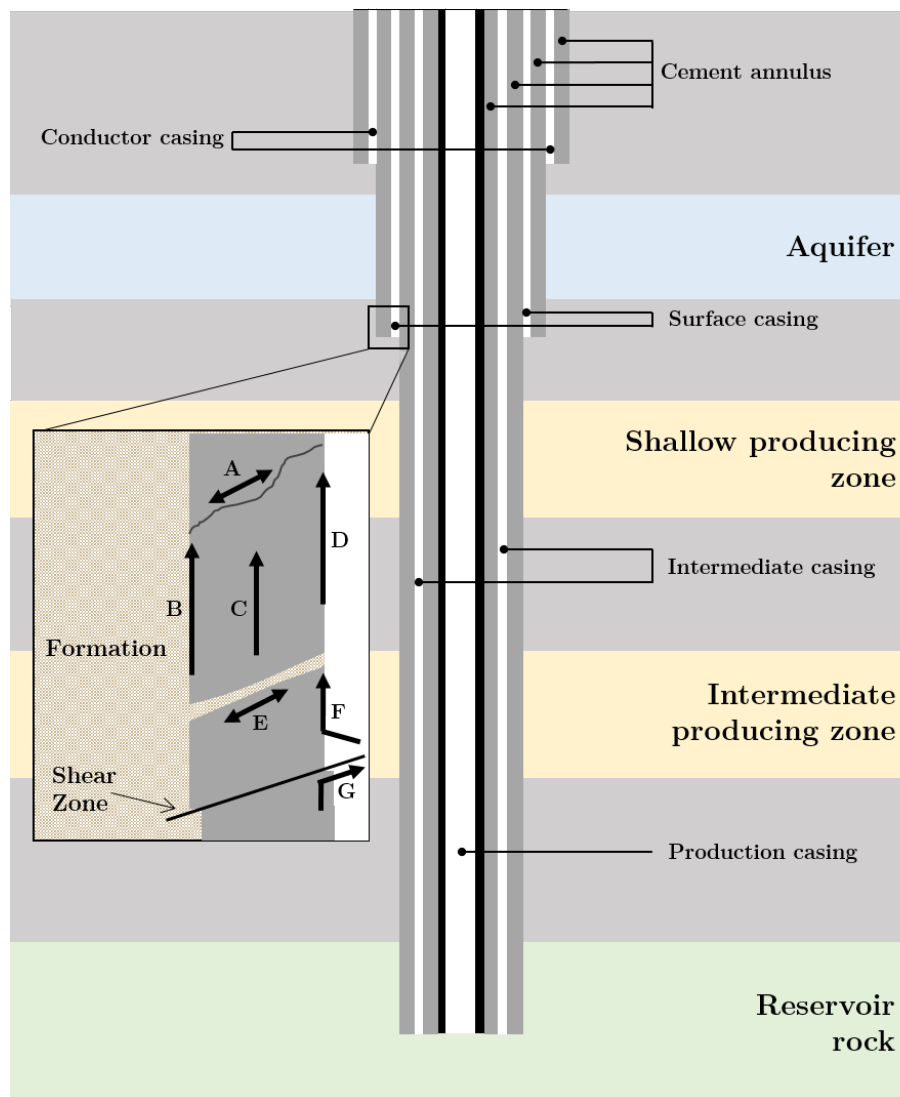
FIGURE 2.6: The ideal well construction for prevention of groundwater contamination and the pathways within the cement, casing and formation through which contaminants could along a wellbore: (a) through fractures in the cement, (b) between cement and formation, (c) through the cement, (d) between cement and casing, (e) through gaps in the cement, (f) across the cement and between the cement and casing, and (g) through a shear in the wellbore. Adapted from Vidic et al. (2013) and Davies et al. (2014).

what could go wrong. Watson and Bachu (2009) concluded most of the problems leading to gas migration are due to poor cementing where uncemented casings are the primary cause of integrity failure and SCP. Dusseault et al. (2000), Brufatto et al. (2003) and Watson and Bachu (2009) all determined zonal isolation is essential in reducing gas migration and SCP and a wellbore is protected so long as there is minimum or no contact between the formation and injected fluids.

2.4.3 Cement failure

Cementing a well is one of the most important aspects of well construction to prevent well integrity failure. As shown in Figure 2.6, a properly cemented well has cement running between each casing, between the formation and casing and cemented to the surface. Watson and Bachu (2009) demonstrated in wells which are much deeper, such as a shale gas well, more leaks were seen due to improper cementing of the upper part of the well. In some wells the upper section was left completely uncemented. Furthermore, they showed as the surface casing depth increased, the gas migration seen also increased insinuating the migration of gas was impacted by the cementing practises around the surface casing. This poor cementing practise is likely to increase the risk of groundwater contamination but is not always the only or ultimate reason for gas migration via cement failure (Fleckenstein et al., 2015).

A lack of cement can present easy pathways for gas migration if the gas reached the annulus. However, preferential pathways for gas migration must be present for the gas to reach an open annulus or to travel vertically along a cemented well annulus or horizontally to surrounding formations or groundwater. Failure of cement can lead to any of the pathways labelled A-F indicated in Figure 2.6 which allow horizontal or vertical movement. A more detailed diagram of the reasons for these pathways is shown in Figure 2.7 and described in more detail below. Several studies have been conducted on understanding the development of migration pathways in cement (Bonett and Pafitis, 1996; Dusseault et al., 2000; Rogers et al., 2004) particularly to ensure the industry use correct regulations for cementing their wells to reduce annular gas flow, SCP and SCVF (Brufatto et al., 2003).

Prior to cement placement, the wellbore is drilled by pumping mud down the well to remove cuttings and present an open wellbore. The mud and cuttings must be properly removed when casings are inserted and cement is ready to be pumped down the well. Without proper removal, gas channels can develop between the cement sheath and rock formations or casings (Dusseault et al., 2000; Frigaard, 2018). Similarly, poor bonding of the cement against the formation or casings can lead to channels between the cement-casing or cement-formation interfaces (Bonett and Pafitis, 1996; Stormont et al., 2015). In addition, if pressures down the well are too high, shallower formations could fracture and cement slurry could be lost to the surrounding rock (Vidic et al., 2013).

The choice of cement and design is vital for ensuring proper placement and setting of the cement (Brufatto et al., 2003). Initially, cement is in a slurry form to enable it to be pumped down the well and into the correct location for setting. It must have the correct properties for the setting process to occur at the right moment which is heavily dependent on temperature, quantity and the characteristics of the retarding compounds used to slow down the setting process. During cement placement, incorrect fluid densities can cause
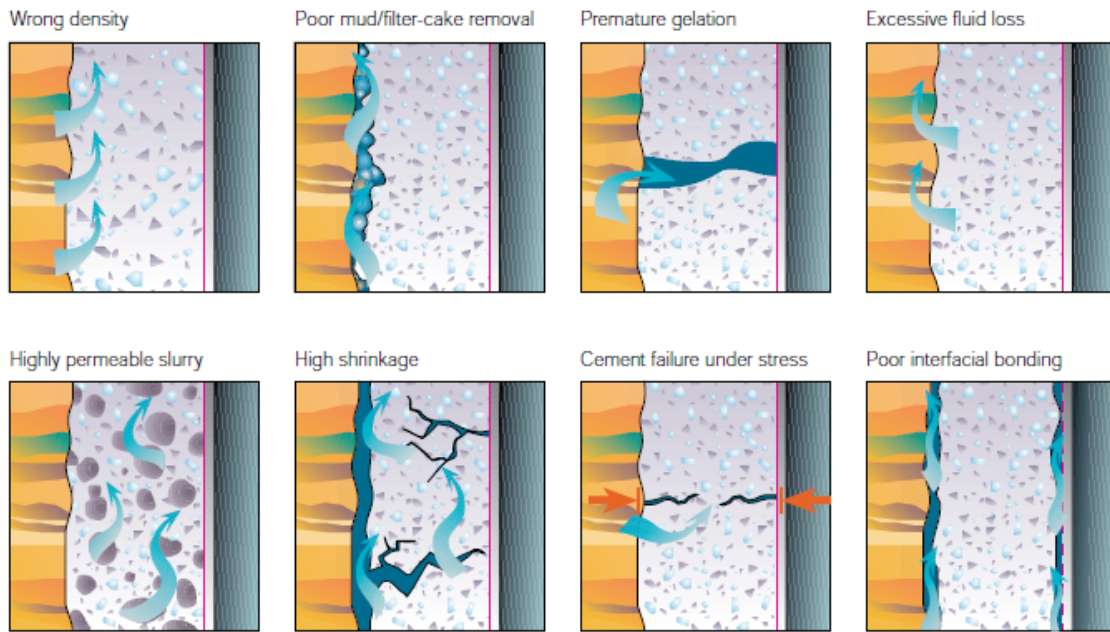
FIGURE 2.7: Major cement failure pathways contributing to gas migration, SCP and/or SCVF (Bonett and Pafitis, 1996).

the development of preferential pathways. If fluid densities are too high, there is a risk of losing cement slurry into the surrounding formation causing a loss of circulation within the borehole or fracturing of a rock interval (Bonett and Pafitis, 1996). A loss of cement could open up horizontal channels in the cement before it has set. A too low density slurry during cementing can lead to poor hydrostatic imbalances and hence vertical pathways can open up.

Cement setting can cause difficulties due to changes in the state of the cement. Premature gelation is the process when cement turns from a slurry state to a gel too quickly; a sudden increase in cement viscosity (Frigaard, 2018). This can lead to a loss of hydrostatic pressure control, opening a horizontal pathway (Bonett and Pafitis, 1996). The difference in pressure between the formation and cement develops a pressure gradient from the formation to the cement allowing the gas to migrate from the rock and invade the partially set cement creating pathways in the cement once it has hardened (Vidic et al., 2013).

During cement setting, fluid is lost and therefore the volume is reduced compared to the slurry (Dusseault et al., 2000). If fluid is lost too quickly or too much, the volume of the cement reduces significantly and opens up available space for gas to enter (Frigaard, 2018). In addition, hardened cement might not bond fully between the required surfaces due to its reduction in volume from slurry to rock (as much as 6% (Parcevaux and Sault, 1984)), which can create vertical pathways.

Even after the cement has been placed and set successfully, permeable pathways in the cement can still develop over time from external stresses and fluid interactions (Dusseault

et al., 2000; Stormont et al., 2015; Stormont et al., 2018). During well stimulation, production and abandonment there are still constant changes in stresses and pressures and expected degradation over long periods of time.

2.5   A UK PERSPECTIVE

The oil and gas industry in the UK has mainly been dominated by offshore conventional and unconventional wells, with only 2152 onshore wells drilled between 1902 and 2013 (Davies et al., 2014), 10% of which have been hydraulically fractured (The Royal Society, 2012). These wells are owned by several large oil and gas companies such as Shell and are located in the North Sea. Most of the oil and gas production has stemmed from these offshore wells, meaning the UK is heavily reliant on imported oil and gas for the countries energy requirements (Stephenson, 2015b).

With an unstable political and economic landscape (Acquah-Andoh et al., 2019) along with depleting offshore finite resources, the UK reliance on imported energy is becoming more of a concern for the country and the expectation of the countries own production of energy is increasing. Finite resources such as oil, gas and coal are being depleted at large rates across the globe hence there is a desperate need to find sources elsewhere for increasing energy requirements. 80% of homes in the UK require gas for heating and cooking, forming a significant part of affordable, 'cleaner' energy than coal and oil (CIWEM, 2014). Energy imports to the UK are expected to increase from 50% to 76% by 2030 (CIWEM, 2014). As imported gas prices rise along with increasing population reliance on gas, domestic gas extraction is becoming more attractive to the UK government (Hammond and O'Grady, 2017).

2.5.1   The history of UK shale gas

Hydraulic fracturing has been an established method for many decades, with the first UK well in 1875 (The Royal Society, 2012). In 1976 the US Department of Energy (USDOE) initiated shale gas projects in the Devonian and Mississippian shales which stimulated Imperial College to evaluate the UK shale gas resources (Selley, 2012). However, Petroleum Revenue Tax discouraged the production of shale gas in the UK and in 1985 results from the Imperial College study were declined, halting shale gas development in the UK. It was not until 2003 when the Petroleum Revenue Tax Act was repealed, the Imperial College study was reconsidered along with advances in hydraulic fracturing technology used in the US. In 2008, the BGS began reviewing UK shale gas resources and a license was awarded to Wealden Petroleum Development Ltd. to cover large potential areas for shale gas such as the Weald (Selley, 2012).

Preese Hall had its first exploratory wells drilled in 2010, and in 2011 the government initiated a review of shale gas operations to determine the environmental impact. Figure 2.8 indicates a significant proportion of shale gas and oil underneath productive aquifers requiring environmental protection. A moratorium was lifted on hydraulic fracturing after it was determined it did not pose a risk to aquifers or seismic events if wells were constructed properly and regulations followed (Prpich et al., 2015). However, two seismic events occurred at Preese Hall and after investigation it was determined to be due to injection of high pressure fluids related to hydraulic fracturing activities (DECC, 2013; Clarke et al., 2014). Hydraulic fracturing was suspended by the UK government due to the concerns raised about its risks and uncertainty on the environment (Prpich et al., 2015).
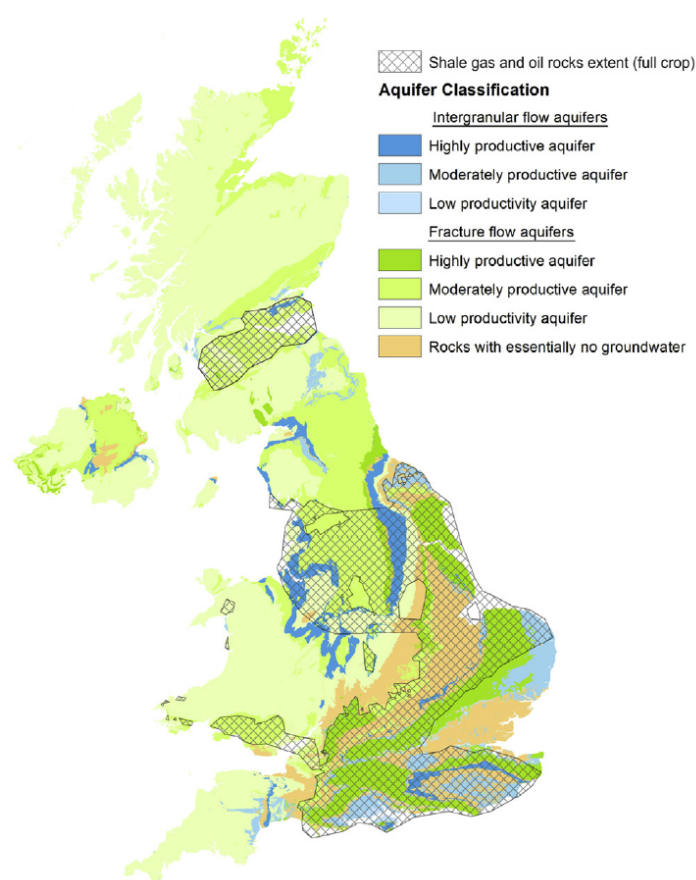
FIGURE 2.8: A map of the UK indicating potential shale oil and gas locations and location of groundwater aquifers. Adapted from Davies et al. (2014).

Due to public resistance and seismic incidences such as those at Preese Hall, support for shale gas in the UK fell considerably between 2012 and 2016 (Andersson-Hudson et al., 2019). New drilling permits were issued in 2016 in England, with the most activity on shale gas development occurring in England and the procedure being indefinitely suspended in Scotland (Andersson-Hudson et al., 2019). The UK's only active drilling site is at Preston New Road in Lancashire where Cuadrilla conducted a pilot project for hydraulic fracturing (Walker, 2018) but the well site experienced excessive earth tremors

under the tight government seismic regulations (Ambrose, 2019). Recently, horizontal wells were drilled at Preston New Road to convince UK policy makers to relax the rules on earth tremors as commonly magnitudes of higher than 0.5 are required to fracture for shale gas (Ambrose, 2019). However, a moratorium has been put in place by the conservative government due to high seismic activity, so all operations have been suspended (BBC News, 2019b; OGA, 2019).

2.5.2 UK shale gas potential

The UK has considerable shale gas resource potential estimated by the BGS and recently tested by the United Kingdom Onshore Oil and Gas (UKOOG) at the Preston New Road site (UKOOG, 2019). There are large uncertainties with technical recoverable gas reserves which can be more accurately determined with extensive exploration and drilling, but extrapolated assumptions indicate a significant proportion of the UK reserves could be equivalent to 25-50 years of the UK requirements of natural gas (Hammond and O'Grady, 2017).

The UK has three main shale gas regions (Figure 2.8); the Bowland-Hodder shales in the North of England (Andrews, 2013), the Jurassic and Liassic shales in the Weald Basin in the South-East of England (Andrews, 2014) and the Carboniferous shales in the Midland Valley in Scotland (Monaghan, 2014). Table 2.3 provides estimates for shale gas resources in the UK within each of these shale basins. The Weald Basin is known to contain mature oil rather than gas and therefore has been ignored here as gas production is the main focus for the UK.

TABLE 2.3: Estimates and calculated values for shale gas reserves in the UK, measured in billion cubic meters. Adapted from Hammond and O'Grady (2017).

Region		EIA	BGS	Cuadrilla (pre-testing: 2011)	Cuadrilla[d]* (post-testing: 2019)
Bowland-Hodder Shale	Gas available	2690	36,800[a]	5660	-
	Technically recoverable	540	80-200	900-1200	Low scenario: 340 Medium scenario: 620 High scenario: 900
Liassic shale	Gas available	60	30[b]	-	-
	Technically recoverable	30	-	-	-
Carboniferous shale	Gas available	-	2270[c]	-	-
	Technically recoverable	-	-	-	-

[a] Andrews (2013)
[b] Andrews (2014)
[c] Monaghan (2014)
[d] Hammond and O'Grady (2017)
* Assuming a total of 4000 lateral wells over the lifetime of the industry (UKOOG, 2019).
EIA: US Energy Information Administration, BGS: British Geological Survey

Various companies such as the US Energy Information Administration (US EIA), BGS and Cuadrilla estimated the available gas and technically recoverable gas from UK resources (Table 2.3). However, more accurate estimates could be proven with further exploration and drilling of wells to allow recoverable amounts of gas to flow up the well. At Preston New Road, initial flow test data was determined from a well in the Bowland-Hodder Shale which indicated excellent shale properties for fracturing, at least 90% methane gas content and the Bowland Shale indicating comparable results to successful US shale gas plays (UKOOG, 2019).

However, the limitations set by the government within the fracturing site did not allow a comprehensive understanding of flow conditions and results required extrapolation and preliminary scaling up (UKOOG, 2019). The 0.5 magnitude seismic limit prevented the injection of proppant to allow gas to flow over a certain period of time. A multi-frac was intended of 41 stages, but only two were managed and only 14% of the intended amount of sand was injected (UKOOG, 2019). Therefore, results indicated in Table 2.3 are preliminary scenarios based off these conditions. It is clear that regulations must relax slightly to allow for more accurate results and understanding of the UK shale gas potential (Ambrose, 2019).

2.5.3 Concerns and pressures

The UK shale gas industry has so far taken a very precautionary approach to onshore hydraulic fracturing. Environmental incidences during hydraulic fracturing in the US have elevated concerns to the UK public with frequent protests preventing Cuadrilla from beginning exploratory drilling and injection (Moore, 2013; Freeman, 2014; Channel 4 News, 2015). Even when Cuadrilla began drilling for shale gas in Blackpool, seismic incidences rapidly suspended the project, adding further concerns for the public. Hammond and O'Grady (2017) highlighted the socio-economic concerns with hydraulic fracturing in the UK. Although exploiting shale gas benefits the UK with energy security, local communities face the largest risks associated with hydraulic fracturing and in comparison with the US, success is a concern due to significantly different population densities between the US and UK (Prpich et al., 2015).

Similar environmental concerns faced in the US have resonated with the UK public such as water use and contamination, induced seismicity, local health and climate change/fugitive gas emissions (Hammond and O'Grady, 2017). Induced seismicity has been a significant concern for residents living near hydraulic fracturing sites; a concern highlighted more in the UK than US, due to higher population densities in drilling areas and more complex geology. However, induced seismicity often occurred in the US from re-injection of waste water (Ellsworth, 2013; US Environmental Protection Agency, 2016a), a practise unlikely to

be used in the UK due to EU Water Framework Directive (WFD) requirements (Hammond and O'Grady, 2017).

Water quantity and contamination is a significant issue for the US and UK. In the UK, it is likely to be an issue to local areas and those productive geological areas with water resource pressure, groundwater sources or sensitive aquatic environments (CIWEM, 2014). To meet the annual target for UK gas consumption from shale gas exploitation, Wood et al. (2011) estimated the annual requirement of water resources assuming six well pads were drilled and three of these required re-fracturing (Table 2.4). High levels of water abstraction can reduce water quality, aquatic life, ecology and recreational activities (Stuart, 2012).

Water contamination is a large concern in the UK particularly with regards to groundwater contamination (Stuart, 2012). Sources of contamination are mostly concerned with shale gas itself, or regions of gas from other overlying high pressure formations, fracturing chemicals used during injection and NORMs from the deep subsurface. The pathways for groundwater contamination have been highlighted in many reviews from activities occurring in the US and conceptualized in Figure 2.5 in Section 2.3. Pathways from well stimulation (fracturing process itself), chemical spills, well failures and handling of waste waters are all main concerns in the UK (Wood et al., 2011; The Royal Society, 2012; Stuart, 2012; Prpich et al., 2015).

Groundwater contamination related to methane leakage pathways has been well documented in the US (Stuart, 2012) and is most often related to poor well construction (Jackson et al., 2011; Osborn et al., 2011; Warner et al., 2013; Darrah et al., 2014). As the potential geological locations for shale gas exploitation in the UK are likely to underlie productive aquifers (Figure 2.8), understanding and quantifying the risks posed to groundwater in the UK and ensuring proper water protection is essential for public and environmental concerns.

TABLE 2.4: Estimate of UK water requirements to meet 10% of the UK annual requirements for gas from hydraulic fracturing (Wood et al., 2011).

Activity	Volume (m^3)	
	Min	Max
Initial fracturing		
Water volume	54,000	174,000
Fracturing chemicals volume	1,080	3,480
Flowback water	7,920	137,280
Flowback waste water content	158	2,746
Re-fracturing		
Water volume	27,000	87,000
Fracturing chemicals volume	540	1,740
Flowback water	3,960	68,640
Flowback waste water content	79	1,373

Furthermore, recent challenges exist with the UK government on aligning shale gas development with clean, renewable energies and net zero carbon emissions by 2050 (Prpich et al., 2015). The distraction of the shale gas industry could prevent further development of decarbonised electricity and whilst bring with it an economic boost and reduction of imported gas, would require substantial renewable energy success to meet the Climate Change Act agreement (Wood et al., 2011; CIWEM, 2014).

2.6 CONCLUSION

Hydraulic fracturing has been used for decades both offshore and onshore but currently has the biggest industry in the US and Canada making these regions the prime target for research. The requirement for natural gas worldwide is increasing, putting pressure on the fast production of unconventional wells. In 2018, the US had over 500,000 production wells (US Energy Information Administration, 2020) and the lifetime of these wells from site setup through to abandonment can last 20-30 years. This large number of wells and the speed at which they are drilled and cased to reach the production stage puts significant pressure on the environment. Hydraulic fracturing practises such as poor well construction reduce the cost and time for longer-term financial gain, but has resulted in negative environmental and societal outcomes.

The concerns which can lead to environmental degradation such as high-volume water usage, high pressures, returning waste waters, toxic chemicals and methane releases are discussed in the literature but there is a significant gap in quantifying these issues across different case studies under varying geological conditions. When managing hydraulic fracturing in countries where the industry is yet to take off commercially, such as the UK, Environmental Risk Assessments (ERA) are vital prior to exploration and are compulsory for new UK wells before securing Petroleum Exploration and Development Licenses (PEDL) (Prpich et al., 2015).

The UK hydrogeological situation is different to that in Canada or the US as the high population density in the UK and the lack of remote areas means groundwater is more of a target for contamination during onshore development. The UK utilises its groundwater across the country much more so than in the remote areas of the US and Canada. Therefore, groundwater has been the focus for this research study. Current research has targeted specific pathways for gas or contaminants to reach groundwater but the studies focus on the same case studies and do not allow generic applications to other parts of the world. Additionally, multiple pathways and the variation in risk based on geological conditions and well constructions are not considered.

A significant collection of pathways which are poorly quantified but are discussed frequently in the literature and known to lead to stray gas contamination are those pathways

through well integrity failure, especially across different stages of a wells life cycle. Literature does not combine the issues of cement failure with SCP and SCVF leading to groundwater contamination and is therefore another focus of this research.

Hydraulic fracturing is a divided industry across the world which brings with it economic benefits and self-reliance but potential detrimental effects on the environment, water resources, human health and society. Assessing and managing risks associated with hydraulic fracturing is vital if individual countries were to use shale gas exploitation as one of their main energy sources. This requires significant expert judgement across integrated disciplines along with knowledge and experience from countries which have already learnt some lessons, such as the US (European Parliament, 2012).

Tight seismic regulations and public and environmental protesters have significantly slowed down and, at times, suspended the development of a UK shale gas industry. Suitable management and risk assessment approaches are a necessity to minimise environmental impacts and maximise social benefits. This is a challenge due to considerable uncertainties and insufficient evidence in environmental outcomes and can rarely be achieved using purely scientific-based evidence, thus requiring the use of expert judgement, qualitative and quantitative information in combination with decision-making techniques.

CHAPTER 3

A REVIEW OF RISK ASSESSMENT AND FUZZY LOGIC APPLIED TO THE OIL AND GAS INDUSTRY

3.1 INTRODUCTION

This chapter aims to discuss the theory behind risk assessment and fuzzy logic with a focus on the literature and its place in the oil and gas industry. The first section introduces risk theory and risk assessment methodologies and processes in relation to this research, concluding with an understanding of scenario modelling and event tree and fault tree analysis. The literature surrounding risk assessments in the industry is discussed, further focusing on hydraulic fracturing. The second part of the chapter introduces fuzzy logic and fuzzy set theory as a concept and discusses the process behind building a fuzzy logic model. The chapter concludes with a literature analysis of fuzzy logic risk assessments and concluding remarks on how this research intends to fill the gaps in the literature.

3.2 RISK ASSESSMENT THEORY

3.2.1 Definition of risk

The definition of risk is often dependent upon the context in which it is used and can present confusion among industries and government (Aven and Kristensen, 2005; Fjeld et al., 2007). Risk is generally defined as a potential loss occurring from natural or human activities, but within an engineering perspective is commonly referred to as the product of probability and consequence from the exposure of a particular hazard to a receptor (Modarres, 2006). Quantifying both probability and consequence of a potential hazard can be an initial approach to risk analysis of an engineered system, where risk analysis

incorporates risk assessment, risk management and risk communication (Figure 3.1) (Modarres, 2006; Fjeld et al., 2007).

FIGURE 3.1: Elements of risk analysis (Modarres, 2006). The focus of risk analysis within this thesis is highlighted.

Risk assessment involves the technical process to obtain quantitative estimates of risk, including determining the probability and consequence of an event or hazard. Risk management incorporates the broader process of balancing risks, costs and social values and the process through which contributors to risk are estimated, evaluated, minimized and controlled (Modarres, 2006; Fjeld et al., 2007). Risk communication involves the interactions between stakeholders, risk assessors and managers to ensure important issues are identified for analysis (Fjeld et al., 2007). This research focuses on developing a risk assessment (Figure 3.1) defined as making a quantitative estimate on the probability of contaminating groundwater which results from fugitive gas migration of methane from the engineering process, hydraulic fracturing.

3.2.2 Risk assessment methodologies

Approaches for risk assessment can be deterministic involving quantitative, qualitative or hybrid processes, or stochastic which are based on classical statistical approaches and accident forecasting modelling (Marhavilas and Koulouriotis, 2012b). Quantitative analysis uses adequate field data or test data to estimate the probability and consequence of a loss (Modarres, 2006). It can be very numerically and computationally intensive and often restricted to a large scope risk analysis where data is abundant. Qualitative risk analysis is a more common approach due to its simplicity and ability to analyse risk with little or no data, although can be very subjective (Modarres, 2006). There exist several common techniques such as a risk matrix which defines qualitative probability and consequence categories as low, medium or high (Ball and Watt, 2013), safety audits used to study human factors focusing on safety critical factors (Cacciabue, 2004) or a Hazard and Operability Study (HAZOP) which is a systematic approach to identifying deviations and risks from normal operations of process equipment (Kotek and Tabas, 2012). Hybrid

techniques can involve quantitative probabilities and qualitative consequences or vice versa, or where the risk is measured quantitatively but qualitative methods are used for policy and decision making (Modarres, 2006). A common hybrid method is Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) where the basic events on the fault trees or branches on the event trees can be expressed quantitatively or using expert opinion. These methods are very suited to scenario development of accidents or risks focusing on either a top-down (ETA) or bottom-up (FTA) approach (Aven and Kristensen, 2005).

Stochastic techniques are often an extension of deterministic methods which use probabilistic analysis and provide opportunities to include uncertainties in inputs caused by subjectivity (Osadská, 2017). Common classical approaches are probability distributions where risk quantification is based on historical data (Torres et al., 2016) or event data models such as Mean Time To Failure (MTTF) or Time at Risk Failure (TRF) models which observe failure or reliability of safety components over time (Marhavilas and Koulouriotis, 2012b). Examples of accident forecasting modelling consists of Monte Carlo simulations, time-series processes, scenario analysis, neural and Bayesian networks (Marhavilas and Koulouriotis, 2012b; Osadská, 2017). A collection of these methods focus on machine learning where initial data can be trained to predict the probability of future events.

Assessing risk deterministically typically models scenarios where input values are known and the outcome is observed and uncertainty in the output is external to the model. A stochastic approach is inherently random with uncertainty built into the model so there can be a variety of outcomes or estimations based on a single input. Both approaches can be useful depending upon the requirements of the risk assessment and often many techniques are appropriate for the circumstance, depending on availability of input data (Marhavilas and Koulouriotis, 2012a). High uncertainty or a lack of data can prevent the application of many quantitative methods for assessing risk, particularly in the oil and gas industry where data might be confidential, contain significant gaps or lack historic information, if the industry is new (Dethlefs and Chastain, 2012; Rozell and Reaven, 2012; Environment Agency, 2013; Lavoie et al., 2014; Garcia-Aristizabal et al., 2017). A parallel application of a deterministic and stochastic approach offers improved, alternative methods where individual elements of expert knowledge, component failure, field data and hypothetical scenarios can improve risk assessments in the oil and gas industry (Marhavilas and Koulouriotis, 2012b).

The risk assessment techniques applied in this research utilise deterministic models using ETA and FTA which allow the construction of failure scenarios with respect to groundwater contamination from hydraulic fracturing, and a stochastic approach using a MTTF and TRF model to determine component failures of a well. Additionally, where component data does not exist or does not provide appropriate probability of failure, expert knowledge and numerical models are applied using fuzzy logic methods, reviewed in Section 3.4.

3.2.3 Risk assessment process

In basic terms, developing a risk assessment involves answering three questions (Modarres, 2006):

1. What can go wrong? (risk scenarios)

2. How likely is it? (probability)

3. What are the consequences? (consequence)

Within the scope of this research, questions 1 and 2 are assessed focusing on how likely it is groundwater is contaminated by methane gas during the well stimulation (injection) and production stages of unconventional onshore hydraulic fracturing. The consequences have not been determined but are opportunities for future work within the field.

Approaching these questions requires considering the hydraulic fracturing operation as a whole by developing initial conceptual models, identifying the pathways to focus on and then narrowing down specific scenarios to eventually develop individual probabilities. In this context, risk scenarios have been developed by considering pathways through which gas could follow to reach groundwater during a particular stage of hydraulic fracturing. This process is better represented using a Source-Pathway-Receptor (SPR) model to work in parallel with the development of risk scenarios (Figure 3.2). The approach used in this research is shown in Figure 3.3 which follow the steps taken, illustrating the process by which event trees are obtained from the overall conceptual model.
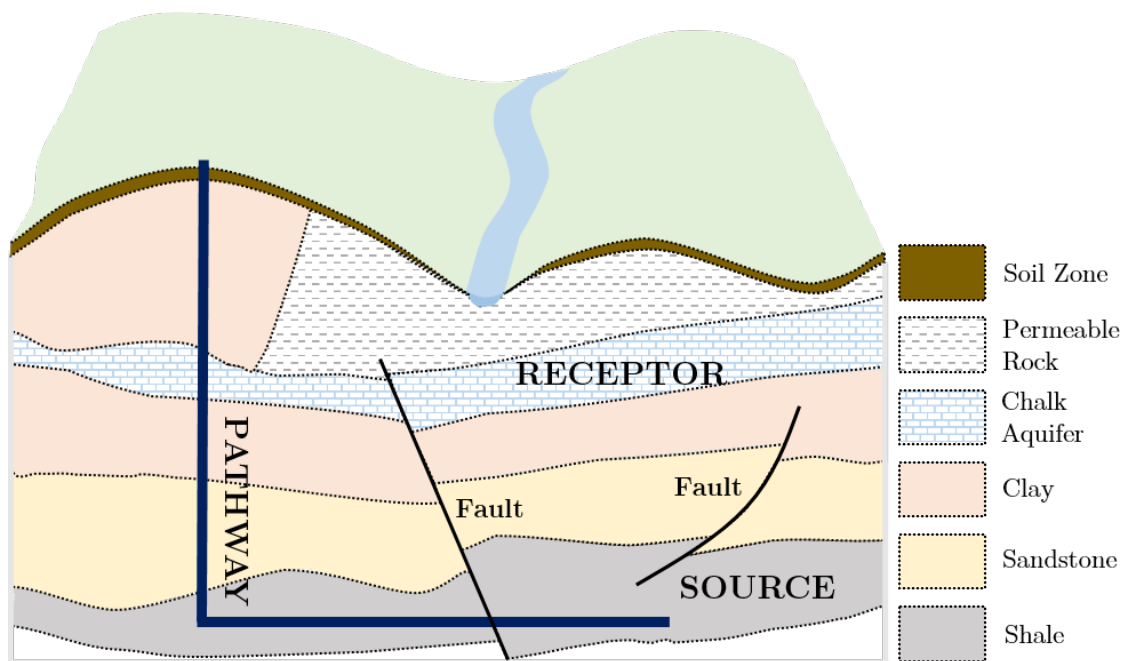
FIGURE 3.2: SPR conceptual model for an onshore hydraulically fractured well. The source is gas originating from the shale rock or an overlying gas-containing formation, the pathway is along the wellbore and the receptor is a groundwater aquifer.

The conceptual model and SPR model are vital for the development of risk scenarios; providing the answer to question 1. Developing these models ensures all hazard and exposure pathways are considered and their risks analysed in detail, providing scientifically valid and thorough answers to questions 2 and 3. Event trees are used in this research to analyse the probability of failure for each scenario (Figure 3.3).
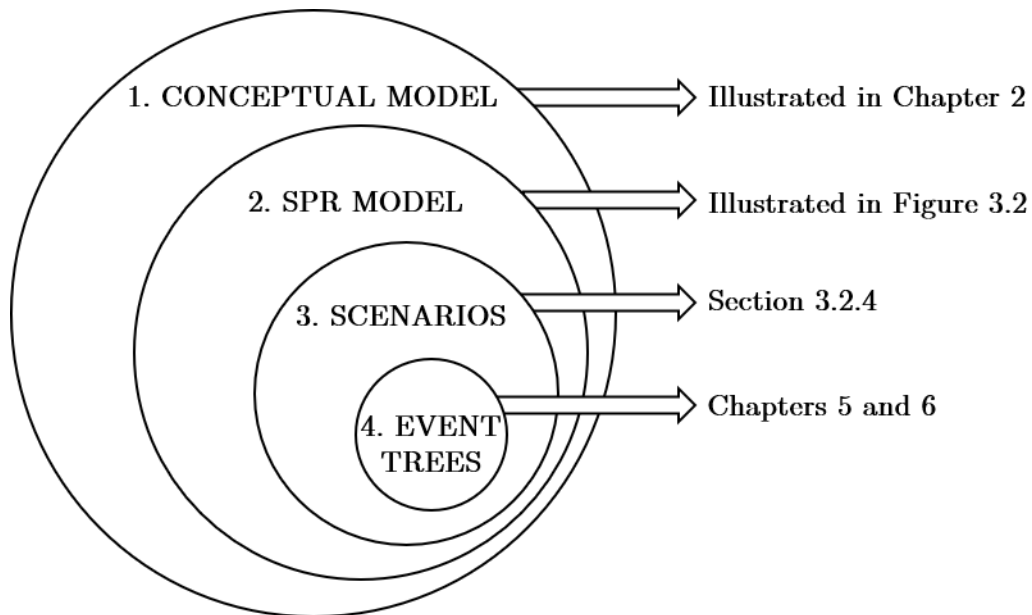
FIGURE 3.3: Systematic risk assessment process to assess groundwater contamination from hydraulic fracturing, indicating where each step is developed in the thesis.

3.2.4 Scenario and logic modelling

As indicated in Figure 3.3, scenarios are developed which are used to produce event trees. The aim of scenario development is to derive a set of scenarios which encompass all potential exposure propagation paths leading to a loss of containment and contamination of the receptor, all following the occurrence of an initiating event (Modarres, 2006). The focus of this research, as indicated in Figure 3.2, is on gas as the source, well integrity failure as the pathway and groundwater as a receptor, so the scenarios must be developed around these areas. In addition, well integrity failure is likely to be most prevalent during the injection and production stages of hydraulic fracturing (Dusseault and Jackson, 2014; Long et al., 2015a), so these are also incorporated into scenario development. In this research, four scenarios are studied:

- **Scenario 1:** Integrity failure during injection from casing failure.

- **Scenario 2:** Integrity failure during injection from tubing/packer failure.

- **Scenario 3:** Integrity failure during production from external formation.

- **Scenario 4:** Integrity failure during production from internal wellbore.

As discussed in the scope of the thesis (Section 1.3), although well integrity failure is a common occurrence during post-closure abandonment (Dusseault and Jackson, 2014), this research does not cover this stage but the techniques used can be applied directly to post-closure of a well.

3.2.4.1 Event and fault tree modelling

Scenarios can be better displayed and probabilities analysed using event trees. These describe the cause and affect relationship between the initiating event and subsequent event progression which lead to a success or failure outcome of the system (Modarres, 2006). For gas to begin migrating along a wellbore, the initiating event must be the failure of the first barrier between the gas source and the well, often a cement annulus or casing or well component. In this study, the failure outcomes (groundwater contamination) are modelled but the total probability of a success (no groundwater contamination) and failure outcome must equal 1. Therefore, the probability of success can be calculated from the probability of failure. The failure outcome of each subsequent progression in the event tree is determined using equation 3.1; multiplying along the branches of the event tree (Modarres, 2006):

$$P_x = \prod_{n=1}^{N} P\left(E_n\right) \tag{3.1}$$

where P_x is the overall path probability outcome, $P\left(E_n\right)$ is the probability of an individual event and N is the number of events along the event tree pathway.

Sometimes the failure of each subsequent event along an event tree pathway cannot be easily quantified if there are no adequate historical records of failure events to estimate the probability. Logic-based analysis methods can be suitable alternatives for a lack of data, with fault trees being particularly common (Rish, 2005; Modarres, 2006; Ahmed et al., 2007; Garcia-Aristizabal et al., 2017).

FTA is a logical model which uses a top-down approach to break the failure event (subsystem) into basic components which have adequate data and cannot be further analysed (Modarres, 2006). It is used to understand the logic leading to the failure of an event or system and their complexity can vary greatly depending on the top event. Only the basic events in the system at the bottom of the tree require quantification, reducing the amount of data needed to calculate the probability of the top event. Fault tree construction is qualitative using logic gates and event symbols.

The most common symbols used for the events are:
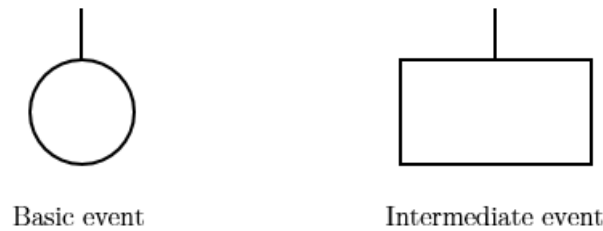
Basic event   Intermediate event

Logic gates are used to describe the relationship between the inputs and outputs. Most common logic gates are:

OR gate: the output occurs   AND gate: the output occurs
if any input occurs.   only if all the inputs occur
                                     (inputs are independent).
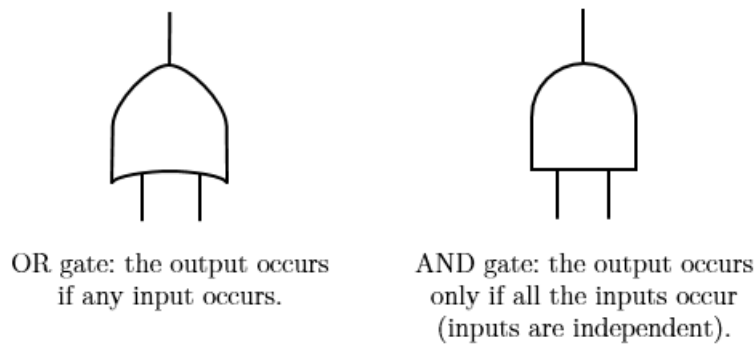
Although fault tree construction is qualitative, classical methods use quantitative algorithms such as Boolean algebra to evaluate the top event of a fault tree from its basic events with known probability of failure values (Modarres, 2006; Guan et al., 2015; Garcia-Aristizabal et al., 2017).

The top event of a fault tree using Boolean logic with AND/OR gates is calculated using equation 3.2 (Modarres, 2006):

$$P\left(TE\right) = \begin{cases} \prod_{i=1}^{n} P\left(BE_i\right) & \text{AND gate} \\ 1 - \prod_{i=1}^{n} \left[1 - P\left(BE_i\right)\right] & \text{OR gate} \end{cases} \tag{3.2}$$

where $P\left(BE_i\right)$ is the probability of the failure of the basic event and n is the number of basic events. The top event for a fault tree consisting of only OR gates can be calculated using the OR gate equation from equation 3.2. Therefore when $P\left(BE_i\right) << 1$, the top event can be approximated using equation 3.3:

$$P\left(TE\right) \approx \sum_{i=1}^{n} P\left(BE_i\right) \tag{3.3}$$

Under highly data-sparse situations, event tree branches or basic events from fault trees might not contain sufficient failure data to produce a suitably accurate risk or probability assessment for the system. In these circumstances, sometimes seen in the oil and gas

industry, fuzzy logic can be used. Fuzzy Event Tree (FETA) and Fuzzy Fault Tree Analysis (FFTA) are useful tools either as a combination or independently for quantifying the failure probability of a component or event where there is a lack of data and crisp values cannot be used without considering the high possibility of uncertainty and imprecision (Ramzali et al., 2015). Further information is given on fuzzy logic analysis and fuzzy risk assessments in Section 3.4.

3.3   RISK ASSESSMENTS IN THE OIL AND GAS INDUSTRY

Risk assessments conducted in the oil and gas industry have taken a variety of approaches. Torres et al. (2016) discusses the current risk assessment techniques used in the industry along with the most appropriate methods to obtain a holistic and integrated risk analysis. Individual risk factors which could lead to water contamination during hydraulic fracturing are the main focus of the review but methods are summarised for conducting comprehensive risk assessments within the industry.

Quantitative Risk Assessment (QRA) methods are most common in the oil and gas industry but were not exclusively used until the 1980s (Torres et al., 2016). Offshore operations, such as in the UK and Norway, widely use QRAs (Skogdalen and Vinnem, 2012; Torbergsen et al., 2012; Cai et al., 2013; Yang et al., 2018) introduced as a technique to support regulatory decisions and safety management systems (Aven and Kristensen, 2005). Traditionally, QRAs have been used to quantify risk in the design and operation stages of offshore installations, particularly for well integrity (Vignes and Aadnoy, 2010; Torbergsen et al., 2012). They generally require numerical estimates of probability and consequence of potential incidents based on engineering evaluation and mathematical techniques (NASA and BSEE, 2017). Detailed QRAs are seldom used in the oil and gas industry due to a lack of safety integrity[1] or experience data to perform causal analysis. Consequently, simpler tools are used which do not support detailed analysis of uncertainty, common cause failures or human reliability (Torres et al., 2016; NASA and BSEE, 2017). Recently, efforts are being made to include Human and Organizational Factors (HOFs) in QRAs (Aven et al., 2006; Skogdalen and Vinnem, 2011) and Bayesian network techniques in the offshore industry (Cai et al., 2013; Khakzad et al., 2013) are used to support uncertainty in QRAs (Aven and Kristensen, 2005), which could be applied to the onshore industry (Torres et al., 2016).

Torres et al. (2016) highlighted other common risk assessment techniques used in the oil and gas industry. Departments such as the Environmental Protection Agency (EPA), US Department of Energy (USDOE) and the Ministry of Defence conducted Environmental Risk Assessments (ERAs) using a variety of techniques which include Geographical

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[1]Defined by IEC 61508-4 (2010) as "the probability of a safety-related system satisfactorily performing the required safety functions under all stated conditions within a stated period of time."

Information Systems (GIS), Environmental Impact Assessments (EIAs) and algorithms (Torres et al., 2016). ERAs are normally performed with laboratory or field data and models to produce quantitative and qualitative decisions, particularly framed as the impact human activity has on the environment (Environment Agency, 2013; Torres et al., 2016). These can be suitable for producing a detailed holistic overview of the effects of the engineering technique on the surrounding environment where data is generally accessible.

Aven et al. (2006) and Ramzali et al. (2015) have used Barrier and Operational Risk Analysis (BORA) in offshore operations to evaluate risks in technical and operational conditions. BORA uses barrier block diagrams, influence diagrams, event and fault trees to model barrier performance which prevents or reduces events from occurring (Aven et al., 2006; Ramzali et al., 2015; Torres et al., 2016). This technique aims to incorporate more detailed analyses reflecting human, operational and organizational factors as well as the technical systems (Aven et al., 2006).

Hazard Identification (HAZID) screens potential hazards as an initial step to conducting a risk assessment where critical and non-critical hazards can be identified. Failure hazard scenarios might be selected using check lists, accident and failure statistics, HAZOPs or historical experience (Germanischer Lloyd, 2008). Generally used as a qualitative study, HAZID might use FTA and ETA techniques to support the methodology where outcomes of the assessment aim to reduce risk levels to a level which is as low as reasonably practicable (Germanischer Lloyd, 2008; Torres et al., 2016).

Most risk assessments in the oil and gas industry have focused on safety analysis and risk reduction at offshore operations (Chen and Fu, 2003; Aven et al., 2007; Vignes and Aadnoy, 2010; Skogdalen and Vinnem, 2012; Khakzad et al., 2013; Vrålstad et al., 2019), which present a different set of risks to onshore and even to unconventional versus conventional oil and gas development. There is a requirement for assessing a new set of risks which offshore risk assessments are lacking and this could be best tackled using a variety of risk assessment methodologies.

3.3.1 Hydraulic fracturing risk assessments

Since the unconventional gas development boom in the US and related environmental concerns, risk analysis and assessments for the impact of hydraulic fracturing on the environment has become increasingly important (US Environmental Protection Agency, 2012; Vengosh et al., 2013; USDOE, 2014; Vengosh et al., 2014; US Environmental Protection Agency, 2016a). The complexity of the environment and subsurface requires assumptions to be made for quantitative risk analysis, in particular when conducting modelling studies for specific pathways (Lange et al., 2013; Jabbari et al., 2017). A qualitative approach might lack the rigorous scientific conclusions but enable a clearer interaction of many components in the system without too many assumptions (Dethlefs and Chastain, 2012; Environment

Agency, 2013). A number of risk assessment studies focusing on onshore unconventional development have been identified as covering one or both of these approaches with varying success.

The Marcellus Shale has been a prime target for shale gas extraction with high economic success, but potentially equivalent environmental damage (Zoback et al., 2010; Gregory et al., 2011; Boyer et al., 2012; Warner et al., 2012; Hatzenbuhler and Centner, 2013; Ingraffea, 2013; Jackson et al., 2013b; Vidic et al., 2013; Gallegos et al., 2015; Llewellyn et al., 2015). The Pennsylvania Department of Environmental Protection (PADEP) enforces violations of environmental laws known as Notice of Violations (NOV) which are publicly available and generally quite comprehensive. Consequently, a large number of studies have analysed the NOVs (Considine et al., 2012; Considine et al., 2013; Brantley et al., 2014; Dusseault and Jackson, 2014), particularly for developing risk assessment methodologies to assess the causes of environmental degradation from hydraulic fracturing (Olawoyin et al., 2013; Ingraffea et al., 2014). A similar database exists in Colorado which issues Notice of Alleged Violations (NOAV), also used to help quantify risks associated with natural gas development in Colorado basins (Gross et al., 2013; Fleckenstein et al., 2015; Sherwood et al., 2016; Stone et al., 2019). These studies allow the development of quantitative risk assessments which are conducted from extensive historical data, identifying environmental incidences, causes and affects of exploration risk and safety impediments in the respective shale gas plays (Olawoyin et al., 2013). However, this approach can only be applied where substantial historical data is available for the specific target formation, which partly explains the reason for substantially more research within the Marcellus Shale compared to other sizeable exploited formations.

Casing and cement failure in conventional and unconventional wells in Pennsylvania were analysed using a historic database of wells (including NOVs from the PADEP) with structural issues between 2000-2012 using the Cox proportional hazards model (Ingraffea et al., 2014). However, the model utilises historic data which illustrates temporal differences more likely due to changes in inspections of wells over the years or rushed developments, rather than factors such as gas migration due to cement changes (Bonett and Pafitis, 1996) or Sustained Casing Pressures (SCPs) from failed casings (Bourgoyne et al., 2000). This study is only successful with the historic collection of data and therefore has not been applied to other areas, in particular those which have very little history.

With onshore development, protecting water resources is a vital concern not often recognised in offshore oil and gas risk assessments. The likelihood of water contamination from natural gas production from the Marcellus Shale was analysed using probability bounds analysis supported by various data sources (Rozell and Reaven, 2012). A worst- and best-case scenario was used to highlight the uncertainty bounds which exist when analysing the risks across five identified contamination pathways. However, the study focused only on the Marcellus Shale and required many assumptions due to a lack of data.

Kissinger et al. (2013) and Lange et al. (2013) assessed the risks to groundwater from fluid migration due to geological characteristics, using a deterministic approach (Lange et al., 2013) and a qualitative analysis of possible hazards and scenarios (Kissinger et al., 2013). Gaps in the database prevented a full probabilistic analysis of the three scenarios for upward migration of fluid and methane across different timescales, presenting a conservative approach with overestimations and significant assumptions (Lange et al., 2013). Conversely, the qualitative study highlighted scenarios in detail leading to fluid migration and their hazards, but due to high parameter and scenario uncertainty, quantitative analysis was beyond the scope of the research (Kissinger et al., 2013).

A qualitative risk analysis was conducted as a primary step in investigating water-related human health and environmental risks from hydraulic fracturing in Germany, which considers the impact pathways and potential hazards of fracturing fluids (Bergmann et al., 2014). Challenges faced in this study consist of a lack of basic information to produce a well-rounded risk assessment, such as information on structures and properties of geological systems and toxicology properties of fracturing additives. This lead the authors to recommend no further above- or below-ground activities in vulnerable water resource areas in Germany until the development of significantly improved data collection and analysis (Bergmann et al., 2014).

Many studies have focused on historical data or modelling to analyse risks, but there is a need for field-focused hydrogeological understanding of the subsurface to fill scientific gaps in unconventional gas development (Jackson et al., 2013a). However, often it is a challenge to access onshore wells for field data, particularly in places such as the US and Canada where wells might be drilled in very remote locations with almost impossible access (Barber et al., 2006; Gross et al., 2013). Equally, there is a struggle with the confidentiality of field data obtained by the well operators (Johnson and Johnson, 2012; Brantley et al., 2014; Long et al., 2015a; Konschnik and Dayalu, 2016). Lavoie et al. (2014) initiated a study attempting to fill some of the hydrogeological gaps in understanding of the Utica Shale by collecting a vast amount of data for a specific local-scale site in Quebec, St. Lawrence Platform. The paper laid out a methodology for the development of a vulnerability risk assessment. The risk assessment allows for a detailed, quantifiable understanding of the risks to groundwater contamination in the Utica Shale but currently is only applicable to the local area which the data is obtained from. The risk assessment has the potential for applying to other areas within Canada but would require significant data collection, time and expertise.

Common factors amongst most of the studies to date on assessing risk during hydraulic fracturing are the lack of data, confidence and certainty in modelling studies. These studies discussed do not focus solely on groundwater contamination and cannot indicate a clear application to other sites, particularly globally. Specific areas have been the main targets for conducting risk assessments and although other countries can learn from mistakes

already been made, it is vital mistakes are prevented in the first place, especially where new ones could be made in unknown geological areas.

This research focuses on groundwater as the receptor to gas migration and develops a framework which allows for a generic application across sites in different parts of the world. In particular, the UK industry will have many risks which are highly unknown and uncertain due to the lack of historic information, compared with the US and Canada. Fuzzy logic is a technique used to handle uncertainty and a lack of data. It utilises knowledge in numerical data or non-numerical data known as linguistic knowledge, which facilitates the expression of rules and facts. The utilisation of fuzzy logic with the discussed risk assessment techniques (Section 3.2.3) allows the development of a novel framework for a generic application of onshore subsurface engineering.

3.4 FUZZY LOGIC

As recognised above, hydraulic fracturing is a complex engineering process with many potential contributors to environmental risk. Risk assessments associated with shale gas can include multiple risk hazards presented in various ways including expert opinions, linguistic descriptors or numerical values. Within engineering and environmental systems, linguistic representation might be preferred over probabilistic, particularly where uncertainty exists. Additionally, hydraulic fracturing operations are influenced by human factors (HOF) where errors during the process can be man-made (Skogdalen and Vinnem, 2012). These are a challenge to numerically evaluate. Alternative, unconventional methods of risk assessments using techniques such as fuzzy logic can be used to tackle insufficient data, incomplete knowledge and a combination of human reasoning and imprecise data (Shang and Hossen, 2013).

Fuzzy logic was first introduced by Zadeh in 1965 to model uncertainties. It suits complex systems where problems arising from ideas, beliefs, judgement, indecision, doubt and probabilities can be solved, unlike the classical scientific methods which do not account for human reasoning (Okwu and Nwachukwu, 2019). Fuzzy logic fills the gap where conventional crisp systems cannot integrate human and computer reasoning for assisting humans in decision-making (Okwu and Nwachukwu, 2019). Fuzzy logic applications in the petroleum industry are mainly related to decision-making for reservoir characterization (Cuddy, 2000; Taghavi, 2005) and candidate-well selection (Zoveidavianpoor et al., 2012) and improving drilling, completion and stimulation techniques (Rivera and Farabee, 1994; Garrouch and Labbabidi, 2003; Murillo et al., 2009). Despite the variety of research in offshore oil and gas risk analysis and management (Aven et al., 2007; Lavasani et al., 2011; Hu et al., 2012; Liu et al., 2013; Lavasani et al., 2015; Ramzali et al., 2015; Cheliyan and Bhattacharyya, 2018), fuzzy logic techniques for assessing risk from onshore hydraulic fracturing has not been touched on, to date.

3.4.1   Fuzzy set theory

In order to model uncertainty, fuzzy logic uses fuzzy sets: a class of objects with a continuum of grades of membership (Zadeh, 1965). Fuzzy sets are characterized by membership functions where the object can be assigned to any number between 0 and 1 (Zadeh, 1965). This differs from a classical crisp set where an individual object is either a member or a non-member of a set (either 0 or 1) (Shang and Hossen, 2013). Fuzzy Set Theory (FST) borrows ideas from crisp set theory but with distinctions to allow for the element of uncertainty (Mendel, 1995).

For a classical set A where the universe of discourse is X and its elements are x, a crisp set A of X is defined as a membership function, $f_A(x)$ (otherwise known as a characteristic function, discrimination function or indicator function) (Mendel, 1995):

$$f_A(x) : x \to [0,1] \qquad \text{where,} \ f_A(x) = \begin{cases} 1 & \text{if } x \in A \\ 0 & \text{if } x \notin A \end{cases} \tag{3.4}$$

A fuzzy set $\underset{\sim}{A}$ of universe X is defined as a membership function, $\mu_{\underset{\sim}{A}}(x)$ (Mendel, 1995; Mahdavian and Javadi, 2019):

$$\mu_{\underset{\sim}{A}}(x) : x \to [0,1] \qquad \text{where} \begin{cases} \mu_{\underset{\sim}{A}}(x) = 1 \text{ if } x \text{ is totally in } \underset{\sim}{A} \\ \mu_{\underset{\sim}{A}}(x) = 0 \text{ if } x \text{ is not in } \underset{\sim}{A} \\ 0 < \mu_{\underset{\sim}{A}}(x) < 1 \text{ if } x \text{ is partly in } \underset{\sim}{A} \end{cases} \tag{3.5}$$

Compared to the classical set, a fuzzy set allows for a continuum of possible choices between 0 and 1, known as the degree of membership. An object can exist in more than one set to different degrees of similarity, unlike a crisp set (Mendel, 1995).

3.4.1.1   Fuzzy membership functions

In FST, a membership function has flexibility in its definition but there are concepts which are often followed. A fuzzy set does not have to be scaled between 0 and 1, but this is generally done to ensure the variables are normalized (Mendel, 1995). This means a fuzzy set is often considered to be normal (Figure 3.4). To preserve similar properties of classical sets such as the intersection and union, Zadeh (1965) proved the notion of convexity can be extended to fuzzy sets (Figure 3.5). A convex fuzzy set has membership values which are strictly monotonically increasing or decreasing or strictly monotonically increasing and then monotonically decreasing, with increasing values for elements in the universe (Ross, 2010). Therefore, fuzzy membership functions are most commonly normal and convex. There are situations in which certain operations on membership functions

produce subnormal and non-convex fuzzy sets, such as the extension principle in fuzzy arithmetic, discussed in Section 3.4.3 (Ross, 2010).

(A) Normal fuzzy set.

(B) Subnormal fuzzy set.
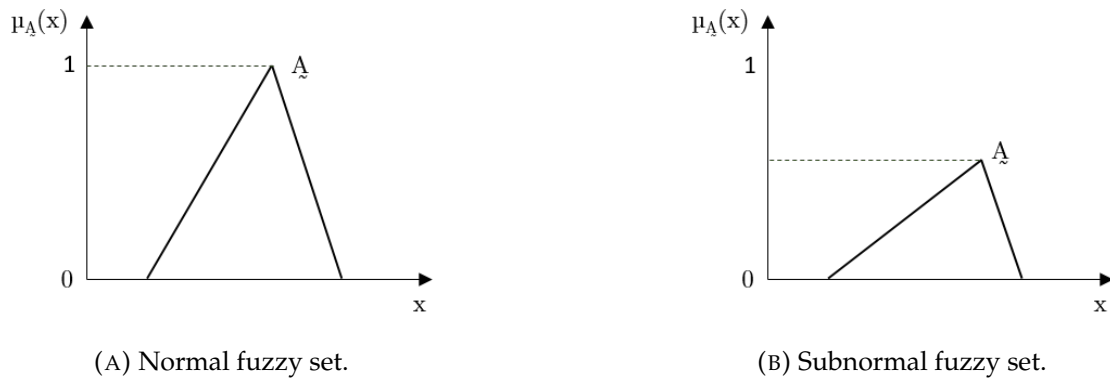
FIGURE 3.4: Normal and subnormal fuzzy sets.

(A) Normal, convex fuzzy set.

(B) Normal, nonconvex fuzzy set.
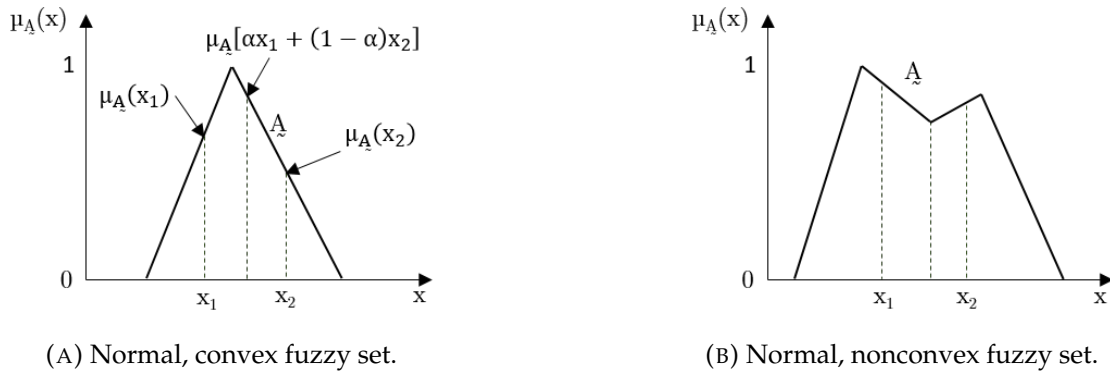
FIGURE 3.5: Convex and nonconvex fuzzy sets.

Membership functions can take a range of shapes as long as they follow the above criteria (equation 3.5), but the most common shapes are triangular, trapezoidal, piecewise linear and Gaussian. Membership functions do not have to be symmetric and do not have to overlap, but overlapping is unique to fuzzy logic and enables decisions to be made in more than one input class, making the system more robust (Mendel, 1995).

Constructing fuzzy membership functions was originally down to a users experience and expert judgement, but it can be a challenge converting qualitative information into a mathematical function. More recently, methods used might depend on the data and expertise available. Sivanandam et al. (2007) suggested a selection of membership assignments using intuition, inference, rank ordering, angular fuzzy sets, neural networks, genetic algorithms or inductive reasoning. Further information on these techniques is explained by Sivanandam et al. (2007). Intuition is common and partly used in this research where little data exists but there is thorough knowledge of the problem.

Neural networks and genetic algorithms are more popular machine learning methods for producing fuzzy functions and rule bases, where the fuzzy inference system is created

or tuned using training and validation data sets (Hong and Lee, 1996; Sun et al., 2007; Cintra et al., 2008). This requires sufficient input and output data which can be divided into two sets of data for training and validation. Inductive reasoning also requires data which is abundant and static and a well-defined database for input-output relationships (Sivanandam et al., 2007). The lack of appropriate data to apply to this problem makes it a challenge to produce a fuzzy system using machine learning or inductive reasoning, particularly as some of the input and output values must be created based on fuzzy logic. Unlike machine learning techniques, an advantage of inductive reasoning is it may not require a convergence analysis to find the optimal solution (Asanka and Perera, 2017). An alternative method for producing membership functions, which is partly data-driven, has been applied to a part of this research and uses box plots to create trapezoidal membership functions (Asanka and Perera, 2017). Information on this method is given in more detail in Chapter 6.

3.4.1.2 Fuzzy operations

Similarly to classical sets, fuzzy sets have operations: union, intersection and complement. They differ in that the operations on fuzzy sets are based on the membership function whereas classical sets can be characterized by their membership functions, a description of their elements or listing of their elements (Mendel, 1995; Shang and Hossen, 2013). The original operations defined by Zadeh (1965) are shown below, where $\mu_{\underset{\sim}{A}}(x)$ and $\mu_{\underset{\sim}{B}}(x)$ are two fuzzy sets defined on the universe X (Ross, 2010):

Union $\qquad \mu_{\underset{\sim}{A}\cup\underset{\sim}{B}}(x) = \text{Max}[\mu_{\underset{\sim}{A}}(x), \mu_{\underset{\sim}{B}}(x)] = \mu_{\underset{\sim}{A}}(x) \vee \mu_{\underset{\sim}{B}}(x)$ $\qquad$ (3.6)

Intersection: $\qquad \mu_{\underset{\sim}{A}\cap\underset{\sim}{B}}(x) = \text{Min}[\mu_{\underset{\sim}{A}}(x), \mu_{\underset{\sim}{B}}(x)] = \mu_{\underset{\sim}{A}}(x) \wedge \mu_{\underset{\sim}{B}}(x)$ $\qquad$ (3.7)

Complement: $\qquad \mu_{\overline{\underset{\sim}{A}}}(x) = 1 - \mu_{\underset{\sim}{A}}(x)$ $\qquad$ (3.8)

These operations are most commonly used in engineering applications in Fuzzy Logic Systems (FLS) (Section 3.4.2) but there are many other fuzzy operations which might be used in a FLS or as part of fuzzy arithmetic. The algebraic sum, bounded sum and drastic sum are all alternatives for the union operator and the algebraic product, bounded difference and drastic product are alternatives for the intersection operator (Mendel, 1995; Mahdavian and Javadi, 2019). Fuzzy arithmetic is an essential but more complex element to the fuzzy model in Chapter 6 and is therefore discussed in more detail in Section 3.4.3.

3.4.2 Fuzzy logic systems

A FLS utilises the elements of FST to produce a unique approximation method which can handle both numerical data and linguistic knowledge in a unified mathematical manner

(Mendel, 1995). A FLS has four major components (Figure 3.6): a fuzzifier to convert crisp inputs into fuzzy inputs, an inference engine containing fuzzy operators, a rule base to link inputs and outputs in the inference engine, and a defuzzifier to convert fuzzy outputs into crisp outputs (Cheng and Ko, 2006).
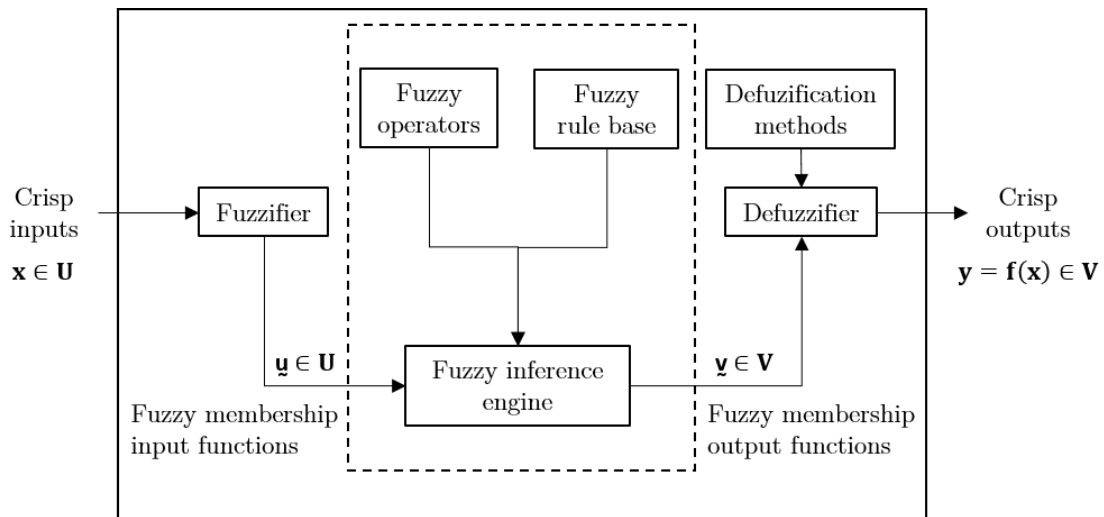
FIGURE 3.6: Components and flow schematic of a FLS. The dotted box outlines the Fuzzy Inference System (FIS) discussed in the next section. Adapted from Mendel (1995).

Membership functions are created to allow the fuzzifier to convert crisp input data into fuzzy data and the defuzzifier to convert fuzzy output data into crisp output data, if required. These membership functions represent linguistic concepts rather than numerical; 'hot', 'cold', 'low', 'medium', 'high' etc. Rule bases using 'IF-THEN' statements connect these input and output membership functions within the Fuzzy Inference System (FIS) so the FLS maps inputs to outputs, which can be expressed quantitatively as $y = f(x)$ (Mendel, 1995).

3.4.2.1   Fuzzy inference system

The important components of the FIS are rule bases, implication, aggregation and fuzzy operations (Figure 3.7). A fuzzy rule consists of a conditional statement in the form 'IF x is A THEN y is B', where x and y are linguistic variables and A and B are linguistic values. The rules are made up of an antecedent which defines the conditions ('IF x is A') and a consequent which defines the action ('THEN y is B') (Caniani et al., 2011). The antecedent of the rule will have a conjunction ('IF x is A AND y is B') or disjunction ('IF x is A OR y is B') where there are two or more inputs. These are the commonly used fuzzy operators discussed above. A fuzzy operator is also used to obtain the consequent fuzzy set, known as the implication process. The implication process is applied for each rule and commonly uses the intersection operator; either the minimum (defined above) or the

algebraic product. Once all rules have gone through implication, the outputs must be aggregated. The standard union and intersection operators are suitable for aggregation where the union maximum operator is the most commonly used (Mahdavian and Javadi, 2019), but alternative aggregation operators such as averaging operators and ordered weighted averaging operators have been used in the past (Ross, 2010).
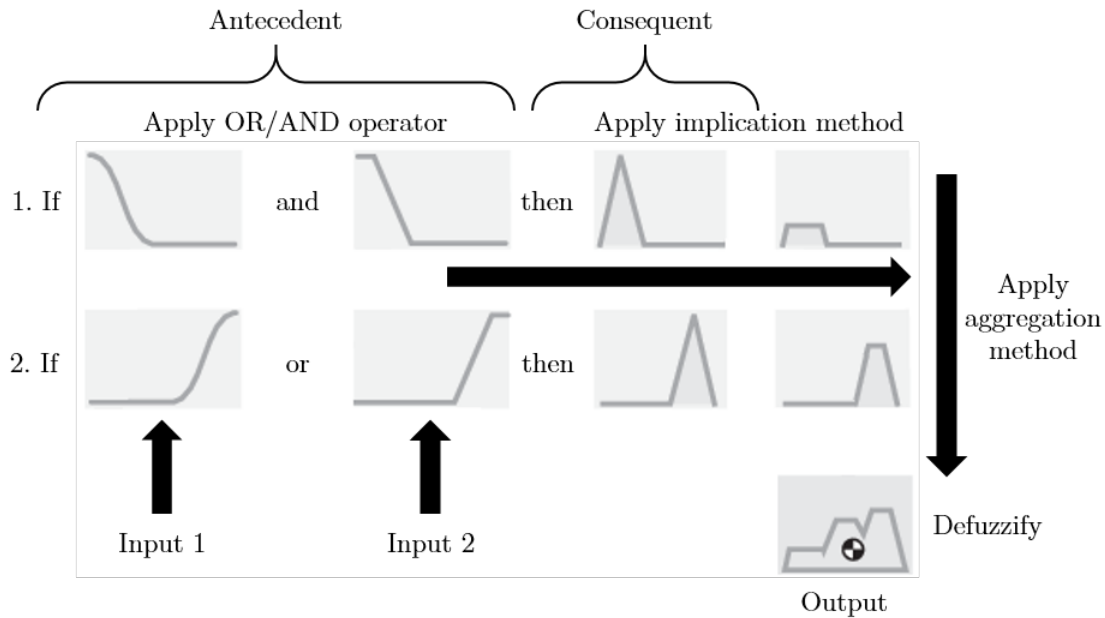
FIGURE 3.7: The FIS elements and flow chart. Adapted from MATLAB (2019).

3.4.2.2 Defuzzification

Once the final aggregated fuzzy set has been produced, a single crisp value can be obtained. In engineering applications, the output as a fuzzy set is generally not hugely useful and so requires converting into a single value which can be understood. There are many methods available for defuzzification often associated with either the mean, minimum or maximum (Talon and Curt, 2017) but the most commonly used ones in engineering are the centroid method, bisector method, middle of maximum method, largest of maximum method and smallest of maximum method (Caniani et al., 2011). Within the context of this research, the centroid method is used:

$$x^* = \frac{\int \mu_{\underset{\sim}{A}}(x) \cdot x \, dx}{\int \mu_{\underset{\sim}{A}}(x) \, dx}$$ (3.9)

where x^* is the defuzzified value, $\mu_{\underset{\sim}{A}}(x)$ is the membership function and x are the elements of the set, as shown graphically in Figure 3.8. The centroid method determines the centre of gravity of the shape to determine the output value. Although difficult to compute in comparison to other methods (Mendel, 1995), it is considered the most prevalent defuzzification technique which yields the most superior results (Lee, 1990; Ross, 2010).
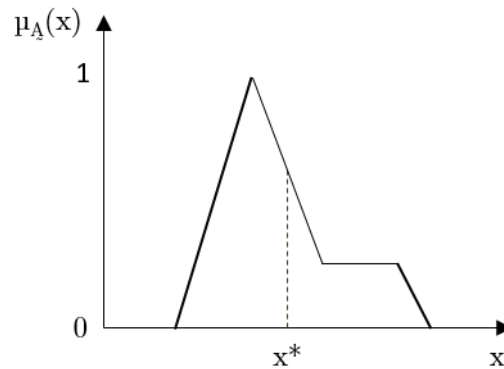
FIGURE 3.8: Centroid defuzzification method. Adapted from Ross (2010).

3.4.3 Fuzzy arithmetic

Building a model often requires arithmetic operations to map inputs onto outputs across a continuous-valued function. In fuzzy logic, conducting arithmetic on fuzzy sets is just an extension of classical arithmetic and is otherwise known as the extension principle, developed by Zadeh (1975). The extension principle is the basic backbone of fuzzy arithmetic. Where two independent fuzzy sets, $\underset{\sim}{A}$ and $\underset{\sim}{B}$, each defined on its own universe, U_1 and U_2, are mapped onto the same universe, V, the extension principle can be defined as (Ross, 2010):

$$\mu_{\underset{\sim}{A}*\underset{\sim}{B}}(u_1, u_2) = \max_{v=f(u_1,u_2)} \left[\min\{\mu_1(u_1), \mu_2(u_2)\} \right] \tag{3.10}$$

where * represents an operation of $+, -, \times$ or $\div$ and u_1 and u_2 are independent input variables.

This equation is expressed for a discrete-valued function, f. Often membership functions are deemed continuous-valued functions but the extension principle discretizes the function in order to propagate fuzziness. The input values are discretized for numerical convenience which often causes erroneous optimum solutions of the output due to portions of the solution space being ignored; a well-known problem with an optimisation process. For a more complex function, improving the output solution will require a significant number of discrete inputs, substantially increasing the computation time. Therefore, less computationally heavy methods are often used which are based around the extension principle and interval arithmetic.

Interval arithmetic is a classical numerical method which often yields reliable results and can be applied directly to fuzzy logic problems in a similar way. In its simplest terms, the process only requires the two end-points, upper and lower bound of the function, to determine the solution, despite an infinite number of solutions existing between these two points (Ross, 2010). To ease the computational burden of the extension principle, many

alternative methods have been developed which utilise interval arithmetic at various α-cut levels to define output membership functions.

Suggested methods for easier computation and reliable outputs compared to the extension principle are the vertex method (Dong and Shah, 1987), the DSW algorithm (Dong et al., 1985) and the restricted DSW algorithm (Givens and Tahani, 1987). In this research, the DSW algorithm has been chosen which uses the full α-cut intervals with a standard interval analysis, unlike the vertex method. The vertex method provides an extremely simplified version of the extension principle which allows for an easy computation but perhaps an oversimplified representation of the output. Additionally, the vertex method is only accurate when the conditions of continuity and no extreme points are satisfied, otherwise certain parts of the interval will be missed and not included in the output interval (Ross, 2010).

The DSW algorithm is utilised by the fuzarith function in MATLAB where 100 α values are selected to conduct the algorithm. For trapezoidal and triangular fuzzy membership functions, 100 points will produce a suitable and accurate output membership function. The α values are selected between 0 and 1 as well as the interval(s) which correspond to those α values. Standard binary interval operations are used to compute the interval for the output membership function and this is repeated for a number of α values (100 values for the fuzarith function).

3.5   FUZZY LOGIC RISK ASSESSMENTS

A variety of risk assessment techniques and methodologies have been discussed in Section 3.2 along with their limitations, particularly with respect to traditional risk assessments. As discussed, conventional techniques such as Monte Carlo, ETA, FTA and Bayseian networks have been used in the past in the oil and gas industry (Section 3.3) and across other disciplines, but due to their quantitative nature and probabilistic functions, require significant data sets and certainty in the data. When assessing risk in engineering, and more specifically the petroleum industry, the methods used must account for difficulties in assessing probabilities, variations in data types (linguistic, subjective and numerical) and a lack of historical and temporal data (Torres et al., 2016). With this large gap in uncertainty on risk assessment outcomes, fuzzy logic is a suitable application to reduce these limitations.

Risk assessment studies within the oil and gas industry are mainly focused on the offshore industry, so applying the fuzzy logic technique to onshore and more specifically hydraulic fracturing is a relatively new approach. In the offshore oil and gas industry, researchers have taken approaches which focused on methods involving FFTA (Hu et al., 2012; Lavasani et al., 2015; Ramzali et al., 2015; Cheliyan and Bhattacharyya, 2018), Analytic

Hierarchy Process (AHP) (Lavasani et al., 2011; Peibin et al., 2012; Zhang et al., 2012; Liu et al., 2013), fuzzy evaluation approaches (Peibin et al., 2012; Zhang et al., 2012; Liu et al., 2013) and ETA (Ramzali et al., 2015). FETA and FFTA mainly uses linguistic variables to include expert judgements which are converted into fuzzy numbers using fuzzy arithmetic. Fuzzy AHP (FAHP) also uses linguistic variables which are applied to fuzzy numbers and reciprocal fuzzy numbers and then follows a standard AHP. The fuzzy synthetic evaluation approach develops membership functions and uses fuzzy arithmetic to compute the functions and hence rank factors, groups and overall risk values.

3.5.1 Fuzzy event and fault tree analysis

As identified earlier, ETA and FTA are suitable hybrid techniques for scenario development and risk analysis within an engineering context and have been the main application in this research. FST applied to these techniques remedies the gap in uncertainty when conducting conventional risk analysis. Tanaka et al. (1983) and Kenarangui (1991) pioneered the work on FETA and FFTA by treating branches and basic events as linguistic terms (Kenarangui, 1991) and fuzzy trapezoidal numbers (Tanaka et al., 1983). These techniques have been developed over the years using methods to collect expert knowledge data, aggregate linguistic data and conduct sensitivity analysis to support validation.

Expert knowledge is a requirement for fuzzy applications to apply information to event trees and fault trees and must ensure no bias in the experts, where possible (Lavasani et al., 2015). Expert elicitation will come from engineers, researchers and scientists working in the field to govern the probabilities of occurrence for branches on event trees or basic events on fault trees. This has been utilised in several studies focusing on FETA and FFTA (Lavasani et al., 2015; Ramzali et al., 2015; Cheliyan and Bhattacharyya, 2018).

Combining expert knowledge data is the next step in evaluating linguistic data. A popular method for aggregating expert judgements for each basic event on a fault tree uses the Similarity Aggregation Method (SAM) developed by Hsu and Chen (1996). This method has been described and applied for FFTA in Chapter 5. Lavasani et al. (2015) and Cheliyan and Bhattacharyya (2018) are recent studies which utilised FFTA for quantifying the risk of a leak in an offshore oil and gas scenario. Lavasani et al. (2015) aggregated the risks using the SAM and then used centroid defuzzification to obtain a crisp possibility value. Cheliyan and Bhattacharyya (2018) used a linear opinion pool method which is a weighted linear combination of the experts probabilities (Clemen and Winkler, 1999; Yuhua and Datao, 2005) and used a left and right fuzzy ranking method (Chen et al., 1991; Yuhua and Datao, 2005) to defuzzify into crisp possibility values.

The methods developed by Tanaka et al. (1983) and Kenarangui (1991) both calculated the possibility of failure of the top event (FTA) and the possibility of occurring events (ETA). Although probability is the desired outcome, it might be necessary to determine

the possibility of something failing even if it has never failed before. The possibility of failure is more predictive than the probability, so the probability of failure is a limiting case of possibility (Tanaka et al., 1983). Onisawa (1988) developed an approach to convert possibility of failures to probability of failures to allow the comparison of equipment failure calculated from objective probability, with expert judgement calculated from subjective qualitative information (Huang et al., 2001). This method has been used with FFTA and FETA in engineering applications to ensure compatibility between failures (Lin and Wang, 1997; Huang et al., 2001; Lavasani et al., 2015; Ramzali et al., 2015) and is described in Chapter 5.

Outside of the engineering field, Bidder et al. (2014) focused on the development of fuzzy event trees for biotelemetry studies. The study aimed to encourage the adoption of this method by developing a biotelemetry event tree specific to their industry and research. Seven linguistic descriptors were developed to assess the likelihood of a successful event in the tree and these events were quantified using expert judgements and the model validated with a case study. Ramzali et al. (2015) applied FETA and FFTA to determine the probability of leakage scenarios in an offshore drilling system during the production phase, using well barrier schematics from NORSOK (2004). The research combined reliability block diagrams and FTA to illustrate a method for determining the failure probabilities within the event tree using expert judgement, SAM to aggregate possibilities and conversion of possibility to probability of failures. The final outcome for each failure scenario in the event tree was not calculated, but the probability of failure for the initiating event was $2.54E^{-11}$ (Lavasani et al., 2015), suggesting the final scenario probabilities of failure will be extremely low. This is expected as multiple failures must occur through many highly reliable well components. The main focus of this study was to illustrate a combination of methods to quantify individual failures and identify the most critical barriers in the system to improve system reliability. Quantifying probabilities of failure where there was insufficient information was successfully achieved by incorporating FST into failure analysis.

FFTA and FETA methods require sensitivity analysis to support the variations in uncertainties and to understand the behaviour of the system. As mentioned above, Ramzali et al. (2015) conducted a sensitivity analysis to determine the upper and lower bounds of leakage to understand the reliability of the system. Cheliyan and Bhattacharyya (2018) computed a crisp probability value of 0.01777 for the leakage in a subsea production system which considered four potential leakage locations in a pipeline system: (1) gas and oil wells, (2) pipelines, (3) key facilities, and (4) third-party damage. This outcome is considered to show a negligible effect of the higher order terms (Cheliyan and Bhattacharyya, 2018). The sensitivity analysis indicated third-party damage and the failure of leakage control in a pipe and connector had the highest rank and hence affected the risk probability the most. The robustness in the probability of the top event of the fault

tree is evaluated using the uncertainty of the fuzzy failure probabilities of all the basic events (indicated by their 'spread' (Singer, 1990; Cheliyan and Bhattacharyya, 2018)). This method was also conducted on conventional FTA to compare a fuzzy description of the basic events versus a conventional description for the top event outcome. The results indicated in a fuzzy system (FFTA), the uncertainty in the crisp value of the top event was significantly lower compared with the basic events (e.g. 30% uncertainty in basic event means only ∼5% uncertainty in the top event). Conversely, in the conventional system (FTA), the uncertainty in the crisp value of the top event was almost 100% greater than the uncertainty in the basic events (Cheliyan and Bhattacharyya, 2018). This analysis demonstrates the crisp value of the top event in the fuzzy system is much more robust compared with the conventional system. Therefore, a fuzzy description of the basic event probabilities is preferred over a conventional method.

Lavasani et al. (2015) focused on a specific leak in a system which looked at the risk of leakage through abandoned offshore oil and gas wells through cement plugs, illustrated initially by Minerals Management Service (MMS) (2000). A case study was used to illustrate the FFTA method using an abandoned well in the Gulf of Mexico. The quantified risk for the well was much smaller than that of Cheliyan and Bhattacharyya (2018) at a value of $2.54E^{-11}$ as the basic events for cement and casing failures had significantly lower failure rates than component and human failure rates in offshore pipelines. A sensitivity analysis was conducted on the fault tree by analysing the influence of the Minimal Cut-sets (MCS) on the top event. MCS1 was the most influential on the top event and this cut-set consisted of leaks through the plugs of the abandoned well. Ranking of MCSs is applied to this research and discussed in Chapter 5. Further sensitivity analysis techniques consisting of the Fuzzy Weighted Index (FWI), probabilistic importance and criticality importance are also conducted alongside MCS analysis (Chapter 5).

The methods illustrated above for FETA and FFTA demonstrated successful results and presented a simple implementation to case studies to obtain intuitive outcomes. The variety of input data was handled in a consistent manner with the application of FST and hence allows a flexible approach to combine subjective and objective events in a variety of scenarios and industries.

3.6   CONCLUSION ON RESEARCH GAPS

Risk assessments are an integral part to well drilling and production whether onshore or offshore. The risks surrounding subsurface gas production are abundant and often well-known but not well understood. Generally within the petroleum industry, the low probability but high consequence risks are the main focus for assessment as these consequences are often related to potential loss of life or loss of production, and hence loss of money (Skogdalen and Vinnem, 2012). However, the cumulative effects of many low

probability/low consequence or high probability/low consequence risks during oil and gas production are essential for the protection of the surrounding environment. During onshore hydraulic fracturing operations, groundwater is under threat from extensive water usage, water quality degradation and waste water disposal (Gallegos et al., 2015). Groundwater is a vital receptor requiring protection from onshore petroleum development.

Risk assessments have been developed within the oil and gas industry using a variety of qualitative and quantitative methods. The qualitative frameworks are more aware of the variety of risks associated with drilling and production but are unable to numerically produce outputs which can allow for risk-free decisions. Numerical models have been developed for individual risks for conventional and unconventional drilling, some which have focused on potential pathways to groundwater contamination. However, these types of models are very complex and are only able to focus on a small aspect of risk analysis within the system. In addition, the extent of assumptions and uncertainty in these models is very high and often applicable to only one scenario or a worst-case scenario. To ensure holistic risk analysis, risk frameworks and models are required which can express the extent of the various risks involved in the whole system allowing for high levels of uncertainty and variations in scenarios.

To overcome the problems of high uncertainty, lack of high quality data and poor application to multiple risks within the industry, researchers have applied expert knowledge and a combination of qualitative and quantitative data to risk assessment approaches using fuzzy logic and FST. Fuzzy logic can utilise linguistic data which might come in the form of expert opinions or use numerical data to build fuzzy membership functions where values can be a member of more than one set with undefined boundaries, unlike that seen in classical sets. Several methods have been used for drilling projects which utilise these fuzzy approaches. Classical methods incorporating the fuzzy approach such as FETA, FFTA or FAHP have been applied along with new methods such as fuzzy synthetic evaluation approaches or general fuzzy construction of risk assessments.

Fuzzy logic will be used in this research to quantify the failure of cement which has currently not been done in the literature. Linguistic knowledge in the form of expert opinions will be used to quantify the basic events of the fault trees developed for cement failure. The application of FST and development of fuzzy membership functions based on engineering judgement will be used to implement an analytical model for SCP where data is not available. Currently, hypothetical data is used which prevents the application to a case study.

Although fuzzy methods have been applied in the oil and gas industry, they have mainly focused on offshore developments and in particular there has been no application using this approach to onshore hydraulic fracturing. As the development of hydraulic fracturing in the UK is still in its preliminary stages and data is not readily accessible, a fuzzy logic

approach is more suitable for quantifying individual risks to groundwater. This work will present a comprehensive risk assessment framework which will incorporate various fuzzy logic methods depending on the available numerical data, literature-based data and expert knowledge. The individual models within the framework will be developed using a case study from an established onshore hydraulic fracturing industry and discussed with respect to a potential UK industry. The following chapter will discuss the case study used and the current status of the UK onshore industry.

CHAPTER 4

CASE STUDY

Hydraulic fracturing is an industry-based engineering technique which has been applied or tested in several countries around the world, with some of the largest industries in the US and Canada. Their extensive historic onshore well-drilling activities provides suitable case studies for model development and application, particularly in areas of comparison between arising environmental issues and suitable environmental regulations. Canada was chosen as the main case study for model development and this application benefited from collaborative engagement at the University of British Columbia (UBC), supporting the research with data collection and discussions. Canada was a preferred country for model development over sites in Europe because of the history of the industry. Canada has a much higher understanding of the risks they face from hydraulic fracturing due to their experiences and this significantly reduces the uncertainty in the model development. Case studies in Europe have faced much more turbulent outcomes from hydraulic fracturing meaning there lacks a consistency in well drilling activities so the data and outputs are much harder to interpret. Developing the model requires strong data either as numerical or linguistic knowledge and this was successfully obtained through a Canadian case study.

A benefit of approaching model development using case study data is that it can encourage the application of the work to countries where the industry is yet to take off but has potential in the future, such as the UK. Interpreting and modelling the experiences faced in North America can be used to understand the risks involved in hydraulic fracturing and the methods to mitigate or reduce these risks when applied to alternative areas. Incidences of fugitive gas or fluid migration have both been prevalent in the US and Canada (Jackson et al., 2013b; Bachu, 2017; Lackey et al., 2017) and equivalent concerns have been raised in the UK at the infancy of its shale gas industry (Stuart, 2012; The Royal Society, 2012; Younger, 2016).

4.1 CANADA

Canada has significant shale gas reserves being exploited consisting of nine gas-bearing shale formations across the country in five provinces (Alberta, British Columbia (BC), New Brunswick, Nova Scotia and Quebec) and two territories (Northwest Territories and Yukon) (Figure 4.1). New Brunswick and Nova Scotia have little success from exploration wells and Quebec has a moratorium on shale gas drilling and hydraulic fracturing (Rivard et al., 2014; Moritz et al., 2015; Rivard et al., 2018). Alberta and BC have one of the largest exploitable reserves of unconventional natural gas in the world (US Energy Information Administration, 2017) where ∽63% remain to be recovered in Alberta but >90% in place in Northeastern BC (NEBC) (Cahill et al., 2019).

FIGURE 4.1: Shale gas formations in Canada containing a mixture of dry gas and shale-hosted petroleum resources (Rivard et al., 2014).

BC has been the major producer of shale gas in Canada with the highest number of wells drilled for unconventional hydrocarbons in shales and tight sands over the past decade (Figure 4.2). Significant and rapid onshore development of shale gas in the US and Canada has generated environmental concerns where both have faced incidences of gas or fluid migration to groundwater or the atmosphere (Jackson et al., 2013b; Bachu, 2017; Lackey et al., 2017). The concerns and research are widespread across Canada (Rivard et al., 2014) but with a large focus on BC due to its increased productivity (Figure 4.2) and substantial numbers of reported well leaks (∽19% (Wisen et al., 2017)) (Chesnaux et al., 2010; Wisen et al., 2017; Wisen et al., 2019). A lack of requirements to monitor aquifers near oil and gas wells in BC has lead to poor knowledge on the impact of leaks on freshwater aquifers (Wisen et al., 2019). Therefore, BC is the case study focus for this research due to significant

numbers of horizontal hydraulically fractured natural gas wells and availability of data compared with other provinces and states.
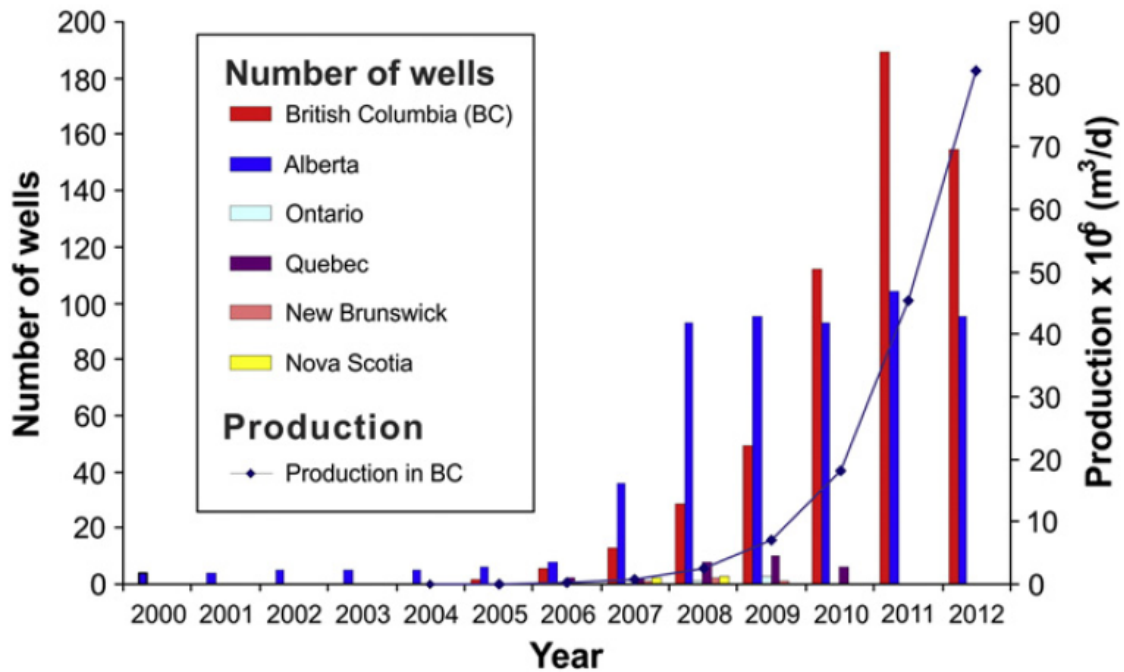
FIGURE 4.2: Number of wells drilled per year for unconventional hydrocarbons across different provinces in Canada and the annual production of shale gas in BC (Rivard et al., 2014). An increasing production rate in BC but a decreasing number of wells suggests the same wells are being successfully re-fractured or more horizontal cases are being added onto the same vertical wells.

NEBC has significant historic and ongoing petroleum development with substantial exploitable reserves (Cahill et al., 2019). The province contains four shale gas basins (Figure 4.3); the Montney, Liard, Horn River Basins and Cardova Embayment (Cahill et al., 2019; Wisen et al., 2019). All four basins have been exploited in the past for conventional gas but since its decline from 2005, unconventional production has taken its place, mainly in the Montney formation. The Liard, Horn River and Cardova are still in their infancy of unconventional exploitation (Wisen et al., 2019). With its unconventional shale gas boom, the Montney exploitation of natural gas is likely to increase in the coming decades (Cahill et al., 2019) and therefore is chosen as the target formation for this research.

4.1.1 Montney formation

The Montney formation is a lower Triassic sedimentary formation (Figure 4.4) which consists mainly of coarse siltstone, sandstone and shale, not making it a true shale (National Energy Board et al., 2006; Hickin et al., 2008; Rivard et al., 2014; Cahill et al., 2019). It is the largest and most productive resource play with 12,719 billion m^3 of recoverable natural gas, 2,308 million m^3 of natural gas liquids and 179 million m^3 of oil (National Energy
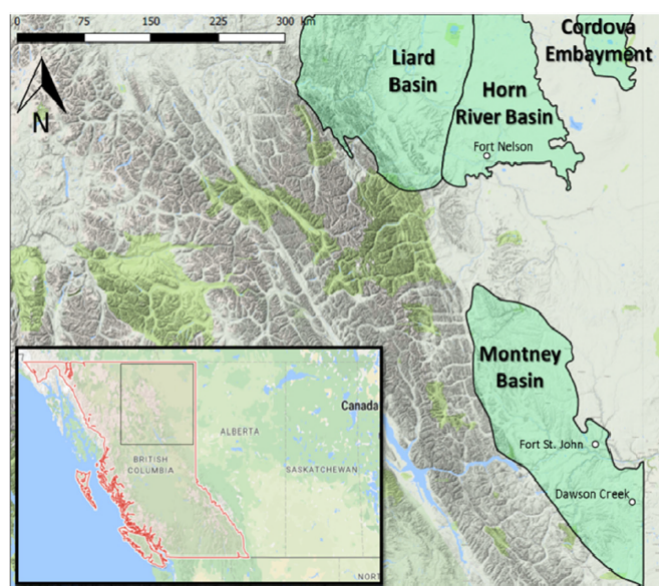
FIGURE 4.3: Four shale gas basins in NEBC (Wisen et al., 2019).

Board et al., 2013). The Montney spans 51,549 km^2 across Alberta and BC, with 26,000 km^2 in BC (Rivard et al., 2014). The thickness of the formation increases westerly from 0-400 m along with the depth to the top of the Montney, increasing from 500-4000 m (Rivard et al., 2014; Cahill et al., 2019).

In BC the majority of the Montney formation exists in the plains of southern and northern NEBC (Ministry of Natural Gas Development). Available data sources from the BC Oil and Gas Commission (BCOGC) consists of 19,337 energy wells in the Montney resource play. However, the majority of these wells do not have all the required data for model development and analysis into gas migration. After selecting the appropriate wells with the data requirements, all of these wells were situated within the southern region of NEBC and were all targeting the Montney formation, suggesting the plains period is the most accurate stratigraphic column (Figure 4.4).

4.1.2 Groundwater in British Columbia

Within the plains stratigraphic column (Figure 4.4), there are several formations potentially containing groundwater. Drilling into the Montney formation will intersect a number of these formations and leave cause for concern on deteriorating groundwater quality from hydraulic fracturing. BC groundwater supplies 22% of the BC population and 23% of the Canadian population with drinking water and feeds livestock in agricultural environments (Rivera et al., 2003; Wisen et al., 2019). Groundwater use and the standards for water wells are unregulated and there is no requirement in BC to monitor aquifers near oil and gas wells (Wisen et al., 2019).
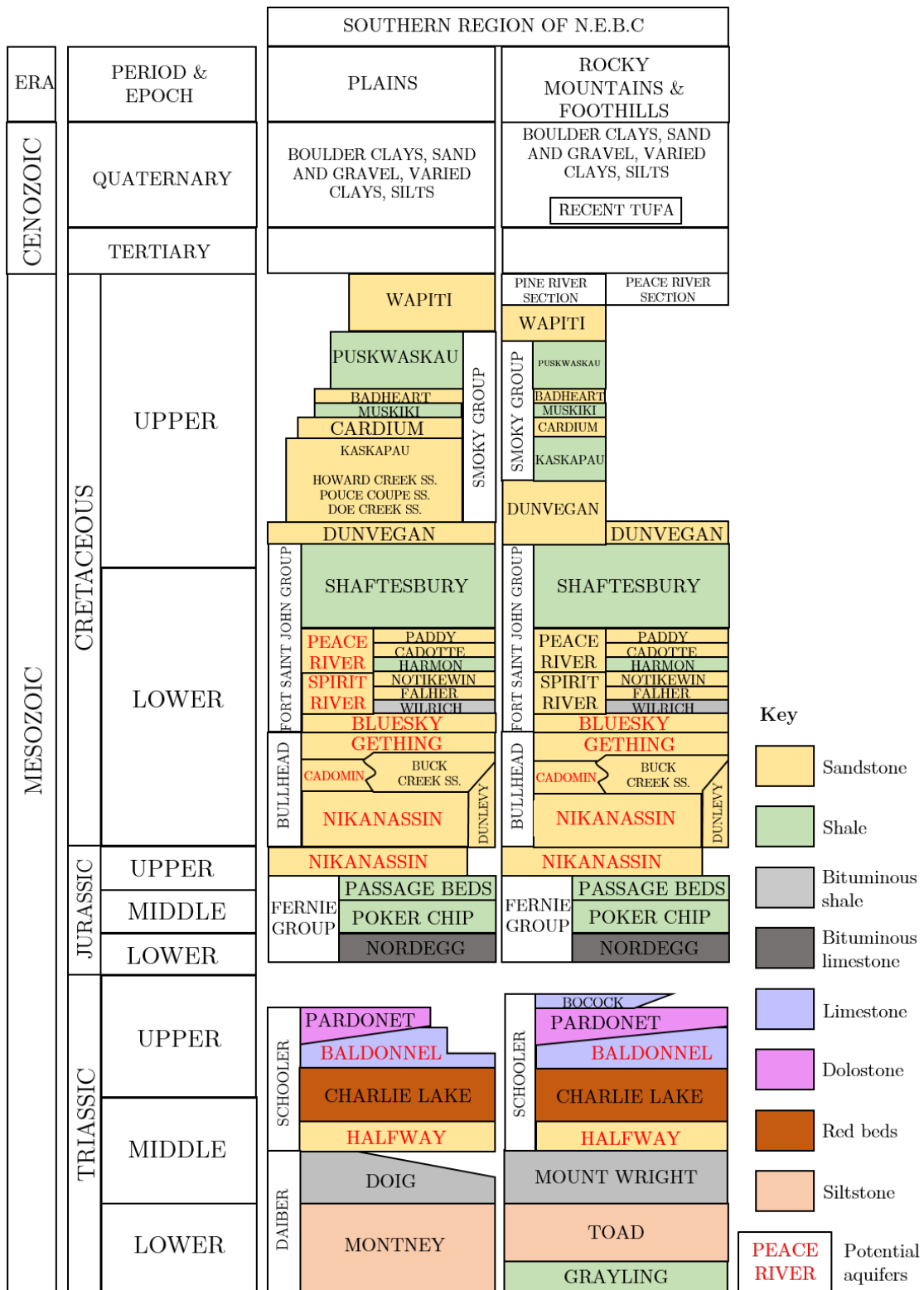
FIGURE 4.4: Stratigraphic columns of the southern region of NEBC, the region of interest. Formations in red are potential aquifers identified by Geoscience BC (2011). Adapted from Geoscience BC (2011) and Ministry of Natural Gas Development.

The lack of monitoring baseline conditions in groundwater prior to hydraulic fracturing makes it challenging to identify gas migration and locate its source. Cahill et al. (2019) discussed the challenge of having a lack of mandatory programmes to characterize groundwater in areas of intense energy development. Despite studies indicating the potential for gas migration from hydraulic fracturing (Chesnaux et al., 2010; Jackson et al., 2013b; Darrah et al., 2014; Llewellyn et al., 2015; Wisen et al., 2017; Wisen et al., 2019), measurements are taken years after recognising well leakage and ignore vital data points such as leakage rates, duration and overall magnitude. Very little data exists in the literature in BC but obtaining it can be a difficult problem logistically and legally (Cahill et al., 2019). A focus on groundwater is clearly required along with alternative modelling studies.

4.1.2.1   Groundwater study area

To encourage further modelling studies of groundwater contamination, understanding and conceptually developing the hydrogeological conditions of the study area are vital. Unfortunately, there is a significant lack of hydrogeological information to determine aquifer characteristics above the Montney formation (Rivard et al., 2014). Up until 2014, the hydrogeology of significant gas- and liquid-producing shales had not been studied in depth, mainly due to their remote and sparsely populated locations (Rivard et al., 2014). Only about 15% of the BC province consisted of classified aquifer systems leaving substantial vulnerable areas lacking data quality and quantity (Rivera et al., 2003). Wisen et al. (2019) applied their research to an undisclosed location in the Montney basin which focused on the impact of hydraulic fracturing on a water supply from four natural springs which feed livestock. The outcomes demonstrated difficulty determining the aquifers which fed the springs and their recharge areas, further signifying the lack of hydrogeological information in BC.

Within the southern region of NEBC, potential aquifers have been mapped but there still lacks suitable hydrogeological knowledge. Figure 4.5 demonstrates the region where the chosen energy wells exist and the presence of aquifers within this area. Only approximately 30% of the outlined region contains mapped aquifers and these generally exist in more populated regions around Fort St. John and Hudson's Hope.

Aquifers are assessed in BC using a classification system which focuses on vulnerability, demand and productivity (Berandinucci and Ronneseth, 2002). Vulnerability of an aquifer measures the influences of contaminants from the surface. Demand and productivity are grouped into a term called 'development' which compares the amount of groundwater withdrawn from the aquifer (demand) to the ability of the aquifer to supply water for use (productivity). The aquifers labelled in Figure 4.5 were classified in Figure 4.6 according to vulnerability, demand and productivity to highlight the potential influence of nearby energy wells on groundwater. A substantial selection of the region defined by
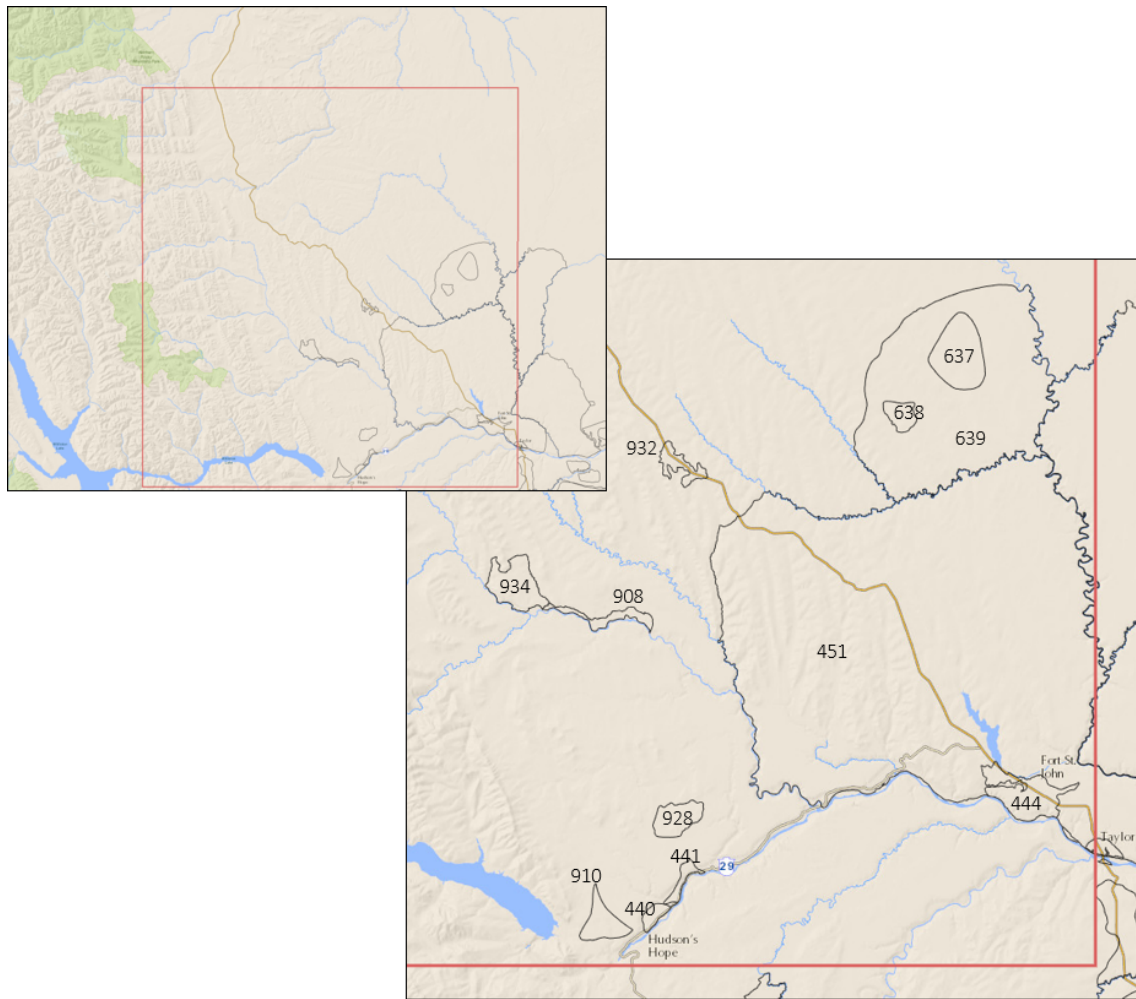
FIGURE 4.5: The region of energy wells chosen for this research (red outline) and the mapped aquifers within the area (black outlines). Each independent aquifer has been labelled.

the chosen energy wells (red outline; Figure 4.5) does not have aquifer information so further collection of this data is vital for a full assessment of groundwater from energy well development.

The aquifers presented demonstrate generally low vulnerability with a few smaller aquifers with moderate to high, suggesting these could be more prone to contamination from energy well development if they are closer to the surface. The demand for all aquifers is quite low, likely due to a much lower population density within the region with the productivity being moderate. A low demand and higher productivity indicate a 'light' level of development; additional development is not a concern provided productivity can meet the demand (Berandinucci and Ronneseth, 2002).

The potentiometric head of an aquifer is used to determine the hydrostatic pressure. This pressure is a good measure for comparing the pressure within a well and external formation pressures to determine if a pressure gradient exists where gas could move
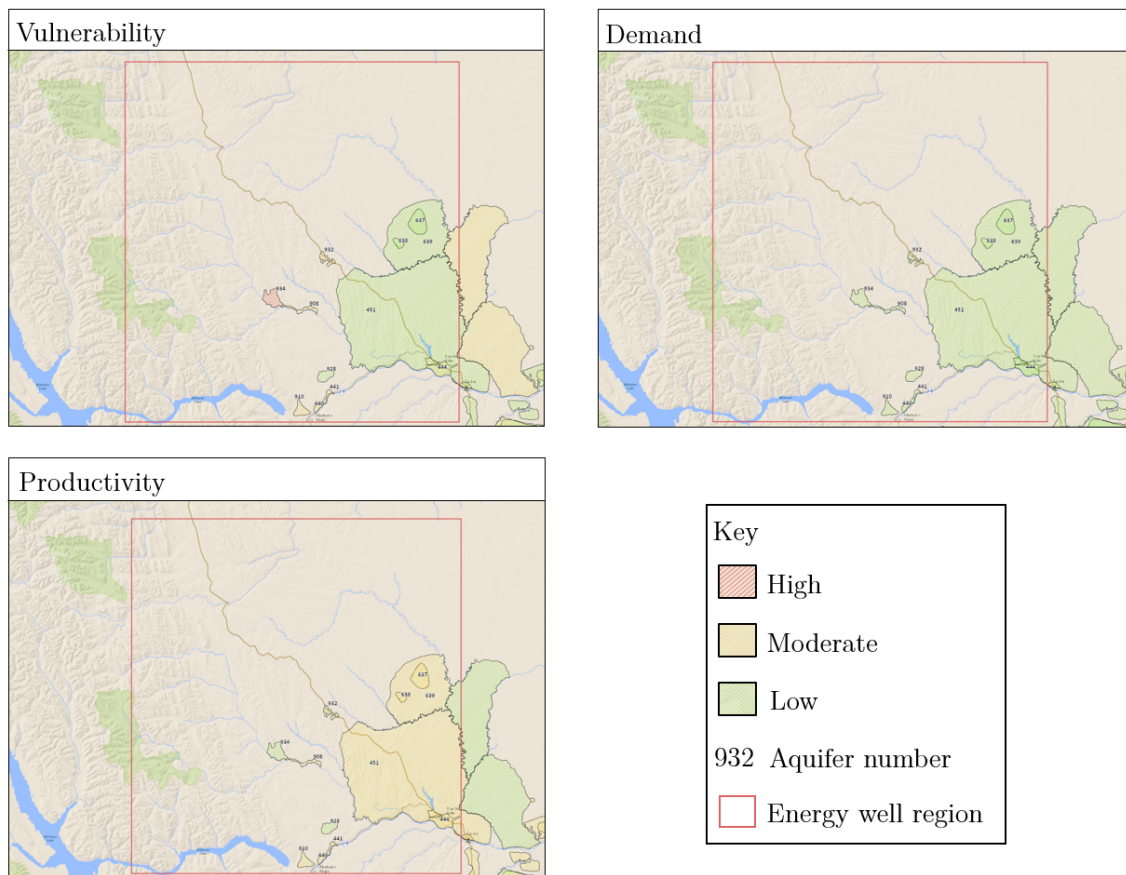
FIGURE 4.6: Classification of the mapped aquifers according to vulnerability, demand and productivity.

into surrounding formations, potentially contaminating an aquifer. Where pressure measurements do not exist, the depth of an aquifer with the potential for contamination is required to determine the potentiometric head of an aquifer above the desired depth (Lackey et al., 2017; Wisen et al., 2019). Unfortunately there exists a level of uncertainty on the location of the water table for the aquifers within the southern region plains of NEBC (Wisen et al., 2019). Despite this, for the mapped aquifers in the south east region (Figure 4.5) groundwater wells are present with the majority containing data on static water level depths (Table 4.1). The average static water level measurements for each aquifer have been calculated in Table 4.1, although the water level across each groundwater well will vary significantly, particularly where there is a high density of groundwater wells and a large aquifer area e.g. aquifer numbers 451 and 639. Therefore, more accurate representations of the water level at the site of a particular energy well was determined by using groundwater well data within the vicinity of the well, where possible.

Figure 4.7 demonstrates a much higher density of groundwater wells present despite aquifers having not been mapped in the majority of the defined region. This has allowed for an improved representation of the groundwater level near most of the energy wells chosen for this research. Where energy wells are drilled and producing in an area of

TABLE 4.1: The availability of data for determining aquifer water level depths, including the calculated average static water level depth for each aquifer and the area.

Aquifer no.	No. of groundwater wells	No. of groundwater wells with static water level depth	Average static water level depth (m)	Area of aquifer (km^2)
908	4	3	11.0	22.9
928	8	5	12.6	37.4
910	10	10	45.6	36.1
932	37	31	27.8	23
934	4	2	9.0	58.3
440	15	9	30.7	13.2
441	16	11	30.5	13.6
451	651	446	26.8	3286
637	7	6	12.0	83.8
638	7	3	6.1	20.4
639	65	48	20.2	844.8
444	33	17	16.5	75.5

no groundwater level data (Figure 4.7; west) or where wells do not contain static water level data, estimations had to be taken based on a mapped aquifer or groundwater well; whichever is nearest.
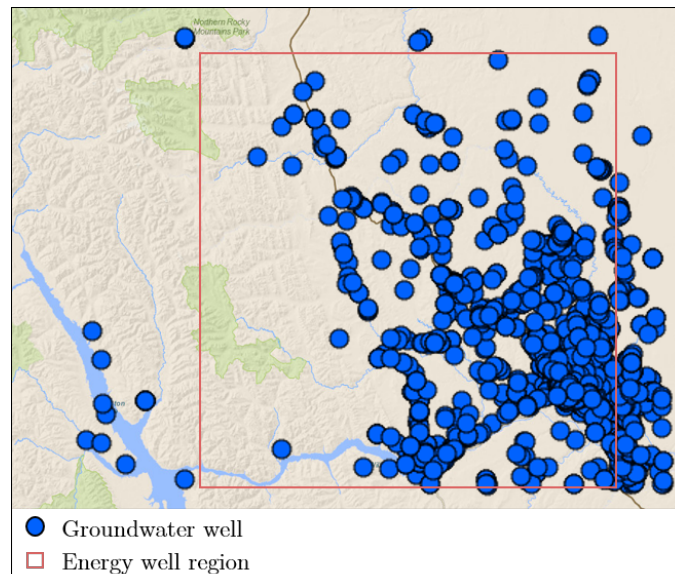
FIGURE 4.7: The location of groundwater wells within the defined region of energy well development. Only approximately 60% of wells contain static water level data.

4.1.3 Drilling regulations

Regulations for well construction can vary between provinces, states and countries and depend upon the reservoir, geology and well operator. All well operators must follow a design which ensures the flow of hydrocarbons from the reservoir to the surface along a

well whilst isolating the oil and gas from surrounding formations and groundwater (US Environmental Protection Agency, 2016b; Wisen et al., 2019). The main variation in well construction and drilling regulations will be the number of casing strings and the depth at which cement is placed. At a minimum in modern hydraulically fractured wells, the design will consist of an outer surface casing string which should be placed and cemented to a depth below usable groundwater and an inner production casing to the depth of the target reservoir which may or may not be cemented to the surface (US Environmental Protection Agency, 2016a; Wisen et al., 2019). Additionally, production tubing and packers might be used to transport the hydrocarbons to the surface during production. Corrosive substances are often present during fracturing and as the production casing cannot be replaced, a production tubing might be used to inject down to prevent casing damage, although this is less likely to be used in high-volume production wells (US Environmental Protection Agency, 2016b).

Further to casing and cement construction, a surface casing vent is always present across all wells as a vital component significantly affecting the potential for groundwater contamination or Greenhouse Gas Emissions (GHG) (Dusseault and Jackson, 2014; Wisen et al., 2017; Cahill et al., 2019; Wisen et al., 2019). The vent can be left open which allows gas to escape at the surface to prevent build-up of pressure at the subsurface and hence possibly contaminate groundwater. This is known as Surface Casing Vent Flow (SCVF) but contributes heavily to greenhouse gas emissions primarily consisting of methane. Alternatively, the vent might be required to be kept closed, reducing emissions but increasing the risk of subsurface build-up within the casing, known as Surface Casing Pressure (SCP) which has the potential to eventually lead to SCP-induced gas migration into groundwater.

4.1.3.1 British Columbia regulations

The regulations in Canada differ across the different provinces and territories, as well as globally (Lackey et al., 2017). In BC there are defined regulations for well drilling and construction and for venting and fugitive emissions (BC Oil & Gas Commission, 2010). Surface casing requirements are slightly different to that of production casing. Surface casing is used in all high-volume hydraulic fracturing wells to isolate the well from groundwater (API, 2009; Fretwell et al., 2012; US Environmental Protection Agency, 2016a; Wisen et al., 2019) and therefore should go to a depth below the bottom of a usable aquifer and cemented to the surface. Where wells are drilled with a shorter surface casing, the next casing string (often production) must be cemented to the surface to provide that layer of protection. Regardless of the surface casing depth, reasonable measures must be taken to ensure intermediate or production casings are cemented to the surface or at least 200 m above the surface casing shoe, although this is not strictly regulated especially where surface casings cover the aquifers (BC Oil & Gas Commission, 2010). During fracturing, production tubing is generally not used inside the production casing.

Wells are fractured directly down the production casing to ensure injection rates are high enough (ideally $12 \, \mathrm{m^3 \, min^{-1}}$) to create the required fracture pattern (J van Besouw, 2019, personal communication, 26 February). Figure 4.8 is an example of two common modern well constructions in BC, Canada. A tubing might be added (without a packer) during production of gas which facilitates the flowback. Initially liquid flow will occur up the tubing at a high velocity but once this rate drops off, flow can occur both up the tubing and annular space between the tubing and casing (J van Besouw, 2019, personal communication, 26 February).

In BC, venting of gas at the surface casing annulus is a required regulation to prevent excessive pressure at the surface casing shoe. The surface casing must be equipped with an open valve (BC Oil & Gas Commission, 2010). Venting must occur in a controlled manner where the quantity and duration of venting is minimized. Checks for SCVF of a well must be made (a) after the initial completion of a well or re-completion, (b) within a year of a rig release, (c) during routine maintenance checks throughout the life of the well, (d) before suspension, (e) before abandonment, and f) before applying for a transfer of the well permit (BC Oil & Gas Commission, 2010). Although there appears to be frequent checks of SCVF, the lifetime of a well can be 20-40 years so checks will only get made during routine maintenance.
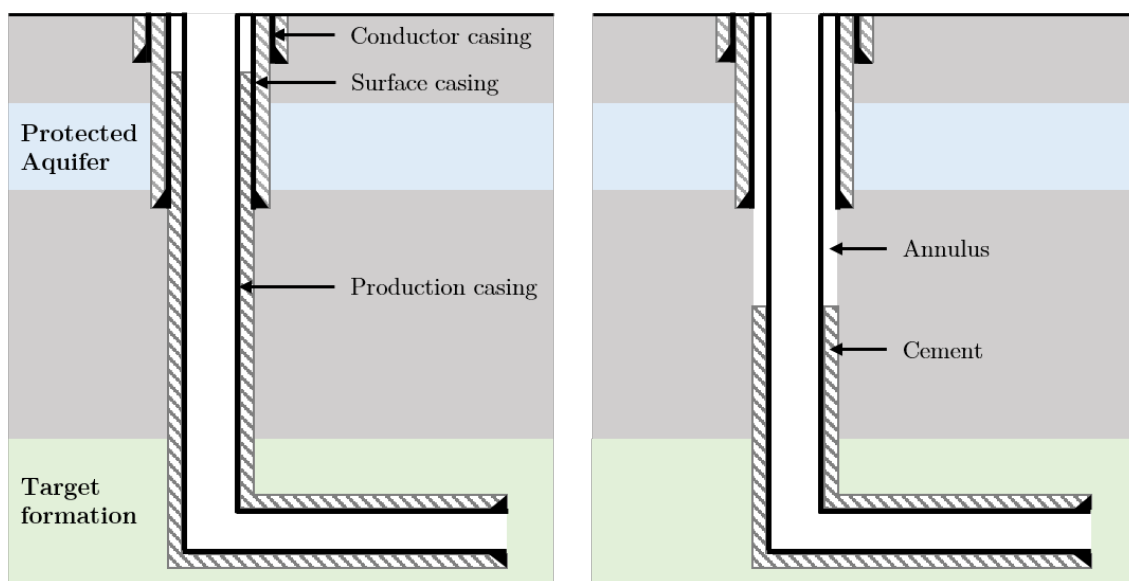
FIGURE 4.8: Diagram of two typical horizontal wells in BC, Canada with alternative construction of cement. The left construction could have shallower surface casing which does not reach the bottom of the aquifer but with the same height of production cement, or higher.

4.2   UNITED KINGDOM

Hydraulic fracturing and shale gas production is still in its infancy in the UK. The availability of shale gas is still being explored with a small number of wells drilled in the Bowland shale for testing but full multi-stage hydraulic fracturing is yet to begin (Harvey et al., 2016). Environmental effects of hydraulic fracturing are still unknown, with the majority of assumptions being taken from the experiences of North America (Andersson-Hudson et al., 2019). Therefore to gauge a better understanding of environmental issues in advance of a potential shale gas industry, extensive and focused data must be collected for application to a variety of methods and models to assess environmental risk.

Over the last decade, the UK has been undergoing assessments on shale gas resource availability across the country (Selley, 2012; Loveless et al., 2018a). Shale formation areas within the UK have been tested for resource estimations by the British Geological Survey (BGS). The Carboniferous Bowland Shale estimates 23.3-64.6 tcm of gas (Andrews, 2013), the Jurassic Shale in the Weald basin estimates 293-1,143 million tonnes of oil (Andrews, 2014), the Jurassic Shale in the Wessex area estimates 32-378 million tonnes of oil (Greenhalgh, 2016) and the Carboniferous Shale of the Midland Valley of Scotland estimates 1.4-3.81 tcm of gas and 421-1,497 million tonnes of oil (Monaghan, 2014). The Carboniferous Bowland Shale has the highest amount of available gas and according to the US experience, has an estimated 10-20% recoverable rates (UKOOG, 2019).

Reported by Andrews (2013), Andrews (2014), and DECC (2013), the main rock formations with the potential for shale gas as a source are the Kimmeridge clay formation, Oxford clay formation, Lias group, Marros group, Bowland Shale formation and upper Cambrian Shale (Figure 4.9). Cuadrilla are the only operator with permission to conduct exploratory hydraulic fracturing in England and Wales with Scotland still under a moratorium from hydraulic fracturing due to environmental concerns and climate change expectations (BBC News, 2019a). Despite the 2,500 conventional onshore oil and gas wells present in the UK owned by many different operators ($\sim$250 currently operating), the only hydraulically fractured wells being used for gas exploration and research developments are those developed by Cuadrilla where licenses and permits have been granted by the regulators. This means in comparison with Canada and the US, the UK has very little field data to develop suitable models to further understanding of the potential environmental impacts and economic viability of shale gas.

Cuadrilla have been granted licenses by the Oil and Gas Authority (OGA) for onshore oil and gas exploration at specific sites in England. These areas have been mapped out in Figure 4.10 with current focuses on the south of England, Yorkshire and Lancashire (Table 4.2) (Cuadrilla Bowland Limited, 2019a). Little development has progressed in most of the prospective shale areas (Table 4.2) with the exception of Lancashire where several

unconventional wells have been drilled and two are currently under exploration at the Preston New Road site (Table 4.3).

According to information detailed in Table 4.2, a substantial number of wells have been decommissioned and the site restored and in areas such as Yorkshire, the focus has still been on desktop studies of the surrounding area instead of drilling and exploration. The only wells producing data to further understand the potential for shale gas exploitation are at the Preston New Road site in Lancashire. Two wells have been drilled at this site although various seismic events have slowed down the operational process (Table 4.3) and most of the data produced from the wells is still confidential or not yet released.

Due to only two currently operational wells in the UK at the same site, the model application to the UK (where possible) must be related to the Bowland Shale formation which is being exploited at Preston New Road.
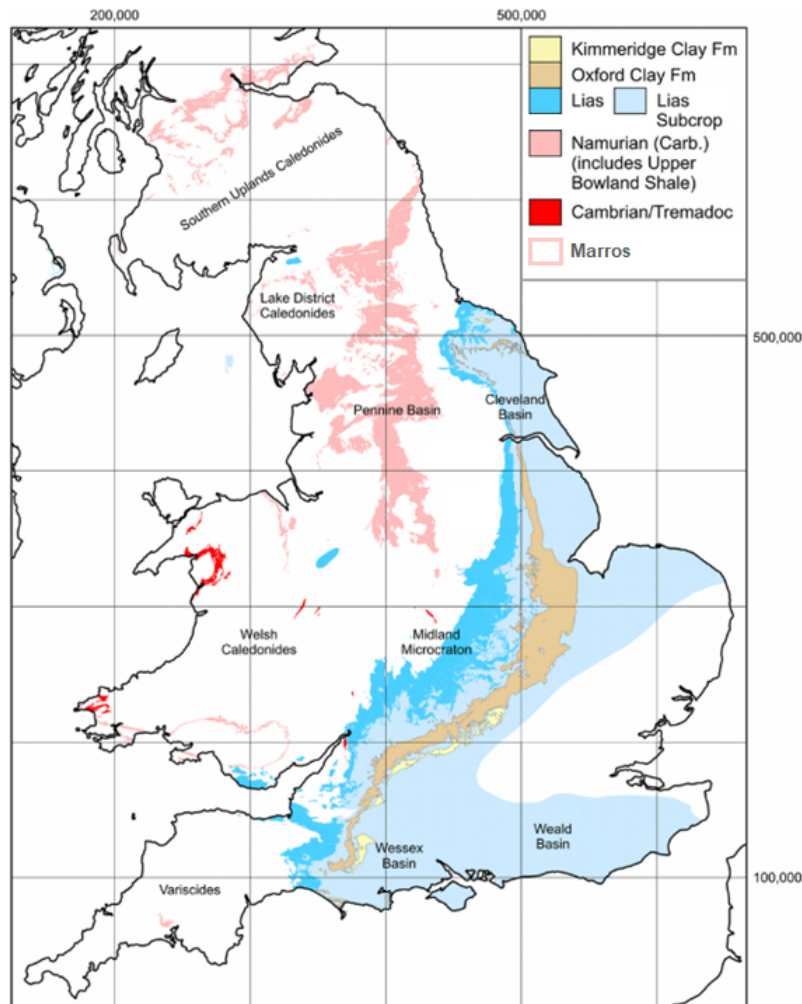
FIGURE 4.9: Major shale formations at outcrop in England, Wales and Scotland. Adapted from Harvey et al. (2016).
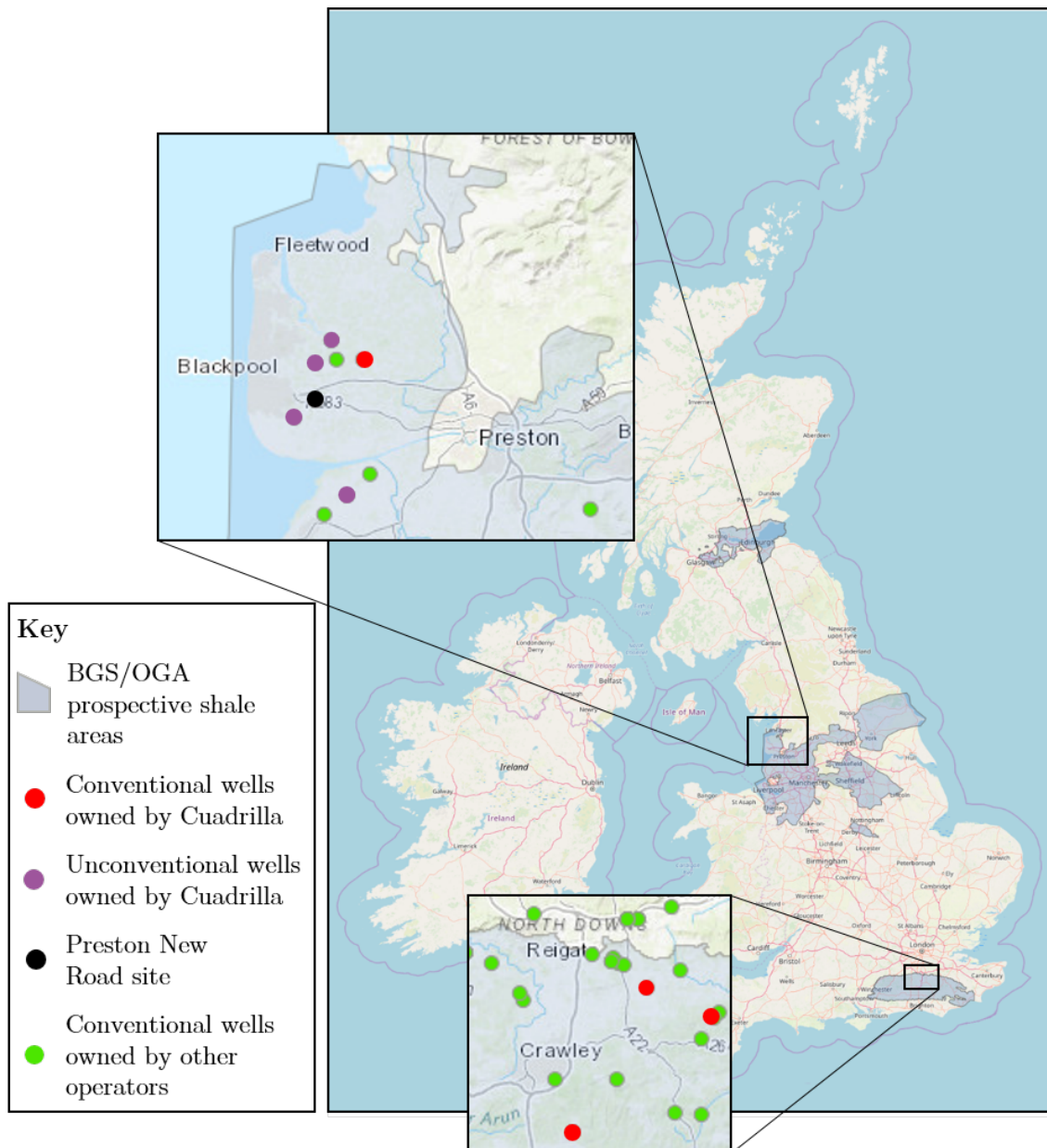
FIGURE 4.10: Prospective shale areas in the UK mapped out by the BGS and OGA with areas in Lancashire and the south focused on the location of energy wells owned by Cuadrilla. Preston New Road is the only current operational shale gas exploration site. The conventional wells owned by other operators are some of the UK's 2,500 onshore wells.

TABLE 4.2: Current status of the well exploration sites owned by Cuadrilla for the development of the onshore oil and gas industry in the UK (Cuadrilla Bowland Limited, 2019a).

Area	Site	Well type	Current operation
South	Balcombe	Conv.	• Horizontal well drilled and completed in 2013 but target rock was limestone so no hydraulic fracturing required. • 7 day flow test conducted on the well in 2018.
	Cowden	Conv.	• Well drilled in 1999 and now owned by Cuadrilla but after initial evaluation in 2010, no further work is intended.
	Lingfield	Conv.	• No work has been carried out since ownership of the land.
Yorkshire	-	-	• No wells but 18 exploration licenses available. • Current work just focuses on desktop studies to understand the geology within the licensed locations.
Lancashire	Becconsall	Unconv.	• Exploration well drilled in 2011. • Planned to pressure test the gas but could not complete within the required time frame of the planning consent. • Decommissioned and plugged the well and restored the site by the end of 2018.
	Clifton	Unconv.	• No plans
	Elswick	Conv.	• Vertical production well which was hydraulically fractured in Sandstone in 1993 but now reaching the end of its producing life.
	Preston New Road	Unconv.	• Two exploration wells currently in operation (see Table 4.3 for more information).
	Roseacre Wood	-	• Planning application in 2014 submitted to drill but denied. • After several appeals, by 2019 a final refusal for Roseacre development meant Cuadrilla did not appeal the decision so no further developments.
	Singleton (Grange Hill)	Unconv.	• Well was drilled in 2011 but no hydraulic fracturing or gas testing. • Decommissioned and restored by mid 2018.
	Weeton (Presse Hall)	Unconv.	• Vertical well drilled in 2010 to test flow rate. • Seismic events in 2011 halted the process and well was plugged and cemented by 2015.
	Westby	Unconv.	• Well drilled at 600 m depth in 2012. • Suspended due to drilling tool stuck in the borehole. • Too much time taken so well was plugged and restored by mid 2014.

Conv.: Conventional
Unconv.: Unconventional

TABLE 4.3: Recent timeline during 2019 to the present of the only two exploratory hydraulic fracturing well operations in the UK at Preston New Road, Lancashire, operated by Cuadrilla (Cuadrilla Bowland Limited, 2019a).

Date	Well operating status
06/02/2019	• First horizontal hydraulic fracturing well drilled. • Drilled down < 2286 m. • Initial flow test results conducted. • Well shut in and monitored to assess gas production.
11/07/2019	• Confirmation of further flow tests and to complete work programme by November 2019.
16/07/2019	• Hydraulic fracturing remobilised and further flow tests.
15/08/2019	• Confirmation of required permits and permissions to fracture up to 45 stages on the second horizontal well at Preston. • Gas flow results from formation expected early 2020.
21/08/2019	• Microseismic event above 0.5 ML threshold so operations suspended. • Well integrity verified and well monitored over 18 hours.
24/08/2019	• Microseismic event above threshold with no impact on well integrity or surrounding environment.
26/08/2019	• Microseismic event above threshold but not during any hydraulic fracturing activities. • Hydraulic fracturing operations remain suspended. • Requirements of technical reviews by Cuadrilla and regulators.

4.2.1   Bowland Shale formation

The BGS conducted assessments of shale gas resources across the UK and in 2013, focused on the geology and resource estimation of the Carboniferous Bowland-Hodder Shale gas play (known as the Bowland Shale in this report) (Andrews, 2013). The upper and lower Bowland Shale covers central Britain (Figure 4.11) and has an organic content of 1-3% but can reach up to 8%, a resource able to produce similar to that of the Marcellus and Barnett shales of North America (Andrews, 2013). To date, only two onshore shale gas wells have been drilled and are currently operating in the UK (between seismicity issues; see Table 4.3) and these are at the Preston New Road site in Lancashire, the target formation being the Bowland Shale. Other shale formations in the UK have not been tested in the way the Bowland Shale has and has therefore been the chosen study area to focus on for this case study application (UKOOG, 2019).

Carboniferous shales are present across a large part of central Britain, spanning from Merseyside to Humberside and Loughborough to Pickering. The Bowland Shale study area has prospective units at outcrop to the south (Figure 4.9) and contemporary deltaic
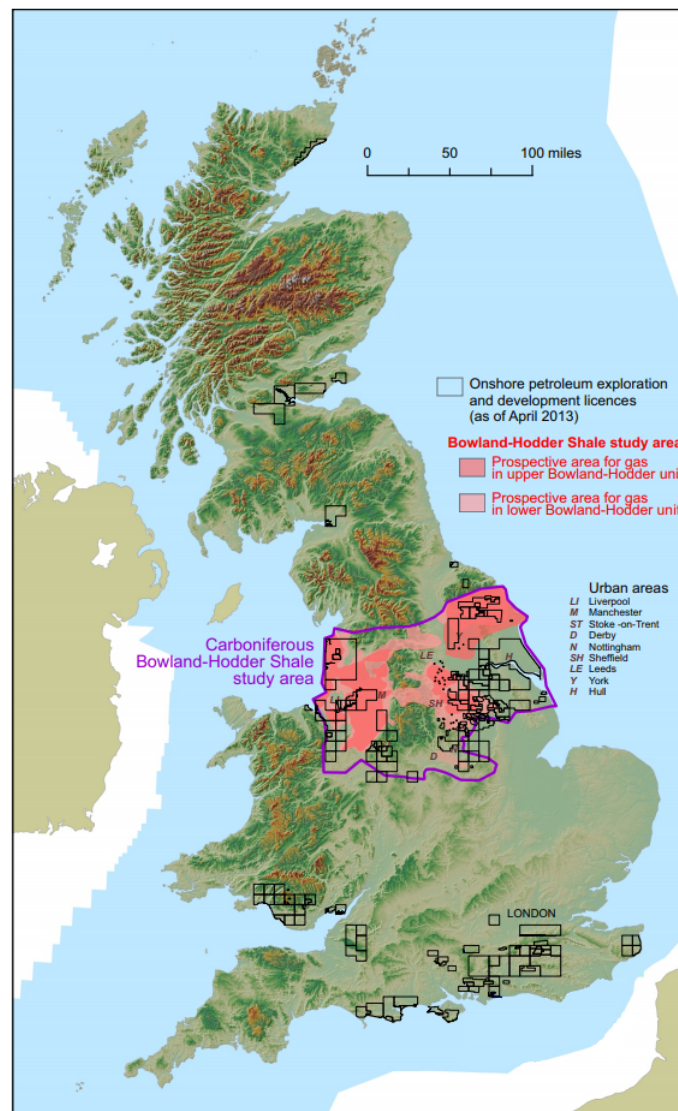
FIGURE 4.11: Carboniferous Bowland-Hodder Shale study area in the UK assessed by BGS as a prospective area for shale gas development (Andrews, 2013).

deposits[1] in the north and north-east (Andrews, 2013). The Bowland-Hodder shales are thickest in the Bowland, Blacon, Gainsborough, Widermpool, Edale and Cleveland basins with sufficient mature organic matter to produce oil and gas (Harvey et al., 2016). There are 64 conventional wells which have penetrated the Bowland-Hodder Shale with many of them in the Upper Bowland-Hodder units. Figure 4.12 is the stratigraphy of the Bowland basin which is an estimation of the subsurface geology where Preston New Road wells are drilled. Conventional wells at Thistleton and Hesketh and unconventional wells at Preese Hall indicate similar geology and are located within the same area as the Preston New Road site (Harvey et al., 2016; Fauchille et al., 2017).

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[1]Deposits of river drift in seas and lakes at the mouth of rivers; accumulation over time forms deltas.
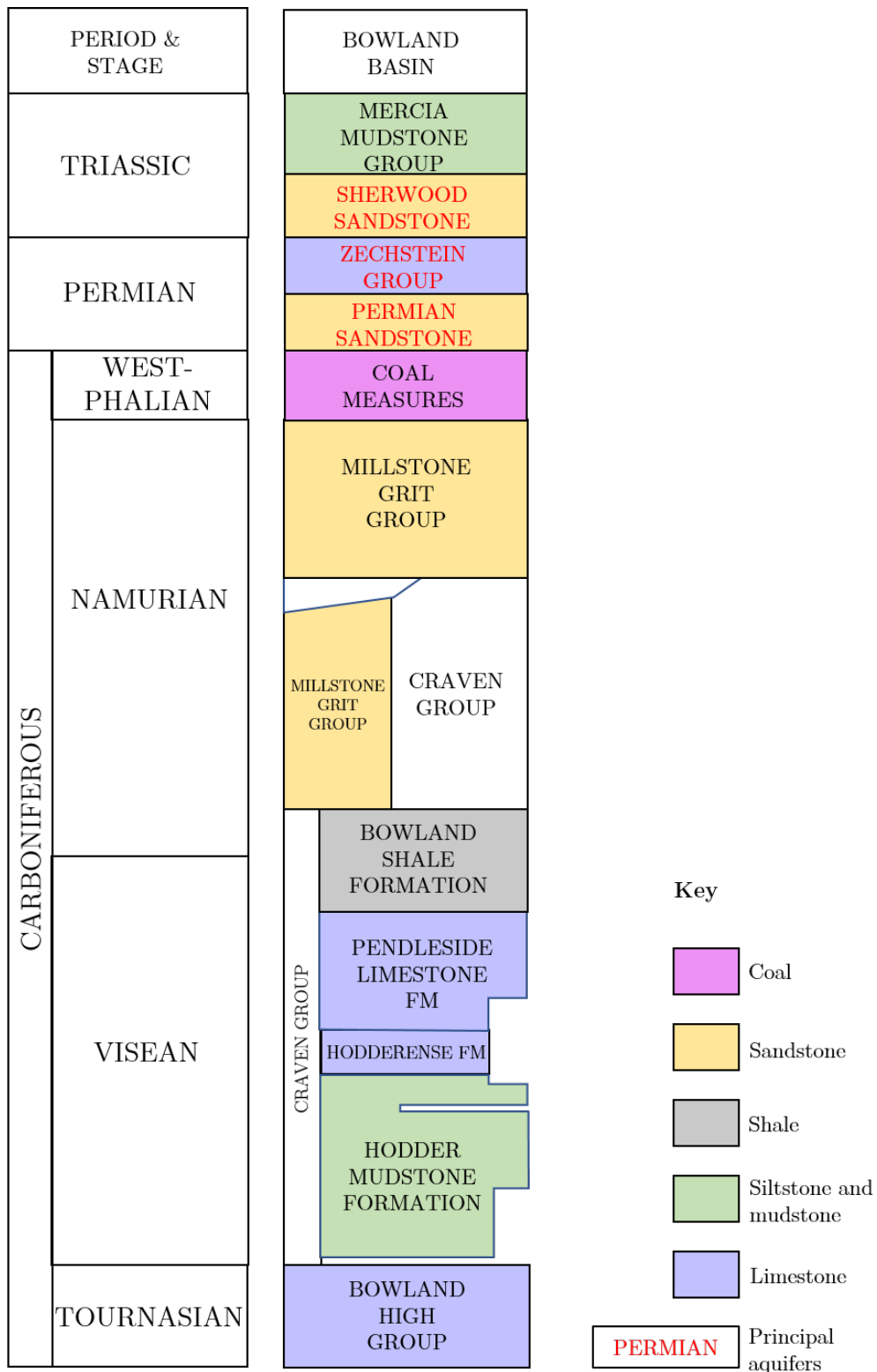
FIGURE 4.12: Stratigraphic column of the Bowland basin in the UK, the region of interest. Formations in red are principal aquifers overlying the Bowland Shale identified by Loveless et al. (2018a).

4.2.2 Groundwater in the UK

Groundwater is a vital source in the UK with an average of 31% used for water resources and up to 100% being used in some areas of the southeast (Loveless et al., 2018a). Principal aquifers provide most of the potable groundwater across England and Wales (Loveless et al., 2018a) and are defined by the Environment Agency (2017a) as 'layers of rock with high permeability and usually provide a high level of water storage. They may support water supply and/or river base flow on a strategic scale'. With the potential for an onshore shale industry in the UK, the much needed groundwater resources must be protected, particularly those areas where aquifers overlie targeted shale formations (Figure 4.13).
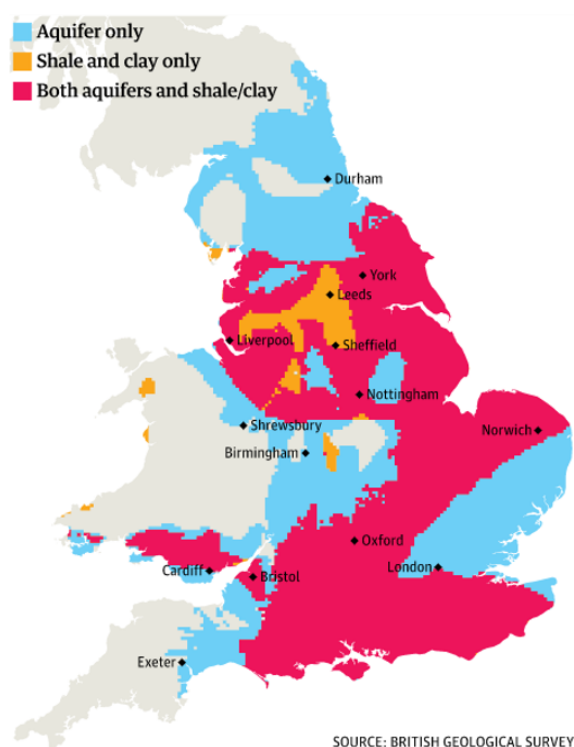
FIGURE 4.13: Map of the UK indicating a large proportion of the shale areas with overlying aquifers.

According to Loveless et al. (2018a), 25 areas in the UK contain principal aquifers which overlie shale gas units as illustrated by the red boxes in Figure 4.14. The aquifer and shale positions in the UK have more complex structural settings compared to the US (Ward et al., 2015) so with complex geological environments, knowledge of aquifer and shale locations are vital for environmental protection (Loveless et al., 2018a).

The Bowland Shale formation underlies 8 principal aquifers (Figure 4.14) with almost all being at least 1000 m above the top of the shale formation. Within the Lancashire region, the Triassic sandstone aquifer is between 800-1600 m above the Bowland Shale in some areas (Loveless et al., 2018b).

Principal Aquifers \ Shale-gas source rock (younger → older)	Kimmeridge Clay Formation	Oxford Clay Formation	Lias Group	Marros Group	Bowland Shale Formation	Upper Cambrian shales
Crag Group	Red	Red	Red	Green	Green	Green
Chalk Group	Red	Red	Red	Green	Red	Green
Lower Greensand Group	Red	Red	Red	Green	Red	Green
Spilsby Sandstone Formation	Red	Red	Red	Green	Red	Green
Corallian Group	Blue	Red	Red	Green	Red	Green
Great and Inferior Oolite Groups	Blue	Blue	Red	Green	Red	Green
Triassic sandstones	Blue	Blue	Blue	Red	Red	Red
Zechstein Group	Blue	Blue	Blue	Green	Red	Green
Permian sandstone	Blue	Blue	Blue	Green	Red	Green
Carboniferous limestone	Blue	Blue	Blue	Blue	Blue	Green
Border Group (Fell Sandstone Formation)	Green	Green	Green	Green	Green	Green

Legend:
- Red: Principal Aquifer overlies shale-gas source rock
- Blue: Shale-gas source rock overlies Principal Aquifer
- Green: No overlap between Principal Aquifer and shale gas source rock

FIGURE 4.14: Matrix of the main shale groups within the UK and the principal aquifers within the geological strata of the shale rock (Loveless et al., 2018a). The focus formation, Bowland Shale, in this case study has been highlighted.

4.2.2.1 Groundwater in Lancashire

Currently, the focus of the UK shale industry is in Lancashire targeting the Bowland Shale. Figure 4.15 indicates groundwater vulnerability of England with a focus on Lancashire to determine the hydrogeology surrounding certain onshore wells. Although not indicated on this map, the bedrock[2] aquifer underneath these wells is classified as a secondary B aquifer and the superficial drift[3] aquifer as a secondary A or B aquifer. Secondary A aquifers are permeable strata capable of supporting water supplies at a local scale and can form an important source of base flow for rivers. Secondary B aquifers are lower permeability which can store and yield limited groundwater due to localised features

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[2]Solid, permeable formations e.g. sandstone, chalk and limestone.
[3]Permeable, unconsolidated (loose) deposits e.g. sands and gravels.

(Environment Agency, 2019a). The aquifers within this area are not as vital compared to principal aquifers in other parts of the UK, but still require sufficient protection.

The groundwater vulnerability is intermediate within the inland area of the onshore wells and in particular, Preston New Road site. However, underneath the Hesketh well in the south of Lancashire lies a highly vulnerable principal aquifer (Figure 4.15). As defined by British Geological Survey (2019), high vulnerability areas are able to easily transmit pollution to groundwater, intermediate vulnerability areas offer some groundwater protection and low vulnerability areas provide the greatest protection.

As with the Canadian case study, the depth of the water level is required to determine the potentiometric head of an aquifer above a desired depth for calculating surrounding formation pressures. The careful monitoring and water requirements by regulators ensures significant water wells are drilled and data is produced on the depths of these wells and the static water level. The only exploratory wells to date are operating at Preston New Road and therefore water depths have been selected at this location (Table 4.4).

TABLE 4.4: Available data from groundwater wells at the Preston New Road site.

Water well reference	Well depth (m)	Aquifer	Static water level depth (m)
SD33/62	33	Superficial deposits	1) 5.5 2) 8.3
SD33/63	30	Superficial deposits	1) 6.0 2) 7.0
SD33/64	26.6	Superficial deposits	1) 7.0 2) 11.8
SD33/65	25.8	Superficial deposits	16.5

Where there are two static water level depths, the average across both will be taken.

4.2.3 Drilling regulations

As the UK shale gas industry is still in its infancy, very few horizontal hydraulically fractured wells have been drilled so regulations will aim to follow good practise guidelines, where possible. Requirements for casing installation are defined by the Department of Energy and Climate Change (DECC) and the Health and Safety Executive (HSE) but the extent to which compliance protects groundwater is assessed on a case-by-case basis by the Environment Agency (Fretwell et al., 2012).

Good casing and cementing practises are mainly focused on protecting groundwater resources so groundwater activity permits must be granted by the Environment Agency if
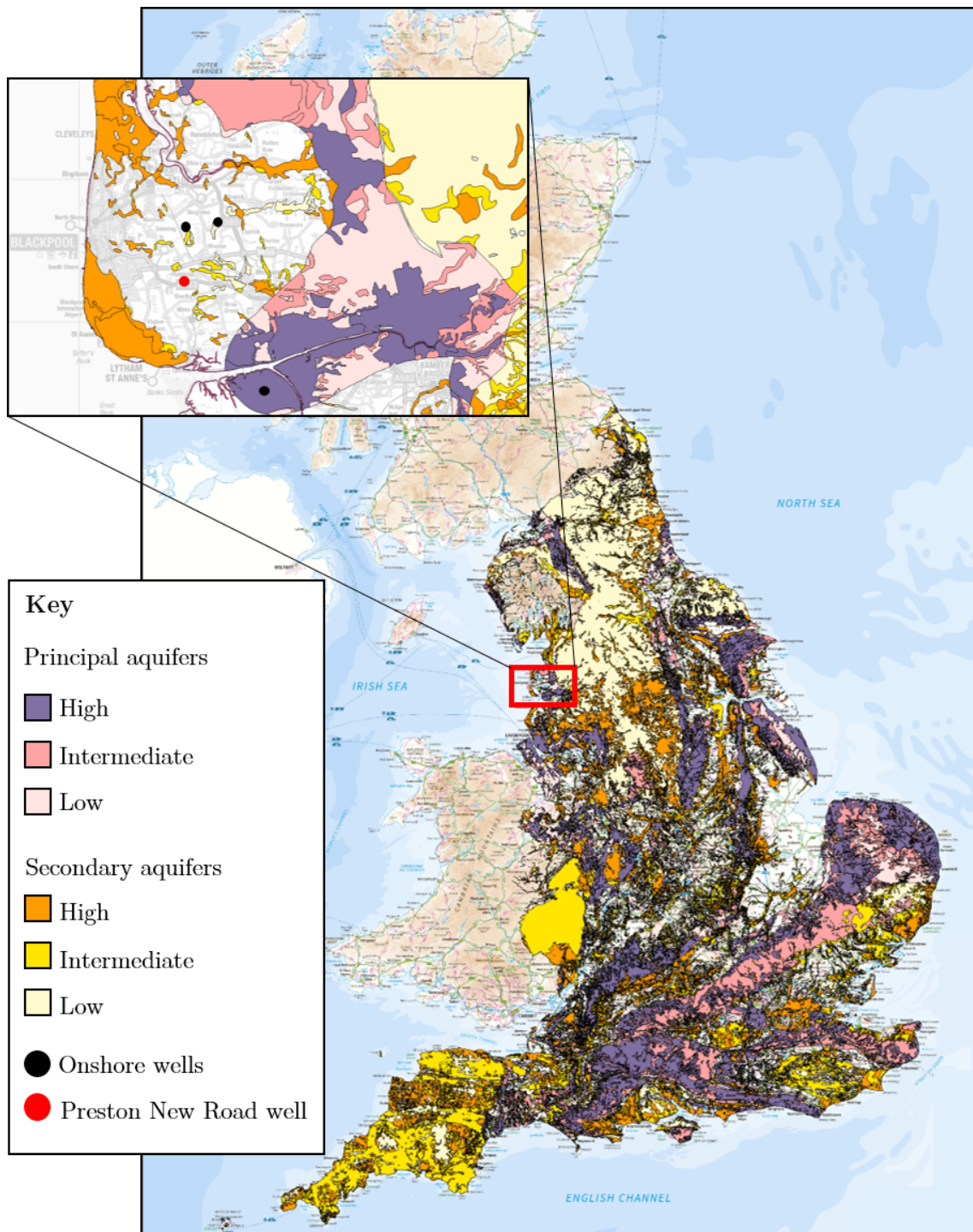
FIGURE 4.15: The vulnerability of groundwater principal and secondary aquifers in England. Hesketh, Thistleton, Preese Hall and Preston New Road onshore wells are indicated to demonstrate the surrounding aquifer vulnerability.

hydraulic fracturing is to occur where there is a risk that pollutants might enter groundwater as a result of the injection procedure of fracturing fluids (Environment Agency, 2019b). In addition, oil and gas drilling is not permitted in Source Protection Zone 1 (SPZ1)

including where aquifers are at the surface and where they are confined. The minimum depth of hydraulic fracturing is 1000 m below the surface and 1200 m below the surface if permitted in an SPZ1 zone (Fretwell et al., 2012; Environment Agency, 2019b).

Regulations for drilling are based off a number of sources such as offshore installations and well designs, HSE guidance, API guidance and experience from other countries such as the US and Canada (Fretwell et al., 2012). The UK aims to construct wells following good practise guidelines, dependent upon the geology and hydrogeology of each individual location. Casings and cement must be installed to ensure all hydrocarbon-bearing formations are isolated from the surface and surface casings must reach a depth which is well below the groundwater body, regardless of other casing string placement. The UK aim to install four casing strings where the conductor and surface casing should be cemented to the surface and the intermediate and production casing should be cemented back to the previous casing shoe or back to the surface for shallow casings (Figure 4.16). Production tubing is recommended particularly as the well completions require at least two barriers to flow between the reservoir and surface, ideally a tubing and packer.
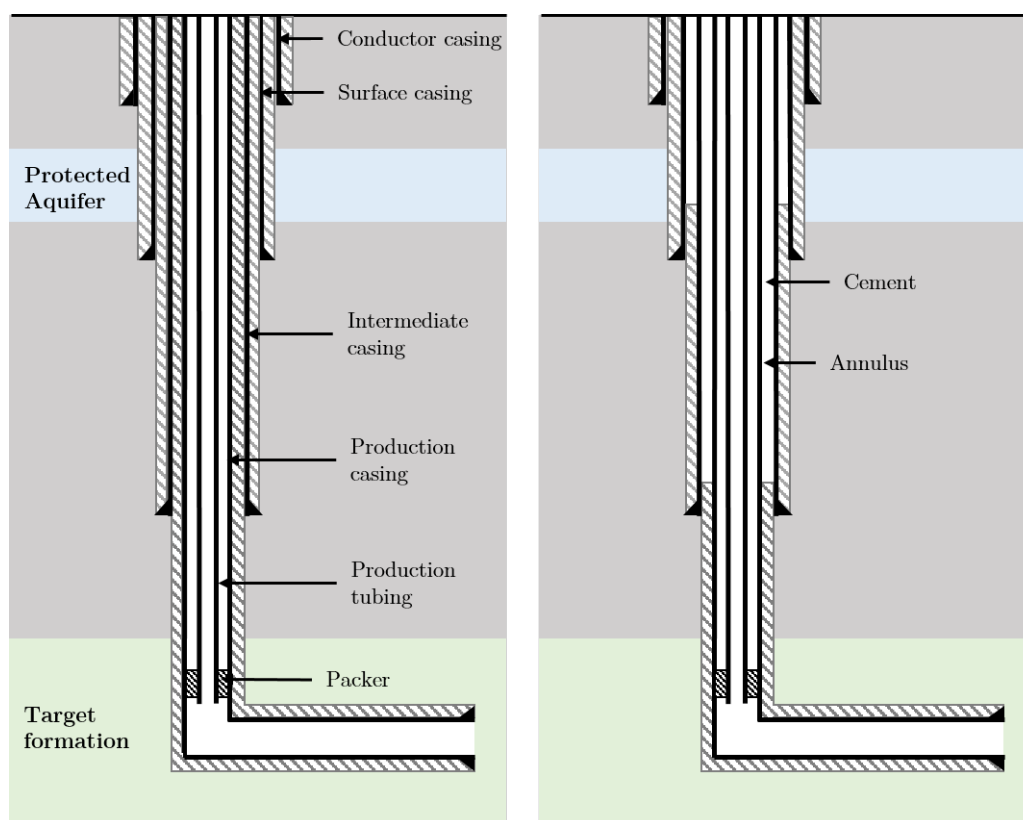
FIGURE 4.16: Diagram of two suggested constructions of horizontal hydraulically fractured wells in England with alternative construction of cement. An intermediate cement and casing might not always be present, but regulations recommend it.

In the UK, it is still not clear whether venting of gas at the wellhead will occur to reduce the potential for groundwater contamination or if the emissions do not follow the climate

change agreement and therefore will be kept closed. It is clear the wellhead aims to be closely monitored but it has been suggested the valve will be kept closed for UK onshore wells (D Llewelyn, 2019, personal communication, 26 February).

4.3 CONCLUSION

Two case studies were chosen for this research to demonstrate application to a real situation. BC in Canada was chosen for model development, using the Montney as the target formation and wells in Lancashire in the UK were chosen for model application, using the Bowland shale as the target formation.

Canada has a substantial onshore shale gas history and the BCOGC keep extensive records of their onshore hydraulically fractured wells, some of which can be found in their public online database sourced from here: https://www.bcogc.ca/online-services. The data used mainly for model development for a production well consisted of well construction information, gas migration data for those tested and target reservoir data. This was successfully supported with a collaborative engagement at UBC in Vancouver, Canada. The most active shale gas formation in Canada is the Montney formation with the majority of wells in the BCOGC database within this formation. Geological information surrounding the Montney formation was extracted to understand the implication of hydraulic fracturing on the hydrogeology of the area.

The UK has been chosen to demonstrate the suitability of the model for a site which has very high uncertainty for its risks to groundwater due to its infancy. Over the past decade, different sites in the UK have been selected for potential unconventional exploration by Cuadrilla, but most have been abandoned following appeals or unsuccessful exploitation. The exploration wells in operation are based in Lancashire and target the Bowland Shale formation and therefore groundwater and drilling data have been used from the UK on these specific wells.

Information on the groundwater surrounding the chosen wells in Canada and the UK was extracted for model development and application to determine the potentiometric head of the aquifers drilled through during hydraulic fracturing. In addition, the construction of the wells is essential for understanding the potential of well integrity failure and was therefore determined from drilling regulation documents in both the UK and Canada.

Both sites presented enough data and knowledge to allow suitable model development and application to a risk assessment framework focusing on groundwater contamination from hydraulic fracturing during injection and production stages of a well.

CHAPTER 5

RISK ASSESSMENT FOR WELL INTEGRITY FAILURE DURING INJECTION

5.1 INTRODUCTION

Targeting unconventional resources involves drilling deep wells into the target formation and, in the case of horizontal drilling, travelling casing along the formation. Fluids are injected down the well at very high pressures to hydraulically fracture the target formation and increase permeability for hydrocarbons to flow. Upon release of these pressures, the hydrocarbons travel back up the well over periods of time, known as production. Well injection, or well stimulation, has been identified as a well development activity linked to the potential for loss of containment leading to gas migration (Long et al., 2015b).

The loss of well containment is a concern for drillers and engineers. Catastrophic barrier failures for onshore wells lead to environmental incidences such as gas or fluid migration to the surface, intersecting and contaminating groundwater aquifers. Well integrity failure can occur across different phases of an onshore wells life, from the exploratory drilling phase up to the final stage of abandonment. Across these different stages, several barriers exist to prevent fluid and gas migration to external surroundings, such as casings, cement, hydrostatic pressures and geological formation pressures. Barrier failure can be any one of these failing, but a catastrophic event requires all the barriers failing leading to a contamination pathway.

Well stimulation is the phase after a well has been drilled when the well is injected with high pressure fluids to fracture the target formation. This process in hydraulic fracturing is short-lived but requires extremely high pressures to travel the length of a deep well (several km's) and cause enough pressure to fracture highly impermeable shale rock. These pressures exert significant stress on the well casing and cement, although stress is reduced if conducted down the tubing rather than casing (Long et al., 2015b). This

increase in stress consequently increases the risk of barrier loss within the system and hence potential loss of well integrity. Analysis carried out by Vignes (2011) on offshore wells in Norway demonstrated 29% of injection wells had well barrier failures and a survey of onshore wells in the Netherlands showed three times as many injection wells demonstrated barrier problems compared to production wells (Davies et al., 2014). At the stimulation stage, pressures used during the process can theoretically lead to problems such as cement or casing deformation, gas migration or induced seismicity (Long et al., 2015b).

Each barrier has a likelihood of failure but this is often not well quantified within the onshore oil and gas industry, particularly with reference to hydraulically fractured wells. NORSOK D-010 standard for well integrity and operations was developed for offshore wells in Norway (NORSOK, 2004) to ensure well integrity was compliant. This is used to visualise barriers for the well across all stages of development but is not directly comparable to onshore regulations. Comprehensive risk analysis conducted on onshore hydraulically fractured wells is essential for reducing or preventing groundwater contamination.

This chapter develops a risk assessment for well stimulation, one of the high risk phases of an onshore hydraulically fractured well. A representative well drilled in British Columbia (BC), Canada and a hypothetical well using UK regulations are applied as case studies to support the risk assessment methodology. These two wells have different constructions to assess the potential variation in probability of failure during injection. A risk assessment for UK hydraulic fracturing is currently hypothetical as there exists very little onshore development and hence a significant lack of data. Therefore the methodology is developed using data from Canada, where there is substantial onshore development. The two locations are not directly comparable due to likely differences in drilling construction, which is accounted for by developing two scenarios (Chapter 3; scenarios 1 and 2).

Environmental risks are well-known in the onshore oil and gas industry, but a lack of numerical data means evaluating these risks using probabilistic techniques is a challenge. Fuzzy Set Theory (FST) is used in this research to develop risk assessments which might consist of numerical data, linguistic descriptors and expert opinions. Event Tree Analysis (ETA) and Fuzzy Fault Tree Analysis (FFTA) are adopted here to conduct a quantitative risk assessment on well integrity issues during well stimulation.

ETA is used to define the pathways for leakage to groundwater during well stimulation with an initiating event as the failure of a tubing, packer or production casing. The event tree branches are quantified with either numerical failure data or expert knowledge. Fuzzy applications to ETA and Fault Tree Analysis (FTA) allow for the variability in data representation. FFTA is used to quantify cement failure in onshore wells. Cement failure is complex and poorly defined with a significant lack of data during hydraulic fracturing. Applying fuzzy logic and FTA to the problem allows for quantifying the problem with expert opinions and linguistic descriptors. Probability of leaks to groundwater during

well stimulation is calculated under different scenarios and using probabilistic and fuzzy methodologies to compare the two techniques. By developing methods which can incorporate various data representations to complex topics such as hydraulic fracturing, more holistic risk assessments can be developed allowing analysis of components in the system which cannot be easily dealt with using classical probabilistic techniques.

5.2 FRAMEWORK

This chapter aims to explore the elements within the integrity of a well which could fail during high pressure injection and combines numerical analysis with fuzzy analysis for a more detailed assessment. The framework for the proposed methodology is indicated in Figure 5.1. There are three main components which form the risk assessment: (1) reviewing and analysing of literature and conceptual model development, (2) numerical quantification, and (3) fuzzy logic analysis. Model development involves constructing event trees and fault trees, numerical quantification is quantifying the trees where crisp values exist and fuzzy logic analysis deals with aspects of the model which lack probability values.

Literature is reviewed to build the conceptual models and develop the event trees and initiating events. Data was collected where possible and applied to the corresponding event tree branches. Where data is unavailable or there exists high uncertainty, fault trees are developed and analysed using expert judgement and the Similarity Aggregation Method (SAM). The fault trees and event trees are quantified and sensitivity analysis is conducted using different importance measures to determine the critical elements of the fault trees and event trees.

The risk assessment framework is developed using industry data and fuzzy methods with ETA and FTA. It is implemented using a new model which combines these techniques to assess the probability of groundwater contamination from well integrity failure during the injection stage of well. The model can be adapted for failures across different countries or constructions by applying a different set of experts for FTA quantification.

5.2.1 Conceptual models

A conceptual model is a requirement for understanding the Source-Pathway-Receptor (SPR) model for a groundwater contamination event. Further development into the pathways allows production of the event trees for determining the probability of successes and failures. Two conceptual models were developed to indicate the pathways for groundwater contamination under two different well construction scenarios during injection (Figure 5.2).
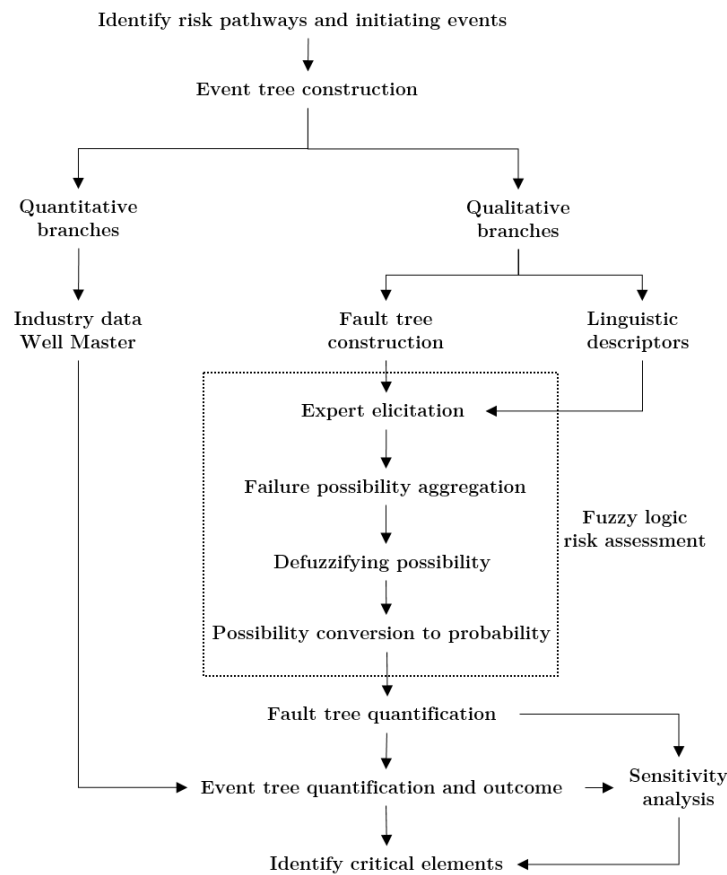
FIGURE 5.1: Framework methodology for constructing a risk analysis for a hydraulically fractured well during stimulation and injection.

Both of these models show two sets of casings (surface and production casing) and the production cement returning to the surface, presenting a fully closed annulus. The depths and heights of the casing and cement along with the number of casings vary significantly across states, provinces and countries due to differing regulations for well constructions (Dusseault and Jackson, 2014; Lackey et al., 2017). Additionally, construction priorities could be based on the age of the well, geological surroundings, economic constraints and a variety of engineering considerations. These two scenarios have been selected based on common protocol for BC (Figure 5.2a) and UK regulations (Figure 5.2b).

A main source of fugitive gas during well stimulation is from inside the wellbore to geological surroundings due to well integrity failure via preferential pathways. During injection, the wellbore has a much higher pressure than the surrounding formations suggesting leak pathways are much more likely to occur from inside to outside rather than from surrounding formations to inside the well. Well integrity failure leading to groundwater contamination is the primary concern in this chapter where well barrier failure is the failure of individual or multiple barriers eventually leading to integrity failure (Davies et al., 2014).
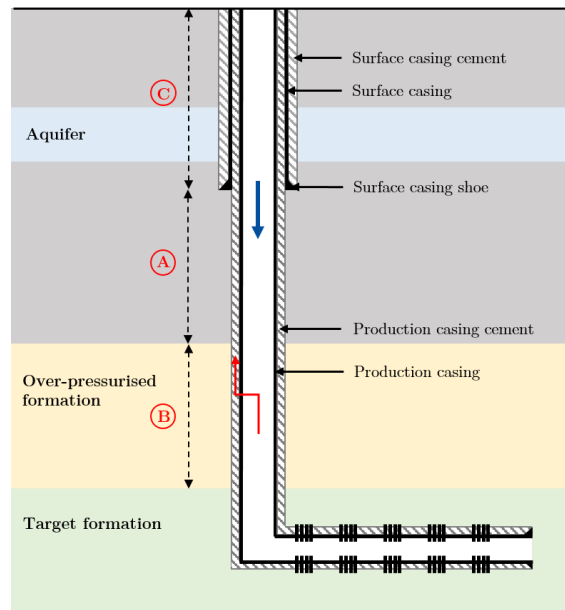
(A) Scenario 1: Well construction diagram where injection occurs down the production casing (Canada).
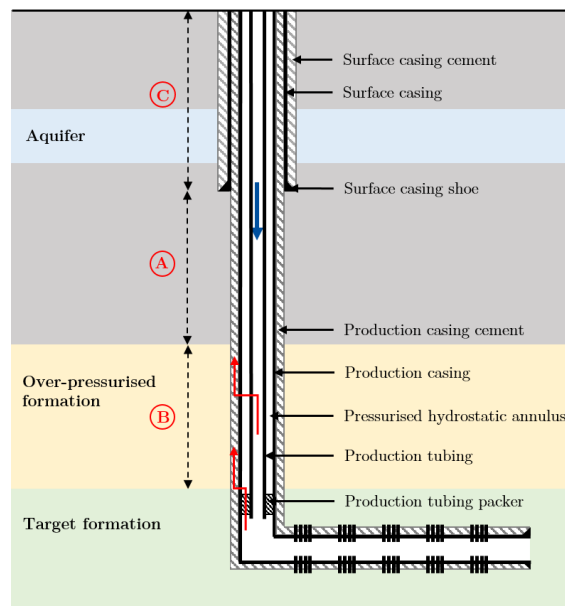
(B) Scenario 2: Well construction diagram where injection occurs down the production tubing and a packer is used to hold the tubing in place and create a pressurised annulus as an added barrier (UK).

FIGURE 5.2: Conceptual model diagrams of two different well constructions for a stimulated well indicating the pathways for groundwater contamination. The red arrows represent the movement of gas or fluids. The letters correspond to different geological zones which have an affect on the pathways of contamination; A) non gas-bearing, permeable formation, B) gas-bearing, over-pressurised formation, and C) high permeability aquifer zone. Further information on the geology is shown in Table 5.1.

In both scenarios, it has been assumed fluids and gases will only move where there is a pressure gradient from a region of high pressure (inside the wellbore) to a region of low pressure (surrounding formations). The high pressures used inside the wellbore could cause casing or tubing degradation, developing pathways for gas or fluid migration. The pressure gradient allows movement into pressurised annuli and/or cement and depending on the location of the leak (A, B or C), horizontal movement into surrounding formations.

The three geological zones A, B or C indicated in Figure 5.2 are implemented to distinguish between three different locations where a leak could occur to produce a different outcome. Geological zone A is considered a region of lower pressure, zone B a region of higher pressure and zone C a region of very low pressure where an aquifer is present. Table 5.1 exhibits the properties each of these zones might take.

TABLE 5.1: Typical geological zone descriptions which could be expected throughout the depth of a hydraulically fractured well.

Geological zone	Formation	Description
A	Normal pressurised formation	Mixed porosities and permeabilities. Rock type: e.g. sandstone/siltstone. Contains formation fluids e.g. saline water.
B	Over-pressurised formation	Tight porosity and low permeability. Gas present but unlikely economically viable. Highly pressurised due to gas and depth.
C	Groundwater zone	Very high permeability and high porosity aquifer zone. Rock type: e.g. limestone/sandstone. Potable or slightly brackish water for anthropogenic use.

5.2.1.1 Case study

Chapter 4 outlines the current hydraulic fracturing industry in Canada with a focus on BC as the main application for this work. In addition the UK industry, which is still new in its onshore development, is discussed to encourage learning from a mature industry and to apply this research to a country in its early stages of hydraulic fracturing. This chapter develops a fuzzy logic based risk assessment based on a well construction scenario used in most provinces in Canada (Figure 5.2a) and often used offshore in the UK industry and in some states in the US (Figure 5.2b).

As Figure 5.2a is a generalized construction of a Canadian well, the diagram was constructed from literature and discussions with industry collaborators in Canada in order to develop the event trees later discussed. However, various incidences of gas or fluid migration into groundwater or the atmosphere have been reported in the US and Canada over the last 50 years with significant variation in incidence rate (Jackson et al., 2013b; Bachu, 2017; Lackey et al., 2017). Therefore, a case study of a leaking onshore well from BC in Canada is demonstrated in this chapter to illustrate the application of this risk

assessment to a stimulated horizontally fractured well which has shown signs of gas migration (Figure 5.3). Gas migration has been reported to the regulator (BC Oil and Gas Commission, BCOGC) at this well based on field observations at the ground surface around the wellhead. However, the underlying cause(s) of gas migration at this well have not been investigated.
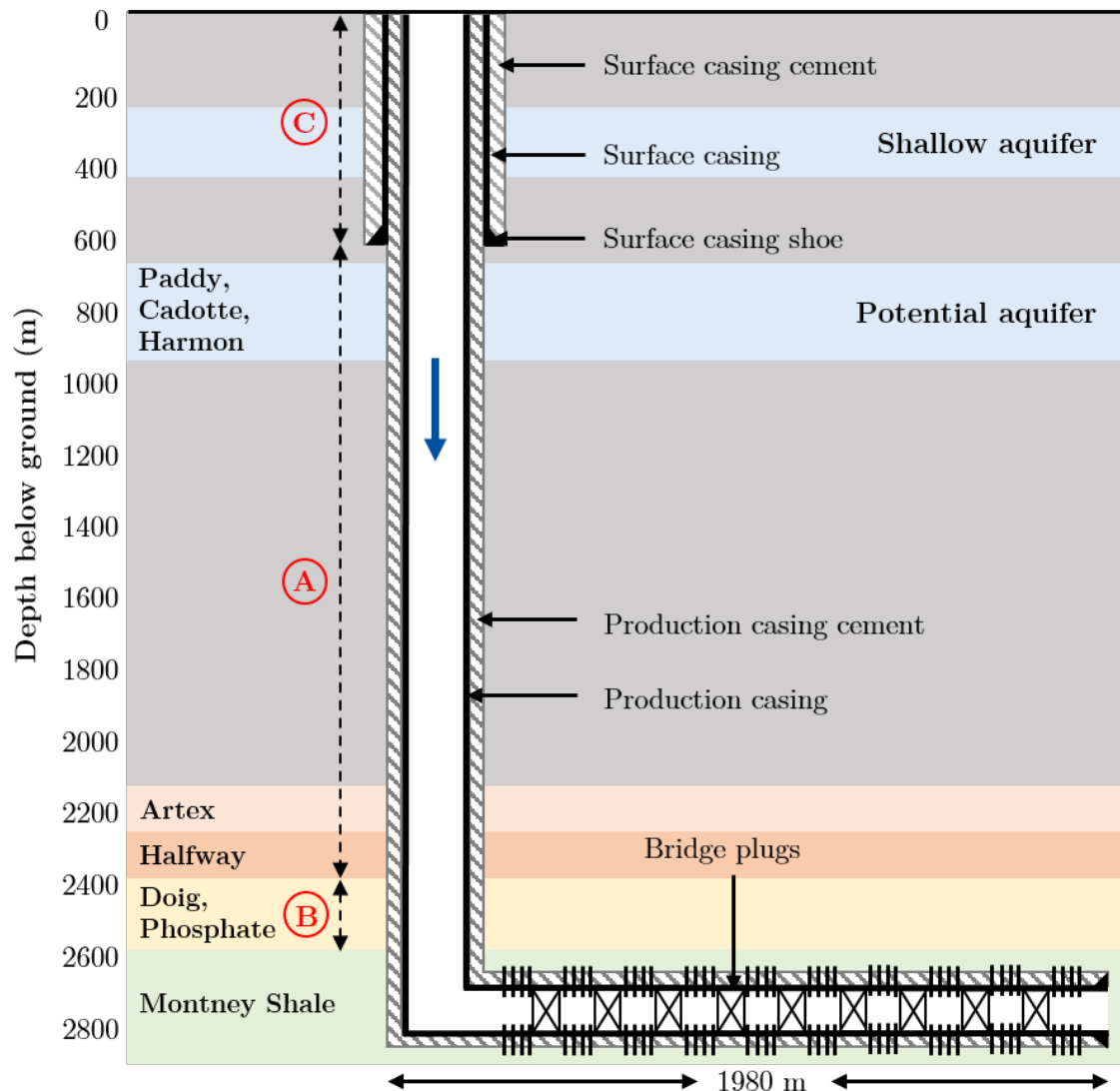
FIGURE 5.3: A hydraulically fractured well in BC, Canada which has evidence of gas migration at the surface. The Montney formation is being fractured and overlying the Montney is the Doig and Phosphate which are both secondary targets for gas production.

As part of quantifying the event tree branches, the method requires probability failures for well components, casings and cement as well as a conceptual model of the subsurface. Through the intersection of a well, the locations of aquifers and their depths are required, the potential pressures of the target reservoirs and the locations and depths of any over-pressurised formations.

The presence or characteristics of any aquifer system around or intersected by this well have not been confirmed but may still exist (Hickin et al., 2008; Cahill et al., 2019). This research focuses on shallow groundwater contamination and therefore a shallow aquifer is conceptualized within the confines of the surface casing and surface casing cement (Figure 5.2a, geological zone C). As the gas migration was recognised at the surface it is possible that migrating gas is passing through or into a conceptual shallow aquifer.

In terms of subsurface gas source zones, as well as the Montney formation, the Doig and Phosphate intersecting the well are considered secondary targets for gas production and will represent over-pressurised gas formations. Other formations intersecting the well, the Artex and Halfway, are sampled as containing gas but of fairly poor shows but could also represent an over-pressurised gas formation. Between the Artex and Harmon lie approximately 1000 m of various formations mainly consisting of sandstone, shale, siltstone and dolomite. These are taken as being mixed porosities and permeabilities with no gas shows but are inferred to contain formation fluids. This geological structure is common in sedimentology basins allowing for a more generic case study application.

5.3   METHODOLOGY

ETA and FFTA combine quantitative industry data and fuzzy data to calculate the potential for groundwater contamination if well integrity failure leads to gas or fluid migration at a given onshore well. Once event trees are developed from the conceptual models presented in Section 5.2, data are collected where possible and applied to the corresponding event tree branches. Where there exists high uncertainty or unavailable data, fault trees are developed and analysed using expert judgement and the SAM.

The methodology presented in this section briefly discusses the construction of event trees and fault trees including how they are quantified. The method for expert elicitation and definition of linguistic levels for FFTA is explained, and the SAM used to mathematically evaluate expert opinions is detailed, including the defuzzification process and turning results into failure probabilities. The section concludes with an explanation of the four importance measures used for sensitivity analysis required to determine the critical elements of the fault trees.

5.3.1   Event tree construction

Event trees are developed from the conceptual models drawn up based on two different scenarios of well construction, presented in Section 5.2. These scenarios were developed based on an extensive literature analysis and discussions with experts in North America and the UK and primarily enable suitable event tree construction, further shown in Section 5.4.

Individual analysis of each branch in the event tree is quantified using either existing failure probabilities or FFTA, if these probabilities do not exist. Failure probabilities are numerical crisp values whereas FFTA uses expert judgement to produce crisp values from linguistic descriptors. This is explained further in Section 5.3.3.

5.3.1.1 Probabilities of failure

Probability failures for components of a well are obtained from the WellMaster database which contains failure data for offshore oil and gas well components, or literature (Rish, 2005) (Table 5.2). These areas are consulted to identify which events can be quantified with raw data and which require further analysis.

Easily accessible databases that include specific attributes pertaining to probability failures of well components are limited to offshore wells, and similar data for onshore wells was not readily available through database searches. Therefore, it is assumed for this research the offshore cement probability failures are similar to onshore probability failures as well construction is very similar whether onshore or offshore (The Institute of Materials Minerals and Mining, 2016). Additionally, the components used in this work (packer, tubings and casings) will be almost identical. Event tree calculations can be easily updated for more accurate probability failures. Failure probabilities for well components can be calculated from the offshore well databases using equation 5.1 (Ramzali et al., 2015):

$$P\left(f\right) = 1 - e^{-\lambda t} \tag{5.1}$$

where $P\left(f\right)$ is the failure probability of one event, λ is the failure rate per year and t is the time of the experiment in years. When the value for $\lambda t < 0.1$, the failure probability is approximately equal to λt.

The offshore database uses reliability calculations to demonstrate an average failure rate (λ) and a Mean Time To Failure (MTTF) based on an exponential distribution (assuming constant failure rate) or a Weibull 2P distribution with the Maximum Likelihood Estimation (MLE) method. MTTF is calculated as the reciprocal of failure rate per year. Often, the two distributions give very similar survival probability shapes and in this research the exponential distribution is applied for finding the probability of failure of each required component at a certain time, t, as demonstrated in similar research methods (Ramzali et al., 2015). In this chapter, the value of t is determined to be four days (0.011 years). This is an average time with which well stimulation occurs for a hydraulically fractured well and hence the time the components of the well will be under such high pressures. The calculated values for the required components are illustrated in Table 5.2.

TABLE 5.2: Failure probability data for required well components.

Well component	MTTF (yr)	Average failure rate, λ (yr^{-1})	Experiment time, t (yr)	Failure probability $P(f) = \lambda t$	Reference
Production packer	1053.50	$9.49E^{-4}$	$1.10E^{-2}$	$1.04E^{-5}$	WellMaster
Tubing	272.88	$3.66E^{-3}$	$1.10E^{-2}$	$4.07E^{-5}$	WellMaster
Production casing	14.45	$6.92E^{-2}$	$1.10E^{-2}$	$7.59E^{-4}$	WellMaster
Surface casing	-	$*1.53E^{-3}$	$1.10E^{-2}$	$1.69E^{-5}$	Rish (2005)

$*$ Calculated using Poisson distribution; average day failure rate converted to average yearly failure rate.

5.3.2 Fault tree construction

Fault trees are constructed where probability failures are not possible to quantify particular event tree branches. In this research, fault trees are constructed for cement failure and pressure failure. The basic events are quantified using values determined from industry or literature. If the basic events cannot be evaluated numerically, expert judgement is used to determine failure probabilities. This approach uses fuzzy logic where linguistic descriptors are obtained from the experts and these are aggregated and evaluated using the SAM (Section 5.3.4).

5.3.2.1 Minimal cut sets

A fault tree consisting of 'OR' and 'AND' gates can be divided up by determining the minimum basic events which are required to obtain the top event. These are known as Minimal Cut-sets (MCS) and are identified for ease of calculating the top event (Chapter 3) and to understand the sections of the tree which have the smallest and largest influence on the top event. A MCS represents all the possible ways the top event can be calculated and is defined as the smallest contribution of basic events which will result in the top event (Ren et al., 2017). All of the failures in the cut-set must occur for the top event to occur. A more detailed understanding of MCSs can be found in Vesely et al. (1981). Using the probability of MCS failure the probability of the top event can be calculated using equation 5.2:

$$P(TE) = 1 - \prod_{i=1}^{m} [1 - P(MCS_i)] \tag{5.2}$$

where $P(MCS_i)$ is the probability of the failure of the MCS_i and m is the number of MCSs. This equation can be approximated when $P(MCS_i) << 1$ using equation 5.3:

$$P(TE) \approx \sum_{i=1}^{m} P(MCS_i) \tag{5.3}$$

5.3.3 Fuzzy fault tree analysis

Conventional FTA is a suitable method when basic events can be quantified using data. In many situations, data is not accessible and there often lies significant uncertainty even with events which can be quantified. FFTA can be used as an alternative to conventional analysis where expert judgement is used to determine the probabilities of the basic events. This process uses linguistic descriptors such as 'very low', 'low', 'medium' etc. to describe the failure occurrence of the basic events rather than a crisp numerical value, which has no flexibility in the decision.

The linguistic terms are defined based on the probability of occurrence over the lifetime of the well and are applied to each basic event by a collection of experts, independently. Appendices A and B includes the information and questionnaires distributed to experts to quantify the basic events using fuzzy analysis. Once the expert opinions have been given to each basic event, the SAM is used to aggregate these opinions and numerically evaluate the basic events (Section 5.3.4).

5.3.3.1 Linguistic probability levels

The decision to use fuzzy logic as a method for quantification is due to the subjective and uncertain nature of the fault trees developed in this research. Fuzzy logic requires the implementation of linguistic variables to a scenario where crisp values are too specific and quantifies these descriptors through fuzzy mathematical methods (Hsu and Chen, 1996).

The method used here converts the linguistic terms to a set of fuzzy membership functions which can include any number from two verbal terms (scale 1) up to thirteen verbal terms (scale 12) (Huang et al., 2001; Lavasani et al., 2015). Determining which scale is sensible for experts to use is based on human capacity to separate out an x number of variables into distinct groups e.g. 'very low', 'slightly low', 'low', 'slightly medium',... etc. Too many linguistic terms will make it hard for the experts to choose between certain groups and too few will produce inaccurate results. Nicolis and Tsuda (1985) suggested an appropriate number is somewhere between five and nine for optimal results. Yuhua and Datao (2005), Lavasani et al. (2011), Liu et al. (2013), Lavasani et al. (2015), Ramzali et al. (2015), and Shan et al. (2017) and Cheliyan and Bhattacharyya (2018) all used scale 6 with success for FFTA. Some researchers have used scales 8 and 12 (Huang et al., 2001; Chen and Fu, 2003; Hu et al., 2012; Bidder et al., 2014) but there are fewer documentations using this many linguistic terms and would not be suitable for this research.

This research uses scale 6, requiring five linguistic terms which are shown graphically in Figure 5.4. These linguistic terms and their corresponding fuzzy membership functions have been defined in Table 5.3. The fuzzy membership functions are a combination of triangular (L, M and H) and trapezoidal (VL, VH) functions. For the SAM approach, all

functions must be of the same shape and therefore the triangular membership functions are converted into trapezoidal functions. This means visually the function does not change but mathematically the function is written as a trapezoidal function. For 'Low' the function is (0.1, 0.25, 0.4) which visually presents a triangle as shown in Figure 5.4. However, by duplicating the middle value of this function at (0.25, 1), visually the shape is still a triangle but the mathematical function is now trapezoidal (0.1, 0.25, 0.25, 0.4). This is done with the 'Low', 'Medium' and 'High' functions as shown in Table 5.3.
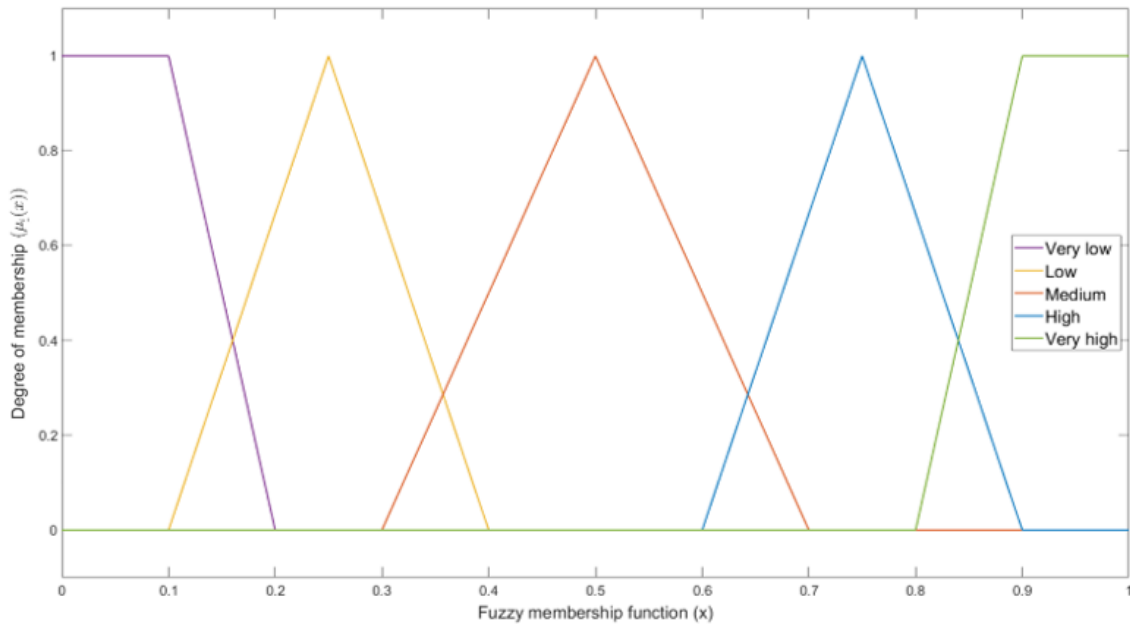
FIGURE 5.4: Fuzzy membership functions.

TABLE 5.3: Conversion of linguistic terms to scale 6 fuzzy membership functions

Linguistic terms	Fuzzy membership	Converted membership
Very low (VL)	$(0, 0, 0.1, 0.2)$	$(0, 0, 0.1, 0.2)$
Low (L)	$(0.1, 0.25, 0.4)$	$(0.1, 0.25, 0.25, 0.4)$
Medium (M)	$(0.3, 0.5, 0.7)$	$(0.3, 0.5, 0.5, 0.7)$
High (H)	$(0.6, 0.75, 0.9)$	$(0.6, 0.75, 0.75, 0.9)$
Very high (VH)	$(0.8, 0.9, 1, 1)$	$(0.8, 0.9, 1, 1)$

5.3.3.2 Expert elicitation

The opinions of experts using qualitative, linguistic information are employed to obtain information on the basic events of all three fault trees. A questionnaire with a set of instructions was developed for the experts and sent to those with the required skill set (Appendices A and B). Judgements given by experts will vary depending on their background and therefore a weighting system is used to account for these variations in decision-making. The weights have been calculated based on professional or academic

title, length of time in profession, education level and age and are indicated in Table 5.4. A challenge is choosing experts without any bias as their opinions will be based on their individual expectations or desires of the outcome (Lavasani et al., 2015). As the topic of onshore hydraulic fracturing is relatively niche and the understanding of changes in cement over time is even more specific, there was not a large pool of experts to choose from for the analysis. As some of the research was undertaken at the University of British Columbia (UBC), experts from this institution and connections within industry were chosen who felt comfortable in providing scientifically valid opinions.

TABLE 5.4: Weighting attributes for experts

Category	Classification	Weight
	Professor	5
	PostDoc	4
Professional or academic title	Graduate	3
	Engineer	2
	Technician	1
	≥ 30	5
	20-29	4
Service time (yrs)	10-19	3
	6-9	2
	≤ 5	1
	PhD	5
	Masters	4
Education level	Bachelors	3
	HND	2
	School level	1
	≥ 50	5
	40-49	4
Age (yrs)	30-39	3
	21-29	2
	<21	1

5.3.4 Similarity aggregation methodology

Expert judgements must be aggregated and converted into a quantifiable, possibility value. Aggregation is conducted using SAM which was developed by Hsu and Chen (1996) to combine fuzzy expert opinions and has been used in engineering research for fuzzy analysis (Lavasani et al., 2015; Ramzali et al., 2015). This process is described in detail below. There are six steps involved in the SAM approach (Hsu and Chen, 1996):

1. Calculate the degree of agreement, $S\left(\underline{A}, \underline{B}\right)$

   The similarity between expert opinions is calculated from the determined trapezoidal

fuzzy numbers of each opinion. Trapezoidal fuzzy numbers are defined as $\underset{\sim}{A} = (a_1, a_2, a_3, a_4)$, $\underset{\sim}{B} = (b_1, b_2, b_3, b_4)$ so the degree of similarity between these two fuzzy numbers can be determined using the similarity function (Zwick et al., 1987) defined in equation 5.4:

$$S\left(\underset{\sim}{A}, \underset{\sim}{B}\right) = 1 - \frac{1}{4} \sum_{i=1}^{4} |a_i - b_i| \tag{5.4}$$

where $S\left(\underset{\sim}{A}, \underset{\sim}{B}\right) \in [0, 1]$; the closer the similarity function is to 1, the more similar the expert opinions. From the degree of agreement, an agreement matrix (AM) can be constructed:

$$AM = \begin{bmatrix} 1 & S_{12} & \dots & S_{1k} & \dots & S_{1n} \\ \vdots & \vdots & & \vdots & \vdots & \vdots \\ S_{j1} & S_{j2} & \dots & S_{jk} & \dots & S_{in} \\ \vdots & \vdots & & \vdots & \vdots & \vdots \\ S_{n1} & S_{n2} & \dots & S_{nk} & \dots & 1 \end{bmatrix} \tag{5.5}$$

2. Calculate the average agreement, $A(E_j)$

   The variation in the similarity calculations between each expert is averaged out to calculate the average agreement of each expert, E_j $(j = 1, 2, ..., n)$ as shown in equation 5.6:

$$A(E_j) = \frac{1}{n-1} \sum_{\substack{k=1 \\ k \neq j}}^{n} S_{jk} \tag{5.6}$$

3. Calculate the relative degree of agreement, $RA\left(E_j\right)$

$$RA\left(E_j\right) = \frac{A\left(E_j\right)}{\sum_{j=1}^{n} A\left(E_j\right)} \tag{5.7}$$

4. Calculate the weights for each expert, w_j

   Each expert might have a variation in importance determined by factors such as their age, length of service or academic qualifications. Weightings, or degrees of importance, are calculated for each expert as shown in equation 5.8 to account for this:

$$w_j = \frac{r_j}{\sum_{j=1}^{n} r_j}, \ j = 1, 2, ..., n \tag{5.8}$$

where r_j is calculated as the sum of each individual experts score from each classification.

5. Calculate the consensus degree coefficient, $CDC\left(E_j\right)$

$$CDC\left(E_j\right) = \beta w_j + (1 - \beta) RA\left(E_j\right) \tag{5.9}$$

where β is a coefficient, or relaxation factor, to account for a difference in importance between expert weightings and relative degrees of agreement, $0 \leqslant \beta \leqslant 1$. If $\beta = 0$, i.e. the degree of importance of each expert is not considered, then $CDC\left(E_j\right) = RA\left(E_j\right)$. Where $\beta < 0.5$ the relative degree of agreement is more important than the expert weightings. Where $\beta > 0.5$ the relative degree of agreement is less important than the expert weightings. The decision maker assigns the value of β (Ramzali et al., 2015).

6. Aggregation of expert opinions, $\underset{\sim}{R}$

   Finally, the individual expert opinions are combined using equation 5.10:

$$\underset{\sim}{R} = \sum_{j=1}^{n} \left[CDC\left(E_j\right)\right] (\cdot) \underset{\sim}{R_j} \tag{5.10}$$

where $(\cdot)$ is the fuzzy multiplication operator and $\underset{\sim}{R_j}$ is the fuzzy number from each expert $(j = 1, 2, ..., n)$.

Aggregating the expert opinions outputs a Fuzzy Possibility Score (FPS) rather than a probability score. This is because expert opinions for basic events differ to probabilistic values from probability failures. It is impractical to expect an expert to directly determine the probability of failure, particularly when linguistic descriptors are used and therefore terminology such as the possibility of occurrence of a basic event is used over probability (Lin and Wang, 1997).

Once the expert opinions have been aggregated using SAM, they need to be defuzzified to convert from a FPS to a crisp possibility score. As described in Chapter 3, the centroid defuzzification technique is used in this research. The distribution of expert opinions should be dealt with equally. The centroid method is associated with the whole part of the mean and therefore takes into account the whole fuzzy set (Talon and Curt, 2017), hence is appropriate for this work.

As the defuzzified output is a possibility score, this must be converted into a fuzzy failure rate to enable compatibility between probabilistic failure rates and expert opinions in FTA (Lin and Wang, 1997). Onisawa (1988) defined a human error rate as:

$$\text{human error rate} = \frac{\text{frequency of an error}}{\text{total chance that a human makes an error}} \tag{5.11}$$

and Lin and Wang (1997) defined a fuzzy failure rate as shown in equation 5.12:

$$\text{fuzzy failure rate} = \frac{\text{frequency of a failure}}{\text{total chance that an event has a failure}} \tag{5.12}$$

To convert from the FPS to a fuzzy failure rate, Onisawa (1988) used a transformation function where the failure probability, P_f is defined using equation 5.13:

$$P_f = \begin{cases} \frac{1}{10^K}, & FPS \neq 0 \\ 0, & FPS = 0 \end{cases} \qquad K = \left[\frac{1 - FPS}{FPS}\right]^{\frac{1}{3}} \times 2.301 \tag{5.13}$$

This transformation function, (1) reserves objectivity in the probabilistic evaluation of failure rates of basic events, (2) represents the variation of human performance, and (3) represents the vagueness of man-machine interactions (Onisawa, 1988; Lin and Wang, 1997). To demonstrate the validity of equation 5.13, the range of FPSs between 0 and 1 satisfy the range of error data for a routine human operation which is $10^{-2} \sim 10^{-3}$ with a lower bound of 10^{-5} (Swain, 1987).

5.3.5 Sensitivity analysis

In FFTA, the top event probability provides an idea of the probability failure of the system, but there is still a need to evaluate the effects each component has on the overall evaluation of probability. It is important to understand the contribution each basic event has to the top event. Sensitivity analysis highlights the weakest components and what improvements should be made to reduce the probability of failure (Zhou et al., 2015). This research uses four importance measures to understand the system and the variation of failure probabilities. MCSs are ranked to determine those with the highest and lowest effect on the top event. The Fuzzy Weighted Index (FWI) is used to determine the contribution each basic event has to the overall system to investigate alternatives or improvements. Probabilistic importance (Birnbaum's structural importance) is the "probability that the system is in a state where a particular component is critical" (Cobo, 1996). Criticality importance is the "probability that event *i* has occurred and is critical to system failure" (Cobo, 1996).

5.3.5.1 Ranking minimal cut-sets

Decision making from risk assessments requires an understanding of where the highest and lowest risk events exist in order to mitigate or reduce the highest risks. A method of FTA which can highlight the magnitude of various risk events in a fault tree involves ranking the individual MCSs to see which ones have the highest and lowest effect on the top event. MCSs which have the highest failure value contribute the most to the overall occurrence probability of the top event. There are several ranking methods of MCSs for FTA and in this research the Fussell-Vesely Importance Measure (FVIM), FVI_i is used as shown in equation 5.14:

$$FVI_i = \frac{P(MCS_i)}{P(TE)} \tag{5.14}$$

where $P(TE)$ is the probability of the top event.

5.3.5.2 Fuzzy weighted index

Fuzzy Weighted Index (FWI) is used here to determine the contribution each basic event has to the overall system to investigate alternatives or improvements. FWI can only be used in FFTA where all basic events are fuzzy in nature. It calculates the fuzzy top event probability eliminating each basic event separately and works out the difference between the total probability of the top event and the total probability of the top event with one basic event eliminated (Cheliyan and Bhattacharyya, 2018).

Initially all probability crisp values of the basic events are converted into triangular fuzzy numbers using Table 5.5 with the lower and upper bounds creating the triangular membership function (Cheong and Lan, 2004). The fuzzy probability top event is then calculated using fault tree theory (Chapter 3). The FWI for a basic event is calculated by comparing the distance between two triangular fuzzy numbers; A_1: fuzzy probability of the top event and A_2: fuzzy probability of the top event eliminating the required basic event. The FWI is calculated using equation 5.15:

$$\delta\left(A_1, A_2\right) = \frac{1}{2}\alpha\left[max\left(|a_1 - a_2|, |b_1 - b_2|\right) + |c_1 - c_2|\right] \tag{5.15}$$

where $A_1 = (a_1, b_1, c_1)$, $A_2 = (a_2, b_2, c_2)$ and $\alpha = 1$.

TABLE 5.5: Upper and lower bounds for converting crisp probability of failure values to fuzzy triangular probabilities.

Probability failure	Lower bound	Upper bound
$0.01 < BE_i$	$BE_i/5$	$2BE_i$
$0.001 < BE_i < 0.01$	$BE_i/3$	$3BE_i$
$BE_i < 0.001$	$BE_i/10$	$10BE_i$

BE: Basic event

This calculation for the distance between the two fuzzy numbers is visualised in Figure 5.5 (Cheong and Lan, 2004).

5.3.5.3 Probabilistic importance

Probabilistic importance can only be conducted on fault trees with MCSs. The importance for each component is determined using equation 5.16 so if the method was conducted on a fault tree with no MCSs, the probabilistic importance would always be 1. The probabilistic importance for each basic event is calculated (Andrews and Beeson, 2003):

$$PI_{BE_i}(q) = P_{TE}\left(1_{BE_i}, q\right) - P_{TE}\left(0_{BE_i}, q\right) \tag{5.16}$$
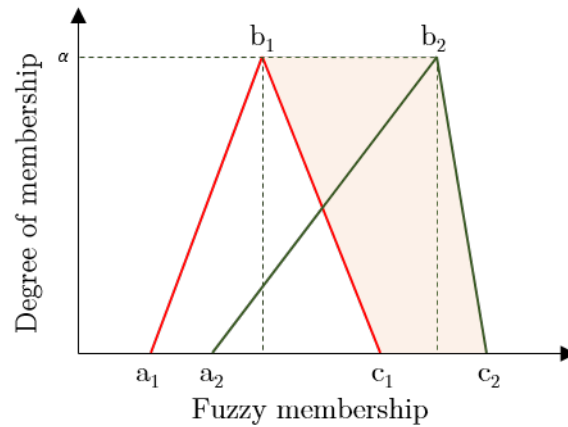
FIGURE 5.5: Distance calculation between two triangular fuzzy numbers.

where $P_{TE}\left(1_{BE_i}, q\right)$ is the probability the top event fails with BE_i failed, $P_{TE}\left(0_{BE_i}, q\right)$ is the probability the top event fails with BE_i working and q is the basic event unavailability for the remaining basic events.

5.3.5.4 Criticality importance

Criticality importance can only be conducted on fault trees with MCSs as it considers the weight of each individual MCS with relation to the failure probability of the top event. If the probabilistic importance has been calculated, the criticality importance is calculated by adjusting the probabilistic importance measure to the failure probability of the basic event as a fraction of the total failure probability of the top event (Cheliyan and Bhattacharyya, 2018). It is calculated using equation 5.17:

$$CI\left(BE_i\right) = \frac{P\left(BE_i\right)}{P\left(TE\right)} PI\left(BE_i\right) \tag{5.17}$$

5.4 RISK ASSESSMENT APPLICATION

The main elements in this chapter focus on the event trees and fault trees and the results from applying the methodology. The event trees are developed from the conceptual models presented in Section 5.2 and where branches cannot be quantified, fault trees are developed. Three fault trees are developed to account for horizontal and vertical cement failure and annulus failure due to pressure changes.

5.4.1   Event tree development

ETA is a bottom-up approach constructed from an initiating event which builds additional events leading to the final success or failure outcomes. Event tree development is the first step to constructing a method which allows quantification of failure probabilities during well stimulation of a hydraulically fractured well. The outcomes of the event tree represent the potential for groundwater contamination either as a failure (contamination) or success (no contamination).

The conceptual models in Figure 5.2 were used to determine the pathways with the potential of causing groundwater contamination from well integrity failure. These pathways are used to develop two event trees demonstrated in Figure 5.6. A main source of gas or fluid migration during well stimulation is from inside the wellbore to geological surroundings due to well integrity failure. Well integrity failure leading to groundwater contamination is the primary concern in this research where well barrier failure is the failure of individual or multiple barriers eventually leading to integrity failure (Davies et al., 2014).

The initiating event for the event trees is the primary barrier failing as it directly experiences very high injection pressures. This will either be the production casing for Figure 5.2a or the packer or tubing for Figure 5.2b, as indicated in Figure 5.6a and 5.6b, respectively. In between the initiating event and outcome, events are developed based on barrier failures in the well and the difference in pressure gradients leading to each consecutive event. Table 5.6 gives details of each event in the event trees.

5.4.2   Fault tree development

Three fault trees have been developed to allow quantification of events which require more detailed analysis. The difference in pressure between the annulus and injection pressure is quantified using a fault tree developed by Rish (2005) (Figure 5.7). Rish (2005) characterized the uncertainty of each basic event in the fault tree using probability distributions which were propagated using Monte Carlo analysis. The random sampling and generation of stochastic results was performed using Crystal Ball, and Latin Hypercube Sampling (LHS) generated the input values for all distributions, performing the analysis with 5,000 iterations (Rish, 2005). The probability distributions for each event failure frequency were developed in a few different ways depending on the available data but are summarised for these specific events in Table 5.7. The top event using these basic event values is calculated at 6.48E^{-11}.
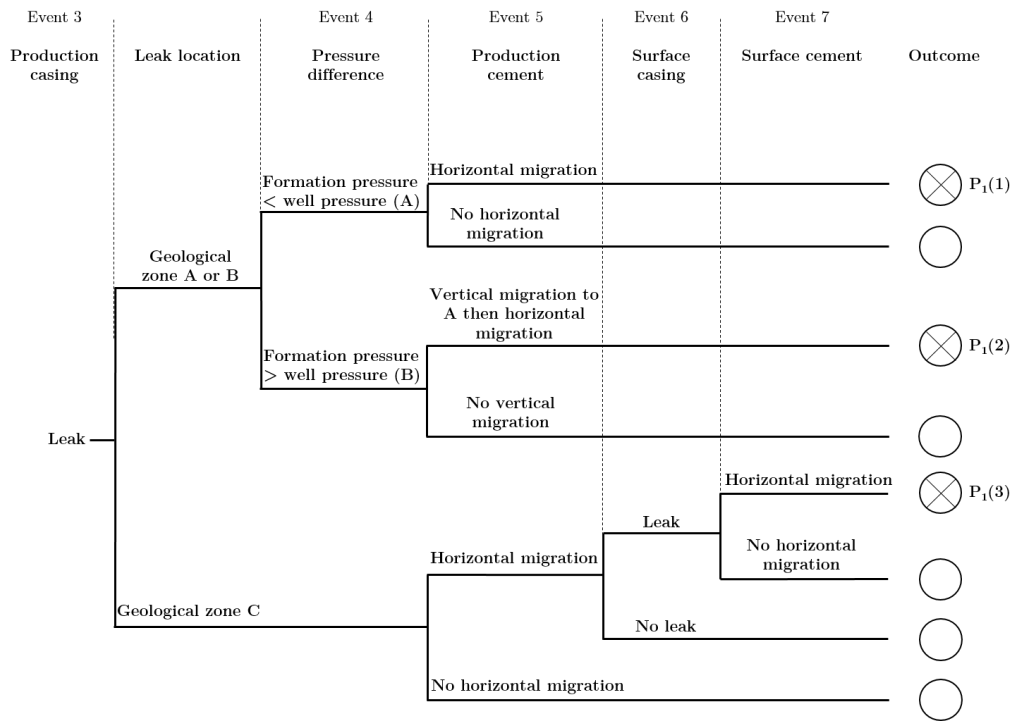
(A) Scenario 1: Production casing leak event tree.
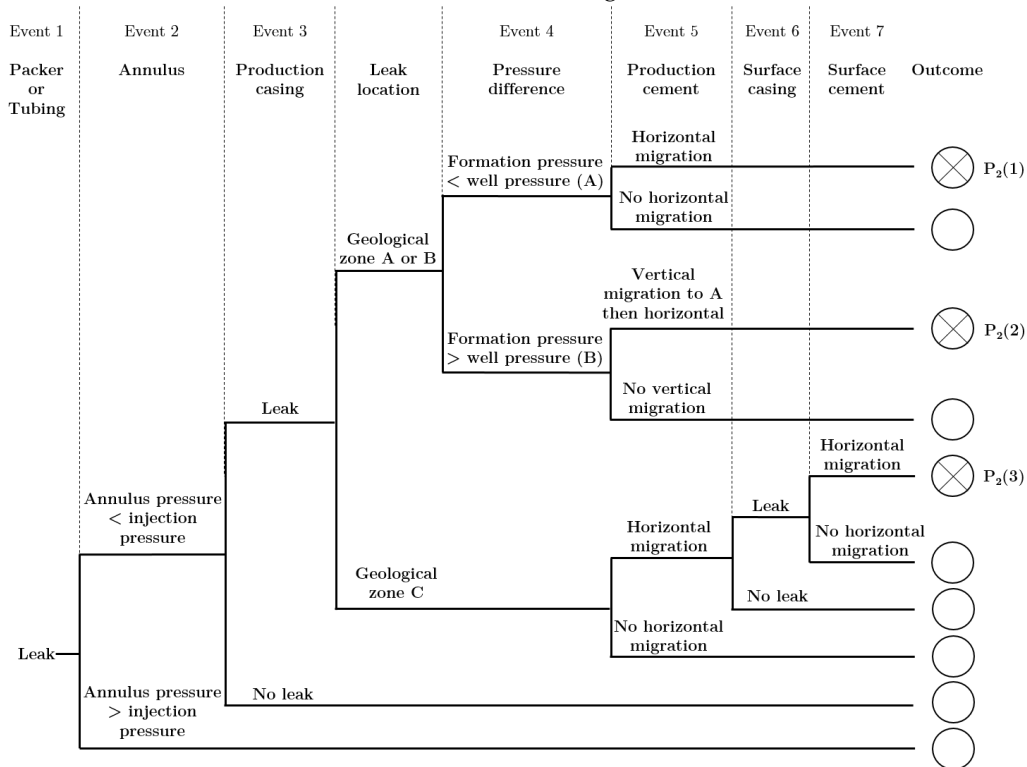
(B) Scenario 2: Tubing or packer leak event tree.

FIGURE 5.6: Two event trees for gas leakage into groundwater during well stimulation. The probability of failure outcomes are defined as $P_x(y)$ where x is scenario 1 or scenario 2 and y is outcome 1, 2 or 3.

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TABLE 5.6: Details of individual events within both event trees including how their probabilities are quantified.

Event/barrier failure	Scenario	Description	Quantitative probabilities
Event 1 Packer or tubing failure	2	• Initiating event	Industry values (Table 5.2)
Event 2 Annulus failure	2	• Pressurised annulus between production tubing and casing. • Failure when pressurised annulus < injection pressure.	FTA (probabilistic and fuzzy, Figure 5.7)
Event 3 Production casing failure	1 and 2	• Initiating event in scenario 1 (Figure 5.6a)	Industry values (Table 5.2)
Event 4 Pressure difference	1 and 2	• Determines direction of gas migration. • FP < WP, gas migration to outside. • FP < WP, vertical migration upwards to surface or region of lower pressure.	
Event 5 Production casing cement failure	1 and 2	• Barrier to support production casing. • Failures in the cement can occur in either the horizontal or vertical direction.	FFTA (Figures 5.8 and 5.9)
Event 6 Surface casing failure	1 and 2	• Second casing barrier to protect groundwater.	*Industry values (Table 5.2)
Event 7 Surface casing cement failure	1 and 2	• Barrier to support surface casing. • Failures in the cement can occur in either the horizontal or vertical direction.	FFTA (Figures 5.8 and 5.9)

FP: Formation pressure
WP: Wellbore pressure
* The database used to gather well component failures indicated no failures occurred over experiment times for surface casings. Therefore, the median probability of failure value was taken from Rish (2005) where it was calculated using a Poisson probability distribution.

TABLE 5.7: Summary of the probability distributions developed by Rish (2005) for the basic events in the annulus pressure fault tree.

Basic event	Probability distribution	Data source
Pr1: Major long string casing fail	Poisson	• Professional judgement. • Based on reported events for long string casing leak at 0.01 times less likely.
Pr2: Pump fails	Triangular	• Industrial reliability database. • Alternative industries e.g. nuclear power industry.
Pr3: Check valve fails	Triangular	• Industrial reliability database.
Pr4: Control system failure resulting in under-pressurisation	Uniform	• Industrial reliability database.
Pr5: Operator error resulting in under-pressurisation	Uniform	• Human error rates derived from human reliability data for similar activities.
Pr6: Control system failure resulting in over-pressurisation	Uniform	• Industrial reliability database.
Pr7: Operator error resulting in over-pressurisation	Uniform	• Human error rates derived from human reliability data for similar activities.
Pr8: Loss of injection capacity	Uniform	• Human error rates derived from human reliability data for similar activities. • Would result only in the event of a human error omission.
Pr9: Auto alarm fails	Uniform	• Industrial reliability database. • Based on fire hazards associated with radioactive waste.
Pr10: Operator fails to detect/respond	Uniform	• Human error rates derived from human reliability data for similar activities.
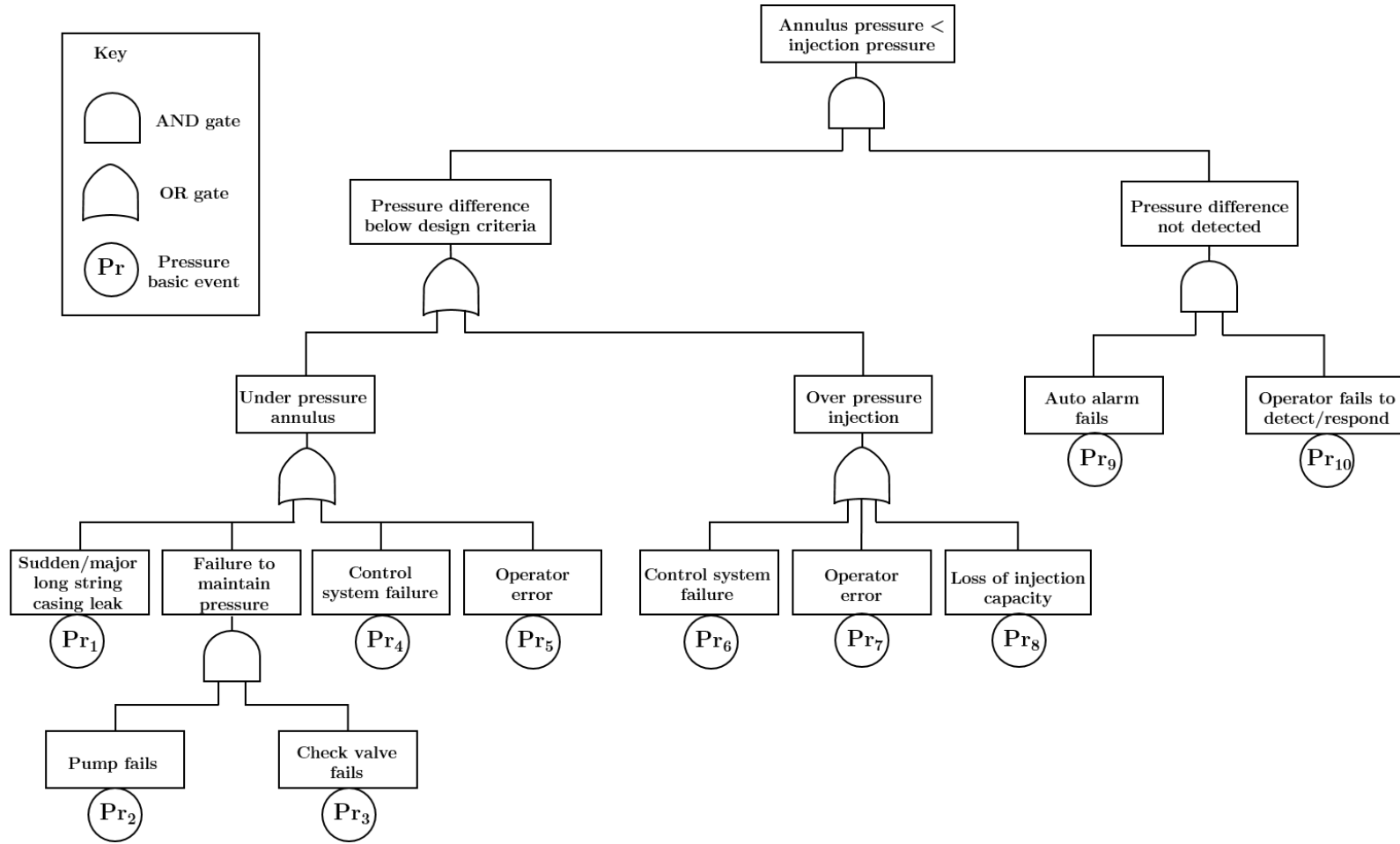
FIGURE 5.7: Fault tree for the breach of the pressurised annulus when the injection pressure exceeds the annulus pressure (Rish, 2005).

This fault tree was also analysed using FFTA in this research to compare the difference in the methods and to support the fuzzy logic technique. Production and surface casing cement failure are both events which are a challenge to quantify. The development of pathways in cement to allow gas or fluids to move out of the well or within the cement-casing or cement-formation interfaces are often the reason for a loss of well integrity (Davies et al., 2014; Rocha-Valadez et al., 2014; Bachu, 2017). However, there is no industry data due to the subjective and ambiguous nature of cement to numerically evaluate the probability of this failure. Therefore, two fault trees are constructed for cement failure for FFTA with the top event being either production of horizontal pathways in the cement (Figure 5.8) or production of vertical pathways (Figure 5.9).

These fault trees were developed from a literature analysis (Bonett and Pafitis, 1996; Dusseault et al., 2000; Brufatto et al., 2003) and discussed with academic and industry experts within Canada and the UK who, in addition, gave their judgements for each basic event.
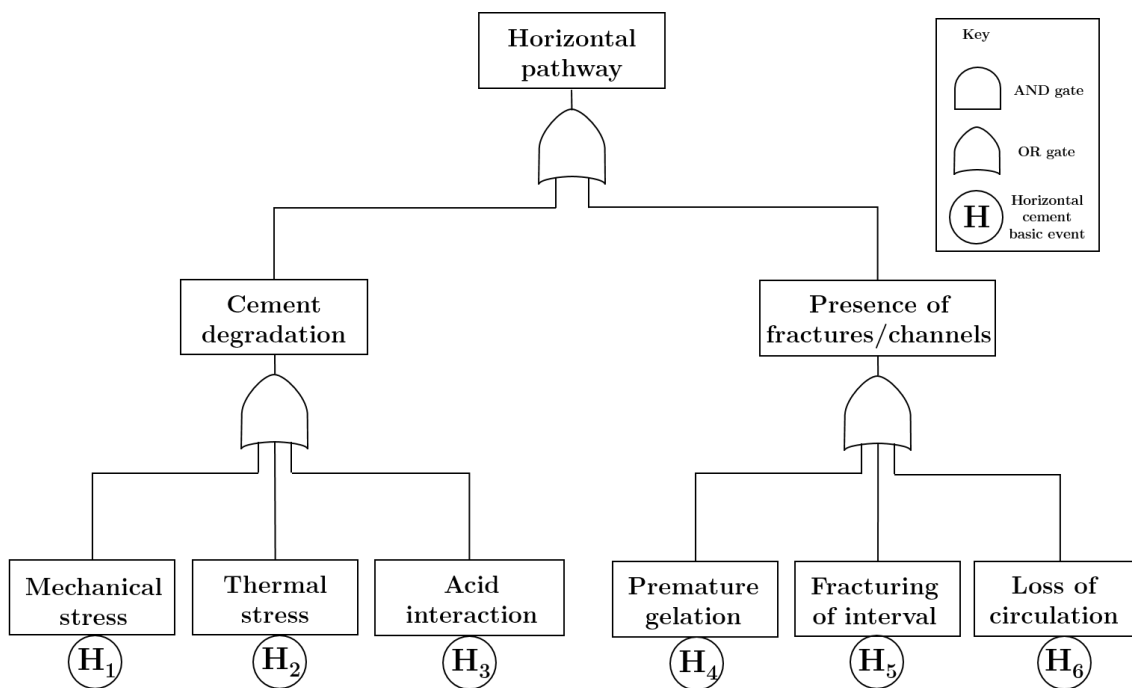
FIGURE 5.8: Fault tree for the development of a horizontal cement pathway causing a failure in the cement.

Failure pathways in cement were considered to occur horizontally or vertically. Horizontal failures could develop either over time from external stresses and interactions or due to poor initial construction and placement which leads to fractures and channels developing as the cement sets (Bonett and Pafitis, 1996). Premature gelation involves a sudden increase in cement viscosity quicker than expected (Frigaard, 2018). This can lead to a loss of hydrostatic pressure control, opening a horizontal pathway (Bonett and Pafitis, 1996). During cementing placement, if fluid densities are too high there is a risk of losing cement
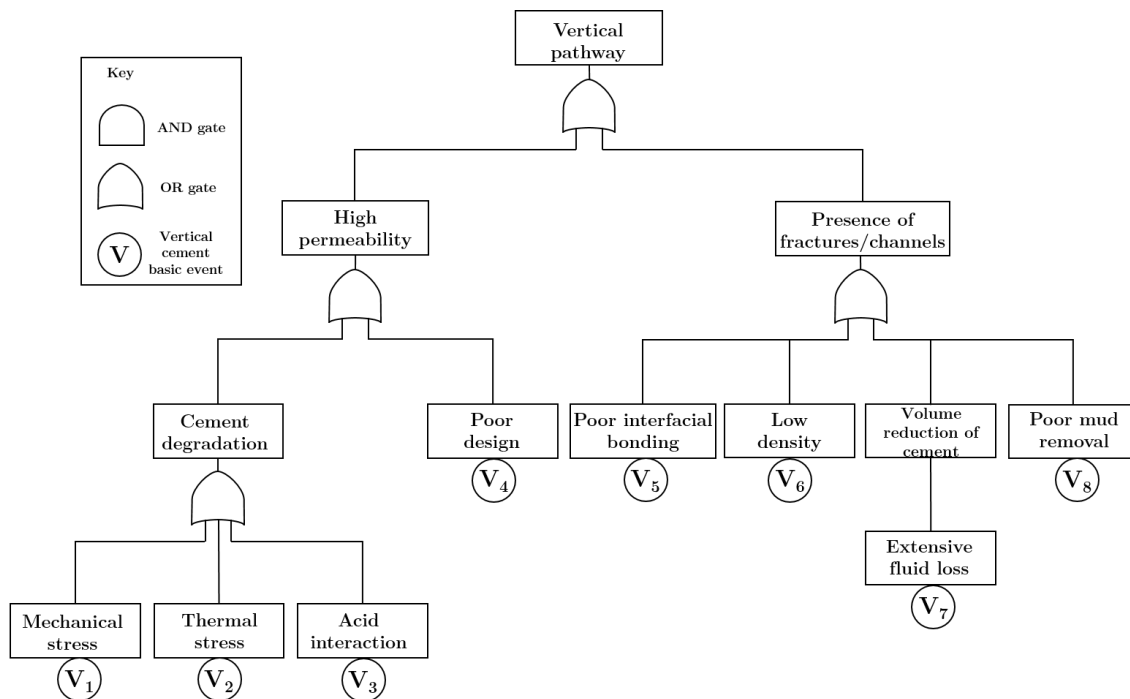
FIGURE 5.9: Fault tree for the development of a vertical cement pathway causing a failure in the cement.

slurry into the surrounding formation causing a loss of circulation within the borehole or fracturing of a rock interval (Bonett and Pafitis, 1996). A loss of cement could open up horizontal channels in the cement before it has set.

Vertical pathways in the cement can also develop from external stresses (Stormont et al., 2015) and interactions or poor cement design, leading to high permeability pathways allowing gas to migrate upwards (Dusseault et al., 2000; Stormont et al., 2018). Additionally, vertical fractures and channels can be developed from poor construction and placement through slightly different mechanisms. A low density slurry during cementing can lead to poor hydrostatic imbalances and vertical pathways. If mud during drilling is not removed properly, gas channels can develop between the cement sheath and rock formations or casings (Dusseault et al., 2000; Frigaard, 2018). Similarly, poor bonding of the cement can lead to channels between the cement-casing or cement-formation interfaces (Bonett and Pafitis, 1996; Stormont et al., 2015). During the cement setting process, fluid is lost but if this occurs too quickly or too much, the volume of the cement is reduced significantly to open up available space for gas to enter (Frigaard, 2018).

5.4.3 Fuzzy fault tree analysis

Conducting FFTA requires expert decisions for each basic event using linguistic terminology as indicated in Table 5.3. In this research study, seven experts in total were used to

quantify the basic events for each fault tree; their weightings are indicated in Tables 5.8 and 5.9. Three of the experts are academics either with PhDs or working towards their graduate degrees specifically in the area of cementing practises in deep horizontal wells (E_1, E_3, E_4). Four experts are industry-based engineers or geologists with undergraduate or postgraduate degrees and extensive experience working in the oil and gas industry, managing engineers (E_2, E_5, E_6, E_7).

The pressure fault tree requires expert knowledge in understanding how the pressures can change during well stimulation. This meant only two out of the original five experts with extensive drilling engineering knowledge were used for this fault tree (Table 5.9; E_2, E_5) and two more were contacted for a complete analysis of the pressure fault tree (Table 5.9; E_6, E_7). The cement fault trees required expert knowledge in cementing practises which was the research focus of the three experts working in academia (Table 5.8; E_1, E_3, E_4) and both original engineers have extensive knowledge in this area (Table 5.8; E_2, E_5).

TABLE 5.8: Chosen experts and their calculated weighting factors for both cement fault trees. Weighting factor rounded to 2 decimal places.

Expert	Professional or academic title	Service time (yr)	Education level	Age (yr)	Weighting score	Weighting factor
E_1	Professor	20-29	PhD	≥ 50	19	0.26
E_2	Engineer	≥ 30	Masters	≥ 50	16	0.22
E_3	Postdoc	≤ 5	PhD	30-39	13	0.18
E_4	Graduate	≤ 5	Masters	21-29	10	0.14
E_5	Engineer	≥ 30	Bachelors	≥ 50	15	0.21
Sum					73	1.00

TABLE 5.9: Chosen experts and their calculated weighting factors for the annulus pressure fault tree. Weighting factor rounded to 2 decimal places.

Expert	Professional or academic title	Service time (yr)	Education level	Age (yr)	Weighting score	Weighting factor
E_2	Engineer	≥ 30	Masters	≥ 50	16	0.28
E_5	Engineer	≥ 30	Bachelors	≥ 50	15	0.26
E_6	Engineer	$10 - 19$	Bachelors	30-39	11	0.19
E_7	Engineer	≥ 30	Masters	≥ 50	16	0.28
Sum					58	1.00

The opinions for all the basic events for all three fault trees were collected anonymously from questionnaires handed out to each expert. From these questionnaires all five experts gave their opinions for the cement fault trees and additionally two of these five gave their opinions for the pressure fault tree. These opinions on a total of 24 basic events are shown in Table 5.10.

5.4.3.1 Aggregation

Once every basic event has been rated (Table 5.10), the opinions of each expert are aggregated using the SAM (Section 5.3.4). To calculate the consensus degree coefficient, $\beta = 0.5$ is used where the relative degree of agreement is equally important as the expert

TABLE 5.10: Expert decisions showing linguistic values and converted fuzzy numbers for all basic events in each fault tree.

FT	BE	Expert decision					Fuzzy number				
		E_1	E_2	E_3	E_4	E_5	E_1	E_2	E_3	E_4	E_5
	H_1	L	L	L	L	L	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)
	H_2	VL	L	L	L	L	(0.0, 0.0, 0.10, 0.20)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)
Horizontal	H_3	VL	VL	L	L	M	(0.0, 0.0, 0.10, 0.20)	(0.0, 0.0, 0.10, 0.20)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)
cement	H_4	M	L	M	M	M	(0.30, 0.50, 0.70)	(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)
	H_5	M	L	L	M	M	(0.30, 0.50, 0.70)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)
	H_6	VL	M	VL	M	M	(0.0, 0.0, 0.10, 0.20)	(0.30, 0.50, 0.70)	(0.0, 0.0, 0.10, 0.20)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)
	V_1	L	M	H	H	L	(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)	(0.60, 0.75, 0.90)	(0.60, 0.75, 0.90)	(0.10, 0.25, 0.40)
	V_2	VL	L	H	M	L	(0.0, 0.0, 0.10, 0.20)	(0.10, 0.25, 0.40)	(0.60, 0.75, 0.90)	(0.30, 0.50, 0.70)	(0.10, 0.25, 0.40)
	V_3	VL	L	L	L	M	(0.0, 0.0, 0.10, 0.20)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)
Vertical	V_4	M	M	M	M	M	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)
cement	V_5	L	M	H	M	H	(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)	(0.60, 0.75, 0.90)	(0.30, 0.50, 0.70)	(0.60, 0.75, 0.90)
	V_6	L	L	L	L	M	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)
	V_7	VL	M	M	L	M	(0.0, 0.0, 0.10, 0.20)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)	(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)
	V_8	M	M	H	H	H	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)	(0.60, 0.75, 0.90)	(0.60, 0.75, 0.90)	(0.60, 0.75, 0.90)
		E_2	E_5	E_6	E_7		E_2	E_5	E_6	E_7	
	Pr_1	L	L	VL	VL		(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.0, 0.0, 0.10, 0.20)	(0.0, 0.0, 0.10, 0.20)	
	Pr_2	L	M	L	M		(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)	(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)	
	Pr_3	L	L	L	M		(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)	
	Pr_4	VL	M	VL	M		(0.0, 0.0, 0.10, 0.20)	(0.30, 0.50, 0.70)	(0.0, 0.0, 0.10, 0.20)	(0.30, 0.50, 0.70)	
Pressure	Pr_5	L	M	L	L		(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	
	Pr_6	VL	M	VL	L		(0.0, 0.0, 0.10, 0.20)	(0.30, 0.50, 0.70)	(0.0, 0.0, 0.10, 0.20)	(0.10, 0.25, 0.40)	
	Pr_7	L	H	L	L		(0.10, 0.25, 0.40)	(0.60, 0.75, 0.90)	(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	
	Pr_8	L	M	VL	H		(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)	(0.0, 0.0, 0.10, 0.20)	(0.60, 0.75, 0.90)	
	Pr_9	L	L	VL	L		(0.10, 0.25, 0.40)	(0.10, 0.25, 0.40)	(0.0, 0.0, 0.10, 0.20)	(0.10, 0.25, 0.40)	
	Pr_{10}	L	M	VL	M		(0.10, 0.25, 0.40)	(0.30, 0.50, 0.70)	(0.0, 0.0, 0.10, 0.20)	(0.30, 0.50, 0.70)	

FT: Fault Tree
BE: Basic Event

weightings. The aggregated trapezoidal fuzzy numbers for all 24 basic events are shown in column three of Table 5.11.

5.4.3.2 Defuzzification

The aggregated fuzzy numbers are converted into FPS crisp values using the defuzzification process; the centroid method (equation 3.9). The FPS for each basic event is shown in column 4 of Table 5.11.

Finally, the FPS needs to be converted to a failure probability to enable compatibility between industry probability failures and fuzzy failure rates. This is calculated for all basic events using equation 5.13 and is shown in column five of Table 5.11. These basic events are ranked within each fault tree (column six) to demonstrate which basic events contribute the most and the least to the top event.

5.4.3.3 Minimal cut-sets

The MCSs for the pressure fault tree can be developed as the fault tree consists of 'AND' and 'OR' gates. Both cement fault trees only consist of 'OR' logic gates and therefore do not have MCSs. The individual MCSs for the pressure fault tree are shown in Table 5.12. Quantitative analysis has been conducted on the MCSs to determine their importance

TABLE 5.11: Calculated aggregated values from fuzzy numbers and the final failure probability rank within each fault tree.

FT	BE	Aggregated possibilities	FPS	Failure probability	Rank
Horizontal cement	H_1	$(0.10, 0.25, 0.25, 0.40)$	0.25	$4.88E^{-4}$	4
	H_2	$(0.08, 0.20, 0.22, 0.36)$	0.21	$2.84E^{-4}$	6
	H_3	$(0.09, 0.19, 0.23, 0.37)$	0.22	$3.27E^{-4}$	5
	H_4	$(0.26, 0.45, 0.45, 0.65)$	0.45	$3.58E^{-3}$	1
	H_5	$(0.22, 0.40, 0.40, 0.59)$	0.40	$2.42E^{-3}$	2
	H_6	$(0.18, 0.30, 0.34, 0.50)$	0.34	$1.27E^{-3}$	3
Vertical cement	V_1	$(0.32, 0.48, 0.48, 0.65)$	0.48	$4.45E^{-3}$	4
	V_2	$(0.20, 0.32, 0.34, 0.49)$	0.34	$1.35E^{-3}$	6
	V_3	$(0.12, 0.24, 0.27, 0.41)$	0.26	$5.59E^{-4}$	8
	V_4	$(0.30, 0.50, 0.50, 0.70)$	0.50	$5.09E^{-3}$	3
	V_5	$(0.38, 0.55, 0.55, 0.72)$	0.55	$6.95E^{-3}$	2
	V_6	$(0.14, 0.30, 0.30, 0.46)$	0.30	$8.71E^{-4}$	7
	V_7	$(0.20, 0.35, 0.38, 0.55)$	0.37	$1.82E^{-3}$	5
	V_8	$(0.47, 0.65, 0.65, 0.82)$	0.65	$1.31E^{-2}$	1
Pressure	Pr_1	$(0.05, 0.13, 0.17, 0.30)$	0.17	$1.13E^{-4}$	10
	Pr_2	$(0.19, 0.36, 0.36, 0.53)$	0.36	$1.61E^{-3}$	2
	Pr_3	$(0.14, 0.30, 0.30, 0.46)$	0.30	$9.12E^{-4}$	5
	Pr_4	$(0.14, 0.24, 0.29, 0.43)$	0.28	$6.77E^{-4}$	7
	Pr_5	$(0.14, 0.30, 0.30, 0.46)$	0.30	$8.80E^{-4}$	6
	Pr_6	$(0.09, 0.17, 0.22, 0.35)$	0.21	$2.82E^{-4}$	8
	Pr_7	$(0.20, 0.35, 0.35, 0.49)$	0.35	$1.44E^{-3}$	3
	Pr_8	$(0.24, 0.36, 0.38, 0.53)$	0.38	$1.95E^{-3}$	1
	Pr_9	$(0.07, 0.18, 0.20, 0.34)$	0.20	$2.27E^{-4}$	9
	Pr_{10}	$(0.17, 0.30, 0.32, 0.48)$	0.33	$1.07E^{-3}$	4

FT: Fault Tree
BE: Basic Event

to the overall system using the FVIM (equation 5.14). The results and ranking of the importance measure are shown in columns four and five of Table 5.12.

TABLE 5.12: MCS values for the top event of the pressure fault tree, including their rankings.

MCS	Event	Failure probability of cut sets, $P(MCS_i)$	$FVI_i(t)$	Rank
MCS_1	Pr1.Pr9.Pr10	$2.74E^{-11}$	$2.12E^{-2}$	6
MCS_2	Pr2.Pr3.Pr9.Pr10	$3.56E^{-13}$	$2.75E^{-4}$	7
MCS_3	Pr4.Pr9.Pr10	$1.64E^{-10}$	$1.27E^{-1}$	4
MCS_4	Pr5.Pr9.Pr10	$2.13E^{-10}$	$1.65E^{-1}$	3
MCS_5	Pr6.Pr9.Pr10	$6.83E^{-11}$	$5.28E^{-2}$	5
MCS_6	Pr7.Pr9.Pr10	$3.48E^{-10}$	$2.69E^{-1}$	2
MCS_7	Pr8.Pr9.Pr10	$4.72E^{-10}$	$3.65E^{-1}$	1

5.4.3.4   Top event fault tree results

The top event for each fault tree is calculated using the fuzzy failure probabilities for each basic event. The top event probabilities for the horizontal cement $P_{HC}(TE)$, vertical cement $P_{VC}(TE)$ and pressure fault trees $P_{Pr}(TE)$ are $8.36E^{-3}$, $3.42E^{-2}$ and $1.29E^{-9}$, respectively.

5.4.4   Event tree analysis

The event trees constructed in Section 5.4.1 indicate the pathways in a well which could lead to groundwater contamination and the ones which do not. The failure probability values for both event trees have been calculated based on probabilistic and fuzzy inputs to the model, indicated in Table 5.13. Two different scenarios were used based on a Canadian case study (Fig. 5.2a) and a likely UK well construction (Fig. 5.2b). Both scenarios have been assessed using fuzzy inputs calculated in this paper and probabilistic inputs calculated from Rish (2005). In both scenarios the user inputs the formation pressure and well pressure in MPa of where the leaks could occur, the groundwater depth and surface casing cement depth in m (the groundwater depth must be less than surface casing cement depth for this model) and if the top of the production cement is above the surface casing shoe (this must be a 'YES' for this model). Additionally for scenario 2, the user must input whether a packer or tubing has failed.

TABLE 5.13: Model values and inputs for each failure event resulting in the loss of gas or fluids from an injection well from a packer, tubing or production casing failure. Two scenarios are presented, one signifies this chapters work (fuzzy analysis) and the other is adapted from Rish (2005) (probabilistic).

	Packer	Tubing	Annulus	Production Casing	Pressure Difference	Production Cement Horizontal	Production Cement Vertical	Surface Casing	Surface Cement Horizontal
Scenario 1 Fuzzy	-	-	-	$7.59E^{-4}$	FP<WP FP>WP	$8.36E^{-3}$	- $3.42E^{-2}$	$1.69E^{-5}$	$8.36E^{-3}$
Scenario 1 Probabilistic	-	-	-	$3.00E^{-5}$	FP<WP FP>WP	-	- $6.00E^{-6}$	$3.00E^{-6}$	-
Scenario 2 Fuzzy	$1.04E^{-5}$	$4.07E^{-5}$	$1.29E^{-9}$	$7.59E^{-4}$	FP<WP FP>WP	$8.36E^{-3}$	- $3.42E^{-2}$	$1.69E^{-5}$	$8.36E^{-3}$
Scenario 2 Probabilistic	$4.00E^{-5}$	$6.00E^{-5}$	$6.48E^{-11}$	$3.00E^{-5}$	FP<WP FP>WP	-	- $6.00E^{-6}$	$3.00E^{-6}$	-

FP: Formation Pressure
WP: Wellbore Pressure

Different output values are obtained based on the well construction scenario and the location at which the leak has occurred (Table 5.15). P(1) indicates a leak at geological zone A, P(2) at geological zone B and P(3) at geological zone C.

The ETA has been conducted using fuzzy methods as described in this chapter and compared against probabilistic values for similar leaks on waste injection wells (Rish,

2005). As described earlier in Section 5.4.2, Rish (2005) developed probability distributions for uncertain failure events on waste injection wells using Monte Carlo analysis. The probability distributions for the event failures used in this research (as shown in Table 5.13) are summarised in Table 5.14. The failure of cement in the horizontal direction was not considered by Rish (2005) and therefore has been neglected in the probabilistic calculations. In this research, horizontal and vertical failure of cement were quantified using FFTA for a more accurate representation.

TABLE 5.14: Summary of the probability distributions developed by Rish (2005) for the events used in the event tree analysis.

Event	Probability distribution	Data source
Event 1: Packer leak	Poisson	• Reported events for specific leaks. • Upper 90th percentile confidence limits of average failure rate/day were used as the rate parameter in a Poisson distribution. • State-by-state analysed data.
Event 1: Tubing leak	Poisson	• Reported events for specific leaks. • Upper 90th percentile confidence limits of average failure rate/day were used as the rate parameter in a Poisson distribution. • State-by-state analysed data.
Event 3: Production casing leak	Poisson	• Reported events for specific leaks. • Upper 90th percentile confidence limits of average failure rate/day were used as the rate parameter in a Poisson distribution. • State-by-state analysed data.
Event 5/7: Vertical cement leak	Poisson	• Reported events for specific leaks. • Upper 90th percentile confidence limits of average failure rate/day were used as the rate parameter in a Poisson distribution. • State-by-state analysed data based on waste migration data.
Event 6: Surface casing leak	Poisson	• Reported events for specific leaks. • Upper 90th percentile confidence limits of average failure rate/day were used as the rate parameter in a Poisson distribution. • Derived from production casing leak with a 0.1 correction due to less likely to fail.

TABLE 5.15: Results from the event trees, Figure 5.6, indicating the different probability outcomes for potential groundwater contamination depending on geological location, well construction and method.

		Method	$P(1)$	$P(2)$	$P(3)$
Scenario 1	-	Fuzzy	$6.35E^{-6}$	$2.17E^{-7}$	$8.97E^{-13}$
	-	Probabilistic	$3.00E^{-5}$	$1.80E^{-10}$	$9.00E^{-11}$
Scenario 2	Packer	Fuzzy	$8.53E^{-20}$	$2.92E^{-21}$	$1.21E^{-26}$
	Packer	Probabilistic	$7.78E^{-20}$	$4.67E^{-25}$	$2.33E^{-25}$
	Tubing	Fuzzy	$3.34E^{-19}$	$1.14E^{-20}$	$4.72E^{-26}$
	Tubing	Probabilistic	$1.17E^{-19}$	$7.00E^{-25}$	$3.50E^{-25}$

The large difference between the probabilistic calculations from Rish (2005) and this research, particularly failure pathways $P(2)$ and $P(3)$ (Table 5.15) is the horizontal cement failure. By considering the movement of fluids or gases horizontally, the probability

of failure will decrease as the cement is acting as a barrier. Despite this difference, the probability values are similar for all three events across both methods. This will be due to the differences in the probabilistic failure rates of certain components compared to the industry values (Table 5.13). Generally, the industry values have higher probability failures than those calculated using probabilistic distributions.

5.5 SENSITIVITY ANALYSIS AND DISCUSSION

5.5.1 Fault tree sensitivity analysis

5.5.1.1 Cement fault trees

Comparison of the cement fault tree values to industry data to verify the fuzzy logic method is a challenge as very little exists on alternative methods for quantifying cement failure. Cement failure is well detected during drilling and injection but probability of failure is often unknown (Calosa et al., 2010; Considine et al., 2013). However, incidences of gas migration due to cement failure indicate vertical cement failure is more likely than horizontal cement failure (Dusseault et al., 2000). The cement tree top event results demonstrate vertical failure is 10 times more likely than horizontal, supporting these hypotheses.

In the probabilistic risk assessment conducted by Rish (2005) for waste injection wells, only vertical migration through the cement was considered and not horizontal. Comparing the vertical values, Rish (2005) obtained a median value of $6.00E^{-6}$ with a lower and upper bound of $2.00E^{-6}$ and $1.00E^{-5}$, respectively, using a Poisson distribution. Using expert opinions on vertical cement failure, the value obtained for vertical migration was $3.42E^{-2}$, a probability >5000 times more likely than indicated by Rish (2005). There is no indication of further research conducted to quantify the failures of cement during oil and gas drilling and therefore little data is available to support or refute these methods. However, the fuzzy fault tree values have been supported by expert opinion which is a part of validation of the method using industry knowledge. The horizontal cement fault tree top failure value was calculated as $8.36E^{-3}$ but there is no information to compare this value to. FFTA can be a new method for dealing with these gaps in the industry.

As both fault trees only consist of 'OR' gates, MCS sensitivity analysis cannot be conducted as there are no MCSs. However, importance analysis of the basic events can be conducted to indicate the contribution of the basic events to the failure of the top event. In Table 5.11 each basic event for each fault tree was ranked according to its failure probability which demonstrated H_4, premature gelation and V_8, poor mud removal, were the biggest contributors to the top event failure probability.

Failure probability values for each basic event in the cement fault trees are all very similar, suggesting they all contribute relatively equally to the top event. The FWI is used to determine to what degree the top event is improved if each individual basic event is removed. These values for the horizontal and vertical cement trees are shown in Table 5.16. Using FWI, H_4 is still considered to contribute the most to the top event failure probability and therefore removing or reducing the risk of premature gelation during the cementing process is important. Gelation is the process in cement setting at which it begins to solidify. If the cement sets too early this can lead to a loss of hydrostatic pressure control in the well and gas or formation fluids can enter the cement annulus leading to horizontal channels (Bonett and Pafitis, 1996). Methods to improve this can involve improved designs of the cementing process such as using casing centralizers or better cementing mixtures (US Environmental Protection Agency, 2016a).

TABLE 5.16: FWI results conducted on the cement fault trees.

Fault tree	Basic event	FWI	Rank
Horizontal cement	H_1	$2.69E^{-3}$	3
	H_2	$1.56E^{-3}$	5
	H_3	$1.80E^{-3}$	6
	H_4	$7.15E^{-3}$	1
	H_5	$4.83E^{-3}$	2
	H_6	$2.54E^{-3}$	4
Vertical cement	V_1	$8.90E^{-3}$	4
	V_2	$2.70E^{-3}$	8
	V_3	$3.08E^{-3}$	7
	V_4	$1.02E^{-2}$	3
	V_5	$1.39E^{-2}$	2
	V_6	$4.79E^{-3}$	5
	V_7	$3.64E^{-3}$	6
	V_8	$1.96E^{-2}$	1

For vertical cement failure, V_8 is considered to contribute the most to the top event failure probability according to the FWI and basic event ranking. Reducing the risk of poor mud removal can help to reduce the failure probability of the top event. Mud removal occurs during the drilling process when cement is used to displace the mud from drilling the borehole. It is vital to eliminate mud channels otherwise lower yield stresses of drilling fluids could cause preferential pathways for gas migration, or water could be drawn from the mud into the cement when the two come in contact. This can shrink and dry out the mud opening up vertical pathways along the annulus for gas to flow. Successful mud removal depends on factors such as downhole conditions, borehole characteristics, fluid rheology and displacement design along with optimal fluid displacement (Brufatto et al., 2003). These factors must be carefully calculated to reduce the risk of vertical cement failure.

5.5.1.2 Pressure fault tree

Probabilistic FTA was conducted for the pressure fault tree using uniform, triangular and Poisson distributions (Rish, 2005) and a top event failure value of $6.48E^{-11}$ was obtained. Using FFTA, a value of $1.29E^{-9}$ was obtained. Both methods indicate a similarly low probability value for injection pressure exceeding annulus pressure, supporting the fuzzy logic methodology. Despite similar values, the fuzzy method calculates a top event failure 100 times more likely than the probabilistic method. Therefore, analysing the failure probabilities of individual basic events helps understand these differences (Table 5.17). Discussion with experts and adjustments of the fault tree developed by Rish (2005) can help to understand these differences and improve the fault tree in the future, where a fuzzy logic methodology might still be more suitable than other quantitative methods.

TABLE 5.17: Comparison between probabilistic calculated values and fuzzy logic values for each basic event in the pressure fault tree.

Basic event	Failure probability (fuzzy)	Failure probability (Rish, 2005)
Pr_1	$1.13E^{-4}$	$3.00E^{-7}$
Pr_2	$1.61E^{-3}$	$5.00E^{-4}$
Pr_3	$9.12E^{-4}$	$3.00E^{-4}$
Pr_4	$6.77E^{-4}$	$1.00E^{-5}$
Pr_5	$8.80E^{-4}$	$3.00E^{-4}$
Pr_6	$2.82E^{-4}$	$1.00E^{-5}$
Pr_7	$1.44E^{-3}$	$3.00E^{-4}$
Pr_8	$1.95E^{-3}$	$1.00E^{-4}$
Pr_9	$2.27E^{-4}$	$3.00E^{-4}$
Pr_{10}	$1.07E^{-3}$	$3.00E^{-4}$
$P(TE)$	$1.29E^{-9}$	$6.48E^{-11}$

Fuzzy logic applications are suitable where human error might be involved. Basic events Pr_5, Pr_7 and Pr_{10} all involve an operator error. Probabilistically, human error was evaluated using a uniform distribution (Rish, 2005) based on work conducted by Swain (1987), so all human-related procedures had the same probability of failure based on the same distribution. In reality human errors vary depending on the situation. The fuzzy methodology accounts for human errors based on real life experiences working on hydraulically fractured wells. Therefore, each operator error leading to a different outcome using individual expert knowledge will have a more realistic output probability.

Results in Table 5.17 indicate a difference in magnitude of approximately 10 for all three operational error basic events (Pr_5, Pr_7, Pr_{10}). This is enough to equalize the values of the fuzzy method and probabilistic method. Additionally, there is a significant difference between the basic event Pr_1 probabilities which might also affect the top event. However, the FWI of this basic event is ranked lowest in Table 5.18 which indicates it has the lowest contribution to the overall system.

TABLE 5.18: Sensitivity analysis results conducted on pressure fault trees showing the FWI, probabilistic importance and criticality importance.

Basic event	FWI	Rank	Probabilistic importance	Rank	Criticality importance	Rank
Pr_1	$6.24E^{-4}$	10	$2.42E^{-7}$	3	$2.12E^{-2}$	7
Pr_2	$3.22E^{-3}$	5	$2.21E^{-10}$	5	$2.75E^{-4}$	8
Pr_3	$5.01E^{-3}$	1	$3.90E^{-10}$	4	$2.75E^{-4}$	8
Pr_4	$3.72E^{-3}$	4	$2.42E^{-7}$	3	$1.27E^{-1}$	5
Pr_5	$4.84E^{-3}$	2	$2.42E^{-7}$	3	$1.65E^{-1}$	4
Pr_6	$1.55E^{-3}$	8	$2.42E^{-7}$	3	$5.28E^{-2}$	6
Pr_7	$2.88E^{-3}$	6	$2.42E^{-7}$	3	$2.69E^{-1}$	3
Pr_8	$3.91E^{-3}$	3	$2.42E^{-7}$	3	$3.65E^{-1}$	2
Pr_9	$1.25E^{-3}$	9	$5.70E^{-6}$	1	1.00	1
Pr_{10}	$2.13E^{-3}$	7	$1.21E^{-6}$	2	1.00	1

The probabilistic importance and criticality importance values for basic events Pr_9 and Pr_{10} are very high indicating if either of these components fail, the system will fail (Cobo, 1996). Therefore it is vital to ensure the auto alarm system for detecting a pressure difference is tested frequently and operators are aware of potential errors in their practise.

Elements of the fault tree could require improvement for a more realistic situation during pressure control. It was suggested the control system failure events Pr_4 and Pr_6 could occur, but in reality would unlikely lead directly to an under-pressurised or over-pressurised system. If this occurrence was recognised, the sand would be flushed from the system and fracturing would stop, eliminating the failure probability altogether.

5.5.2 Event tree sensitivity analysis

Results in Table 5.15 indicate the large difference in probability for all three contamination events between scenario 1 and scenario 2 due to fewer barriers present in scenario 1. Production tubing is not used in scenario 1 which automatically eliminates the annulus pressure barrier. This pressure barrier was quantified using FTA and when calculated using either a probabilistic method or fuzzy method, the probability of failure is low at $6.5E^{-11}$ and $1.3E^{-9}$, respectively. Therefore, this element of the event tree has the largest effect on reducing the probability of groundwater contamination.

Assuming any one of the three failure events occurs, the method used in this research indicates scenario 1 would give a failure probability of $6.57E^{-6}$, and scenario 2 a failure of $8.82E^{-20}$ for the packer leak and $3.45E^{-19}$ for the tubing leak. If these probabilities are converted back to a fuzzy possibility, the values would be 0.08, $1.76E^{-3}$ and $1.93E^{-3}$, respectively. The linguistic terminology for these numbers fall into the categories 'very

low' which indicates the event is rarely encountered, never reported or highly unlikely over the stage of the well.

The result of $6.35E^{-6}$ for a scenario 1 well relates to the case study of a leaking well in BC, Canada which was hydraulically fractured in the Montney formation (Fig. 5.3). Within the Montney resource play, 19,337 wells have been drilled where 26 were shown to exhibit gas migration at the surface (Cahill et al., 2019), although the leaks could have occurred across any stage of the wells and it is unclear what initiated the leaks. This research demonstrates a risk assessment for a leak occurring at the production casing during well injection and gives a percentage probability of this occurring of 0.0006%. It is estimated the probability of gas migration occurring in wells drilled in BC in the Montney formation is 0.13%. Although these values are significantly different, the reasons for gas migration to the surface which could lead to potential groundwater contamination are not necessarily from the well injection process but could have occurred during drilling, production or abandonment. Additionally, this chapter only assesses risk of certain components failing related to well integrity but the risk potential increases cumulatively with the addition of other leak or migration pathways.

5.6 CONCLUSION

As a large controversial industry facing future fast growing developments worldwide, onshore hydraulic fracturing requires careful risk analysis and safety planning to ensure protection of the natural environment whilst utilising our energy resources in a sustainable way. This research has successfully developed a framework which analyses the risk to groundwater during well stimulation of a hydraulically fractured well. Common risk assessment techniques such as ETA and FTA have been utilised but they have been developed on a novel application which focused on cement failure and high pressure injection. The framework was successfully applied to a hydraulically fractured well in BC, Canada and a hypothetical well construction in the UK.

Conducting a risk analysis on subsurface environments is a huge challenge due to high uncertainty and lack of data. Fuzzy methods have been used to deal with areas in engineering which lack data and certainty. Therefore a combination of ETA and FTA along with fuzzy applications provides a framework to deal with the weaknesses and decreases the uncertainty experienced in conventional quantitative risk assessments, by eliminating binary information and replacing it with a range of linguistic inputs. This research tested the FFTA method against a conventional FTA method to demonstrate and validate the strength of using fuzzy logic. The outputs for both methods were similar supporting the use of FFTA and the fuzzy method was able to handle the quantification of human error more successfully than a standard uniform distribution.

The success of the fuzzy model enabled application to other areas within the injection stage which were a challenge to quantify. Well injection involves high water pressures injected down a casing or tubing which puts significant strain on the surrounding structure of the well, especially the cement between casings and formations. Cement failure during well stimulation is a challenge to quantify and there exists very little data surrounding this topic. Therefore, the fuzzy model was successfully applied to the failure of cement in both the horizontal and vertical directions. The incorporation of linguistic descriptors with expert opinions addressed the challenges in expressing cement failures and unknowns based on human error, especially on deciding cement selection or ensuring full removal of mud cuttings during drilling.

Sensitivity analysis was conducted to test the robustness of the fuzzy model under the presence of uncertainty. Importance measures are used in FTA to understand where safety performance in the system can be improved. FVIM, FWI, probabilistic importance and criticality importance are all successful measures in identifying critical aspects of the system. They allow an increased understanding of the relationship between inputs (basic events) and outputs (probabilities) of the system, demonstrate where unexpected relationships might occur and allow simplification of the model where inputs might have little affect on the output.

The quantification of cement allowed a more accurate representation of well integrity failure during well injection. The potential for groundwater contamination from well integrity failure was successfully applied using ETA to a hydraulically fractured well in BC, Canada and a hypothetical well construction in the UK. Due to an extra injection tubing and pressurized annulus, the UK construction had a significantly lower risk of groundwater contamination compared with the well in BC. The UK has not got an onshore hydraulic fracturing industry and therefore the UK scenario output cannot be compared against any historic data for validation. However, an estimation for gas migration in the Montney formation in BC indicated 0.13% failure rate which can be compared against the 0.0006% failure rate in this research. Although the values are significantly different, the value calculated in this work is specifically during the injection stage of a well for particular pathways whereas the historic value from BC is gas migration at any point in a wells life. Cumulative effects of failures over the lifetime of a well can be conducted using these methods for a more similar representation of well failure leading to gas migration.

The risk assessment framework applies a collection of known risk analysis methods to a new industry with the novel addition of quantifying cement failures. The addition of incorporating horizontal cement failure as well as vertical microannulus paths improves the accuracy of well integrity failure. An aspect of the fuzzy method is compared to a conventional technique which demonstrates the success of this research, and further validations on new methods requires alternative quantitative risk assessment approaches for comparison of methods directly applied to onshore oil and gas.

CHAPTER 6

RISK ASSESSMENT FOR GAS MIGRATION FOR A PRODUCTION WELL

6.1 INTRODUCTION

The production stage which involves gas returning to the surface is the longest stage of hydraulic fracturing. Production rates decline much quicker in unconventional wells compared to conventional, but can still be in the producing stage for 11+ years (Hardy, 2015). The risk of well integrity failure during gas production to the surface increases over time, increasing the risk of fugitive gas migration into groundwater. The structure of a well plays a big part in the potential for fugitive gas migration during production (Fleckenstein et al., 2015) and is therefore considered in this chapter using the development of event trees. As conducted in Chapter 5, event trees are used to demonstrate the failure of individual barriers which can lead to well integrity failure and groundwater contamination when multiple barriers fail.

The main elements which can lead to gas migration during production depend upon whether a well annulus is open or closed, the potential for cement failure (determined in Chapter 5) and whether the surface casing vent is open or closed. A closed well annulus is likely to have a lower risk of gas migration compared to an open annulus (Fleckenstein et al., 2015; Lackey et al., 2017) and an open surface casing vent valve allows venting to the atmosphere, reducing the impact on groundwater (Dusseault and Jackson, 2014). In this chapter, a model is developed using fuzzy logic to determine when a well annulus might be open or closed and the highest risk pathway to groundwater is numerically modelled where an open annulus leads to Surface Casing Pressure (SCP)-induced gas migration into groundwater.

The model is developed using data (where possible) from hydraulically fractured wells in an area in British Columbia (BC), Canada. Despite the vast numbers of wells drilled,

data sets are often incomplete or lacking important measurements which help determine the construction of a well or pressure changes within annuli. This work uses a tool which handles this uncertainty in measurements and data to provide a potential for SCP-induced gas migration into groundwater for production wells. Technical inputs which directly influence SCP when a well is producing are used, with the rate of gas leakage and the time for gas leakage to occur in order to determine the percentage of potential gas migration.

This chapter starts by presenting the theory and numerical calculations behind SCP-induced gas migration. The next section focuses on the design of model development which uses conceptual models and Event Tree Analysis (ETA) for barrier failure representation and outlines the case study and model validation application. Model development is discussed in Section 6.4 which uses fuzzy logic membership functions and the Mamdani Fuzzy Inference System (FIS) to build the fuzzy logic model and the numerical model is constructed. Section 6.5 uses a one-factor-at-a-time (OAT) sensitivity analysis approach to demonstrate the potential variability in the model and is used as a validation tool for the fuzzy model. Finally, the chapter concludes with the results and discussion and the applicability of the model to alternative branches in the event trees.

6.2 THEORY

The movement of fugitive gas into and out of a gas-producing well depends on many factors and requires a certain set of conditions. The theory described in this section explains the physical and mathematical concepts of fugitive gas migration from a leak. Gas migration can occur under any well construction scenario but at different probabilities of occurrence. The theory described here focuses on a well design with suitable surface casing depth but production cement which does not reach the bottom of the surface casing shoe, presenting an open annulus. This is indicated in Figure 6.1 and is the model for the basis of the equations.

Fugitive gas venting either at the annulus or at the surface away from the well can originate from the target formation, hydrocarbon-bearing formations sitting above the target or from inside the well. Gas invasion into faulty cement can occur from these external formations assuming the pressure differential allows the flow of gas into the cement annulus. The gas can then migrate up the well annulus and either vent into the atmosphere at the open Annulus-A casinghead valve or cause a build-up of pressure inside the well annulus if this vent is closed, leading to SCP. This pressure eventually reaches a critical point where it equals the surrounding formation pressures and any further build-up causes SCP-induced gas migration into groundwater (Lackey et al., 2017). The requirement for a closed or open casinghead valve depends on regulations of the state or country (Lackey et al., 2017).
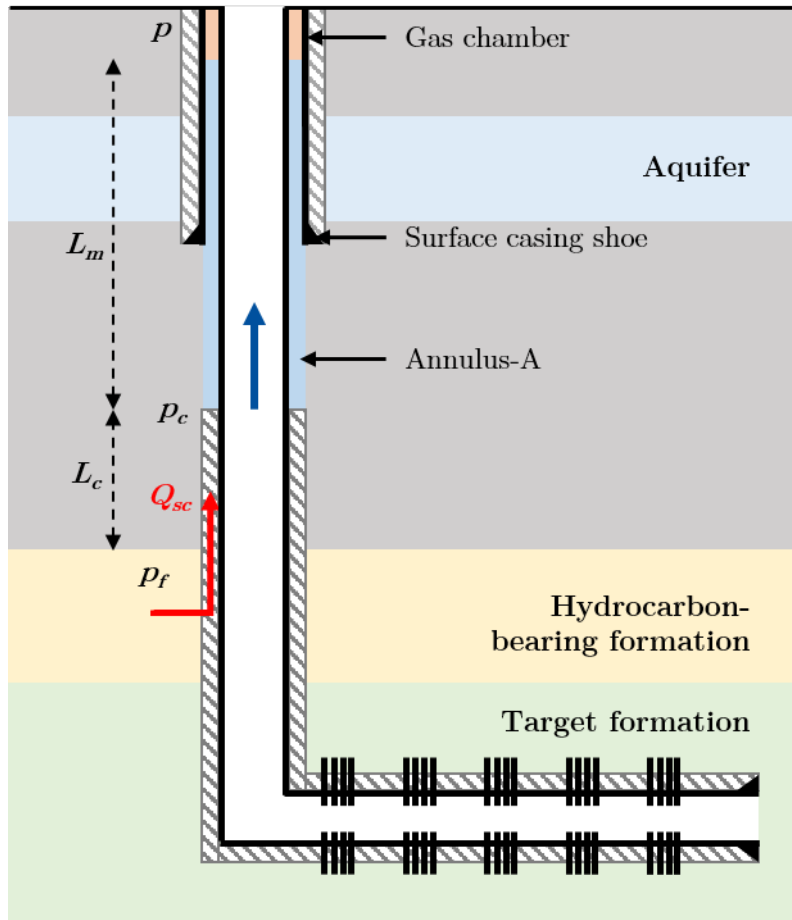
FIGURE 6.1: Conceptual model of a cement annulus adapted from Rocha-Valadez et al. (2014). p_f: formation pressure, Q_{sc}: gas flow rate, p_c: cement top pressure, p: casing head pressure, L_m: mud column length, L_c: cement column length.

6.2.1 Surface casing pressure

A numerical solution for the build-up of SCP inside a well annulus as in Figure 6.1 has been derived and modelled by Xu and Wojtanowicz (2001) and Xu (2002). Rocha-Valadez et al. (2014) presented an analytical solution to the model for the same well schematic and the mathematical expressions have been applied to this study.

The gas will flow into the faulty cement annulus if there is a pressure gradient between the external formation and the annulus. The flow of gas into the cement can be determined using Darcy's Law:

$$Q = \frac{kA}{\mu} \left(\frac{dp}{dx} \right) \tag{6.1}$$

where Q is the flow rate of gas in $\mathrm{m^3\,s^{-1}}$, k is the permeability of the cement path in $\mathrm{m^2}$, A is the area of the cement column in $\mathrm{m^2}$, μ is the gas viscosity in cP $\left(\equiv 1 \times 10^{-3}\mathrm{Pa\,s} \right)$, p is the change in pressure between the formation and cement top in Pa and x is the distance of the gas travelled in m, or the length of the cement column from the leak location. All

calculations are in SI units (not oilfield units) to support data inputs from the case study in Canada.

As the gas travels through the cement annulus, the gas flow rate will change due to a change in depth, which can be accounted for by considering the flow rate, temperature and pressure at standard conditions and the flow rate at in-situ temperature and pressure (Rocha-Valadez et al., 2014). This can be shown using the ideal-gas law at standard conditions and the ideal-gas law at in-situ conditions where the compressibility factor (or gas deviation factor) Z, must be accounted for outside of standard conditions:

$$p_{sc}V_{sc} = nRT_{sc} \qquad \text{(standard conditions)}$$
$$pV = ZnRT \qquad \text{(in-situ conditions)}$$
$$V = \frac{Zp_{sc}V_{sc}T}{pT_{sc}}$$

Divide both sides of the equation by time (t), we get an expression in terms of the flow rate:

$$Q = \frac{Zp_{sc}Q_{sc}T}{pT_{sc}} \tag{6.2}$$

Substitute equation 6.2 into equation 6.1 to obtain an expression for gas flow rate into a faulty cement annular column. The changes in temperature, pressure and compressibility factor as the gas flows through the cement are considered to be minimal and therefore these are taken as the initial conditions:

$$\frac{dp}{dx} = \frac{Z_i p_{sc} Q_{sc} T_i \mu_i}{kApT_{sc}} \tag{6.3}$$

Equation 6.3 can be integrated to obtain the gas flow rate (Q_{sc}) in terms of formation pressure (p_f), cement top pressure (p_c) and cement column length (L_c):

$$\int_{p_c}^{p_f} \left(\frac{kAT_{sc}p}{p_{sc}} \right) dp = \int_0^{L_c} (Q_{sc}\mu_i Z_i T_i) \, dx$$

$$Q_{sc} = \frac{kAT_{sc}\left(p_f^2 - p_c^2\right)}{2\mu_i Z_i T_i L_c p_{sc}} \tag{6.4}$$

The pressure at the top of the cement is unlikely to be known within field conditions so is determined numerically. During the influx of gas, the gas percolates through the mud column and sits at the top of the mud column due to buoyancy. Over time, this compresses the mud column length but this change is compensated by the change in mud density. Therefore, it can be assumed the pressure exerted on the mud column (hydrostatic pressure of the mud column) is constant (Rocha-Valadez et al., 2014). This means the pressure increase at the top of the cement can be attributed solely to the increase in the

pressure within the annulus (Rocha-Valadez et al., 2014). The cement top pressure is calculated by adding the pressure at the top of the mud created by the gas (casinghead pressure) and the hydrostatic pressure of the mud column (Xu, 2002):

$$p_c = p + g\rho_m L_m \tag{6.5}$$

where p_c is the pressure at the top of cement in Pa, p is the casinghead pressure in Pa, g is gravity at 9.81 m s^{-2}, ρ_m is mud density in kg m^{-3} and L_m is mud column length in m. $g\rho_m L_m$ is the hydrostatic pressure of the mud column.

Equation 6.5 can be substituted into equation 6.4 to obtain an expression for gas flow into a cemented annulus (Rocha-Valadez et al., 2014):

$$Q_{sc} = \frac{kAT_{sc}\left(p_f^2 - (p + g\rho_m L_m)^2\right)}{2\mu_i Z_i T_i L_c p_{sc}} \tag{6.6}$$

According to equation 6.6, gas will only flow into the annulus ($Q_{sc} > 0$) if:
$p_f^2 - (p + g\rho_m L_m)^2 > 0$
i.e. $p_f > p + g\rho_m L_m$

This makes intuitive sense as the external formation pressure will be larger than the combined annulus pressure, causing a pressure gradient which allows gas to move from outside to inside the well annulus. As the casinghead pressure increases with an influx of gas, eventually an equilibrium will be reached where $p_f = p + g\rho_m L_m$ and there will be no influx of gas. In this case, the maximum casinghead pressure has been reached; $p = p_{max}$.

6.2.2 SCP-induced gas migration

In the case of Figure 6.1, there is a shallow groundwater aquifer and a surface casing shoe which sits just below the aquifer (a standard construction to protect groundwater). The aquifer will be a lower pressure than the formation where the gas leak originates from. This is due to a shallower depth and much higher permeability in the aquifer compared to the hydrocarbon-bearing formation near the horizontal well. When the gas has reached the surface casing shoe, a lack of cement and a closed Annulus-A casinghead valve allows the gas to migrate underneath the casing shoe and outside the annulus into groundwater. This is known as SCP-induced gas migration. Figure 6.2 illustrates the lengthening of the gas column over time to reach the critical point at which gas can migrate outside the annulus.

Lackey et al. (2017) assessed fugitive gas migration into shallow groundwater via this pathway and determined how to calculate the critical SCP. Similarly to deep formation pressure, casing pressure with respect to the surrounding formation is calculated based
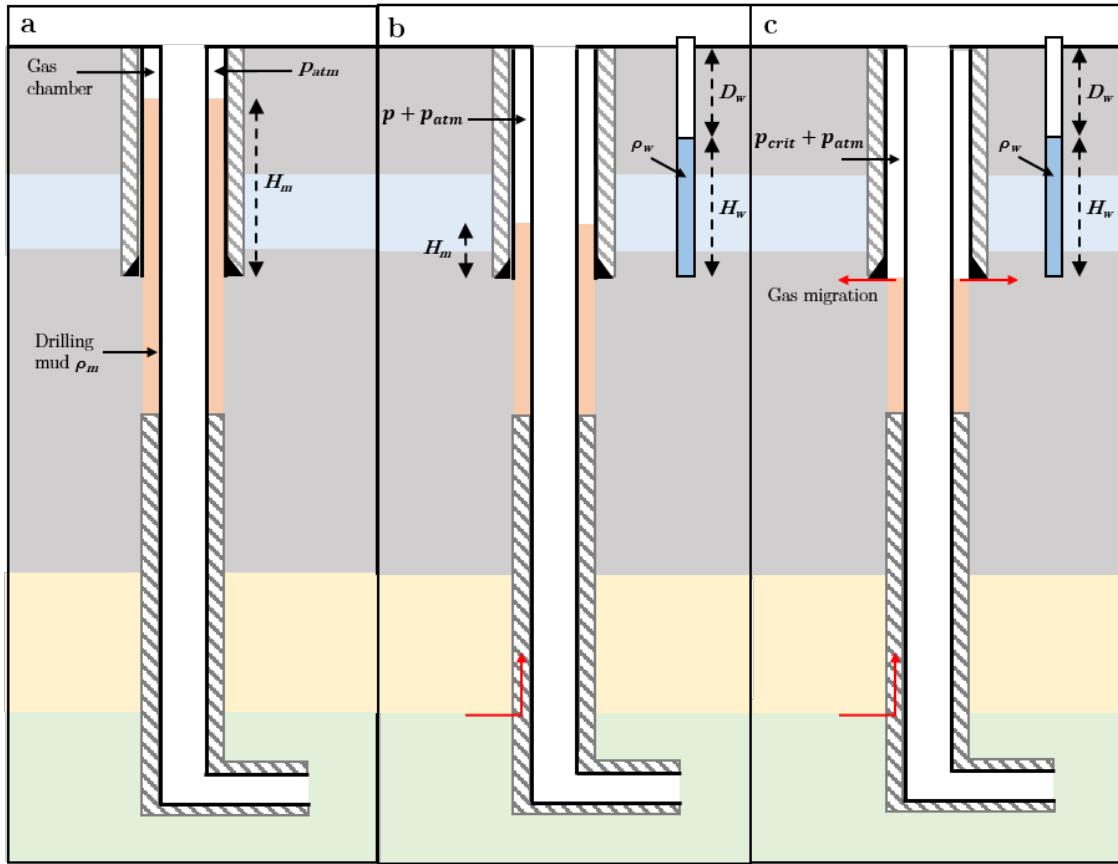
FIGURE 6.2: Stages leading to SCP build-up and eventually SCP-induced gas migration under the surface casing shoe from a leak originating at the target formation. (a) A well in its natural state before gas flows into the faulty cement annulus, (b) a flow of gas into the annulus causes a build-up of gas in the gas chamber leading to SCP, (c) continuous influx of gas causes the top of the mud column to reach the base of the surface casing to reach critical SCP where the pressure equals the surrounding hydrostatic pressure of the aquifer. Any further increase in gas exceeds the hydrostatic formation pressure and leads to gas migration. Adapted from Lackey et al. (2017).

ρ_m: mud density, p_{atm}: atmospheric pressure, H_m: mud column length above surface casing shoe, p: casing pressure, ρ_w: water density, D_w: static water depth, H_w: potentiometric head above surface casing shoe, p_{crit}: critical casing pressure.

on the hydrostatic column above the surface casing shoe and the surrounding formation pressure:

$$g\rho_m H_m + p = g\rho_w H_w \tag{6.7}$$

where H_m is the height of the mud column above the surface casing shoe, ρ_w is 1000 kg m^{-3} for water density and H_w is the height of the potentiometric surface above the surface casing shoe. Once H_m reaches the surface casing shoe i.e. $= 0$, the casing pressure is now critical as any further build-up could lead to gas migration outside the annulus:

$$p_{crit} = g\rho_w H_w \tag{6.8}$$

Therefore, the SCP at the critical point when the gas has reached the surface casing shoe can be calculated based on the hydrostatic pressure of the surrounding formation. This assumes that if gas leaks into an open well annulus, over time the pressure in the annulus will build-up to reach the surrounding aquifer pressure. If the aquifer pressure is still less than the pressure of the deeper formation where the original leak is, further inflow at the leak will encourage gas migration into the aquifer.

6.2.3 Gas flow and time

Once the critical casing pressure has been determined, equation 6.4 can be used to calculate the flow of gas into the annulus at this casing pressure. It is assumed the gas flow is at a steady state and therefore the flow of gas into the well equals the flow of gas exiting the well. Equation 6.4 is used to determine the flow rate through the cement column. The gas must also travel through the mud column before it reaches the top. However, due to the cement column being significantly longer with a much lower permeability than the mud column, it is assumed when the gas reaches the top of the cement, it immediately reaches the top of the mud column with no entrapment of gas in the mud column (Xu, 2002). Therefore gas flow is determined based on the flow through the cement.

The time taken for the well to reach critical SCP is also determined. The volume of gas in the gas chamber is calculated based on the area of the annulus and depth of the surface casing and the flow rate is used to determine the time. The time taken for the well to reach critical casing pressure and the flow of gas into the aquifer are used to determine the variation in probability of SCP-induced gas migration across different wells.

6.3 DESIGN AND METHODOLOGY

Fugitive gas migration along vertical pathways within a wellbore is a common problem during gas-producing hydraulically fractured wells. Gas transport leads to SCP which in turn can cause Surface Casing Vent Flow (SCVF) to the atmosphere, SCP-induced gas migration, gas circumvention or gas dissolution into potential groundwater aquifers or surrounding rock formations to eventually reach the surface. Gas migration is often dependent on well construction and regulations, surrounding geological formations and pressure changes and almost always due to faulty cement or improperly cemented gas-bearing formations (Lackey and Rajaram, 2019).

6.3.1 Conceptual model

Gas migration can originate from the target reservoir if a fault in the cement has occurred within this region. Shallower gas-bearing formations, particularly those which are over-pressurised, can also be the source of fugitive gas where a fault in the cement exists or poor well construction has left an open annulus surrounding this formation (Figure 6.3). Additionally, a leak in the production casing can cause gas within the well to move out into an open annulus.
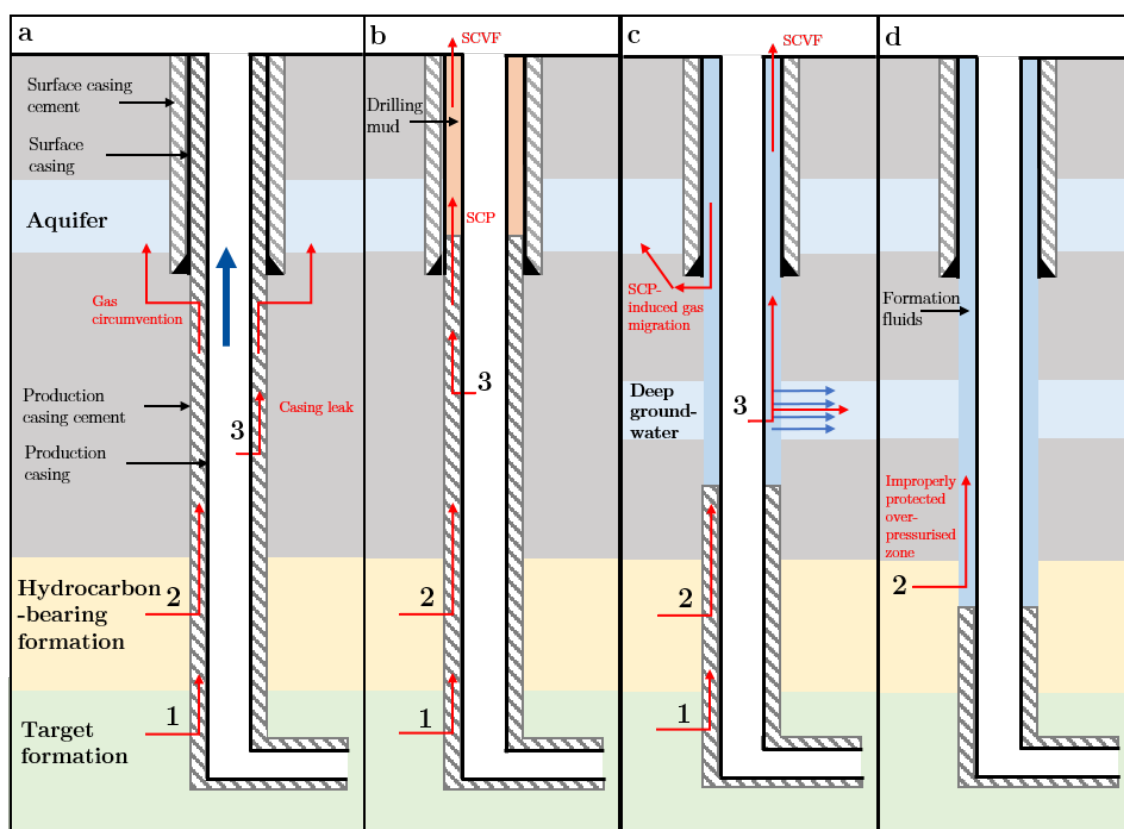
FIGURE 6.3: Conceptual models of four different scenarios of well construction based on changes in production cement height showing fugitive gas migration pathways from faulty cement. (a) Fully cemented well showing gas circumvention leading to groundwater contamination, (b) partially cemented well to the base of the surface casing showing SCP and/or SCVF leading to atmospheric releases, (c) partially cemented well above a hydrocarbon-bearing formation showing deep groundwater contamination, SCVF to the atmosphere and SCP-induced gas migration to shallow groundwater, (d) partially cemented well only securing the target reservoir showing easy gas migration into an open annulus with the potential of groundwater and atmospheric contamination. The numbers 1-3 represent the three sources of gas leaks: (1) faulty cement within the shale gas reservoir, (2) faulty cement within a shallower gas-bearing formation, and (3) production casing leak allowing producing gas inside the wellbore to migrate outside.

Poor well construction can be signified by the cemented annulus along the production casing, often the outermost annulus, not reaching the surface of the well and hence leaves an open annulus along certain sections of the well. Figure 6.3 shows four wells of varying

production cement lengths: fully cemented to the surface (a), cemented to the base of the surface casing (b), cemented above shallower gas-bearing formations (c), or cemented just above the target reservoir (d).

A fully cemented well has the lowest risk of gas migration but where faults could develop in the cement, gas migrates along vertical cement pathways and where higher quality cement overlies poor quality cement, gas circumvention occurs where gas is forced into preferential pathways into surrounding formations (Lackey and Rajaram, 2019). An open annulus behind the surface casing and surface casing cement allows pressure to build-up if there is an in-flow of gas further down which can lead to SCP or SCVF. If an annulus is left fully open to the surroundings, this gives access to horizontal gas migration in deeper groundwater flows. Additionally, a build-up of pressure in the annulus can lead to SCP-induced gas migration when the pressure is lower at the base of the surface casing compared to the annulus pressure. Finally, a significantly high risk well construction where the cement does not cover over-pressurised gas-bearing formations allows easy movement of gas to migrate into an open annulus leading to deep groundwater gas migration, SCP and/or SCVF.

In Figures 6.3a and 6.3b, a fault in the cement could be 'healed' if SCP builds up in the cement annulus column and reaches a pressure equal to or greater than the original formation pressure surrounding the location of the leak. If the cement is of decent quality along the annulus above the leak, gas circumvention will not occur and gas flow into the annulus will stop due to a lack of pressure gradient between the formation and annulus.

6.3.2   Event tree development

As conducted in Chapter 5, event trees are developed from the conceptual models in Figure 6.3 to clarify the pathways which can lead to groundwater contamination and demonstrate the probabilities of each event occurring (Figure 6.4). These event trees represent scenarios 3 and 4 illustrated in Chapter 3; integrity failure during production from an external formation and integrity failure during production from an internal wellbore.

The theory behind gas migration, SCP and SCVF demonstrated in Section 6.2 has been explained using a mathematical model developed by Xu (2002) and Rocha-Valadez et al. (2014) using the example of a wellbore construction which has an open annulus, as indicated in Figure 6.3c or 6.3d. The theory focuses on the increase of SCP within a closed surface casing vent valve system leading to the potential occurrence of SCP-induced gas migration; pathway P_3 (3) and P_4 (3) in Figure 6.4. The theory assumes the leak occurs at a gas formation (source 1 or 2 in Figure 6.3) through a partially cemented annulus, but could be adapted for a casing leak (source 3 in Figure 6.3). Therefore, the model developed for this chapter will mainly focus on P_3 (3) shown in Figure 6.4a, but discussions will be made on alternative pathways within the event trees related to model development and
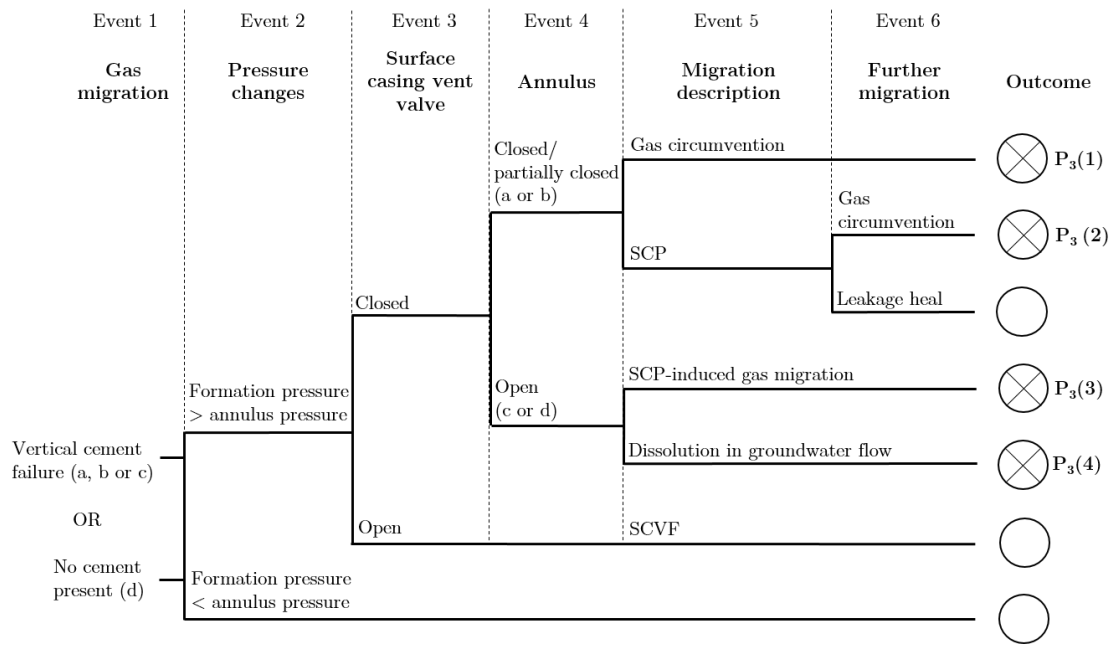
(A) Scenario 3: Vertical cement failure event tree.
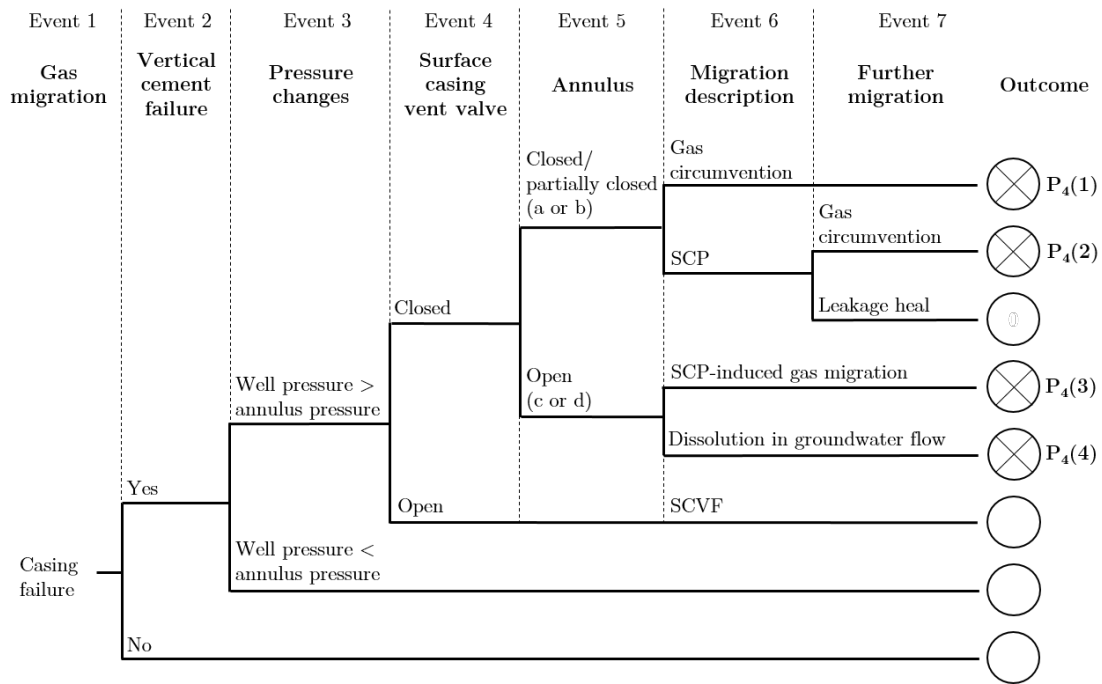
(B) Scenario 4: Production casing failure event tree.

FIGURE 6.4: Two event trees for the probability of groundwater contamination from cement failure or production casing failure leading to gas migration in a production hydraulically fractured well. Letters a, b, c and d represent the four diagrams in Figure 6.3. The potential groundwater contamination incidents are defined as $P_x(y)$ where x is scenario 3 or 4 and y is outcome 1, 2, 3 or 4. $P_x(4)$ is more likely to occur in deeper groundwater.

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risk assessment. Within this model, it is assumed the leak has occurred in the reservoir formation to suit the availability of data.

6.3.3 Case study and data collection

In this thesis, BC in Canada is selected as the case study for model development of both injection and production hydraulically fractured wells with a more detailed description of the site explained in Chapter 4. Model development in this chapter requires data inputs to formulate the probability of SCP-induced migration dependent on well construction and geological conditions. The inputs for each well required to understand SCP are: mud column length (L_m), mud column density (ρ_m), reservoir formation pressure (p_f), cement column length (L_c) and reservoir temperature (T_i). Parameters are required to calculate gas flow which are: cement permeability (k), area of cement column (A), gas viscosity (μ_i), Z-factor (Z_i) and standard temperature and pressure (T_{sc}, p_{sc}). These stay constant during the use of the model but can be altered if required.

Well data was received from the BC Oil and Gas Commission (BCOGC) which consisted of all horizontal wells drilled in the Montney formation between 2008 and 2017. A significant challenge with quantifying well failure is a lack of data, incomplete data sets or too few data entries to make sensible statistical conclusions. Therefore within these documents, well IDs were selected which ensured all columns of data were present to avoid gaps in data inputs and due to the large number of wells drilled in Canada, this elimination still produced 915 individual wells.

Mud column length, mud density, shallow hydrostatic formation pressure and cement column length are all required data inputs for the model which are not obligatory measurements for petroleum field engineers and therefore do not exist in the data set. Table 6.1 explains the data manipulation required to obtain suitable data sets.

Mud density is estimated using gravity and the pressure gradient at the target formation depth; data which is provided. Further information and calculations are provided in Section 6.4.2.2. This data set calculates the density of mud at the Total Vertical Depth (TVD)[1] of the well but the model requires the mud density of the mud column above the top of the production cement. Mud density is expected to decrease slightly as depth decreases and therefore is determined more accurately as a function of the mud column length.

Mud column length is an unknown within the data set so further work is required to determine these inputs. As an alternative method, fuzzy logic is used to produce the input functions, discussed in more detail in Section 6.4.

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[1]The TVD of a well is not to be confused with the Measured Depth (MD). Vertical depth corresponds to the depth at which the bottom of the vertical section reaches but MD is the distance along the wellbore and considers deviated sections of a wellbore. This is illustrated later in Figure 6.9.

TABLE 6.1: The availability of well data for model development from the BCOGC database and the solutions for dealing with insufficient or incomplete data sets.

Model inputs	Data availability	Solution	Data type
Mud column length, L_m	None	Fuzzy logic functions using casing depths, hydrocarbon-bearing formation depths and Measured Depth (MD).	Fuzzy linear function
Mud column density, ρ_m	None	Calculated using target formation data. Fuzzy logic function using mud column length.	Fuzzy linear function
Reservoir formation pressure, p_f	Full data set	Available in the data set for every required well. Location of leak adjusted in model to match formation pressure measurements.	Crisp value
Shallow hydrostatic formation pressure, p_{sf}	Partially	Calculated using static groundwater levels and surface casing depths.	Crisp value
Cement column length, L_c	None	Calculated using reservoir formation depth and mud column length.	Crisp value
Reservoir temperature, T_i	Full data set	Available in the data set for almost every required well.	Crisp value

The leak location could be from the overlying hydrocarbon-bearing formation (Figure 6.1) or reservoir formation. However, data only exists for reservoir formation pressures before depletion and therefore the leak is considered to occur from the target formation rather than the overlying strata.

The shallow hydrostatic formation pressure is estimated based on static water levels near where each well is drilled (Figure 6.2) and fresh water density. To determine the potentiometric head (H_w), the static water depths (D_w) were obtained from the BC groundwater wells and aquifers registry and subtracted from the surface casing depths (D_{sc}) (*British Columbia Groundwater Wells and Aquifers*). Further information on this source and calculation is covered in Chapter 4.

6.3.4   Procedures for model validation

Validation aims to demonstrate the applicability of a model to real world applications; to indicate how accurate the model is for its intended purposes (Thacker et al., 2004). A key point in model validation is to recognise its accuracy for a specific scenario (Thacker et al., 2004); in this case for a well drilled as indicated in Figure 6.3c.

A challenge often faced in model validation is a lack of sufficient data, in particular with models developed using fuzzy logic (Shang and Hossen, 2013), where data scarcity was the initial reason for using fuzzy logic techniques. The data provided by BCOGC did not

always divulge the construction of each well, making it a challenge to determine which wells had the required construction for the model.

The data employed for model development consisted of 915 individual wells due to the extensive numerical values for surface casing depths, target formation depths and MDs. However, a significant reduction in pressure measurements meant only 337 wells could be used to determine mud column length and maximum casing pressure. Out of 337, 256 wells were said to have production cement tops higher than the base of the surface casing, making those wells constructed as in Figure 6.3a or b, while the rest were not declared. This can be used as a method of validation for the first part of the model in estimating the mud column length. Due to a lack of reservoir temperature measurements, only 311 individual wells could be run through the whole model to calculate gas flow and time.

The aim of the model is to determine the probability of SCP-induced gas migration leading to groundwater contamination from critical casing pressures. Wells exhibiting signs of gas migration seen at the surface are known within the BC province but these are not an exhaustive list, ignoring especially those which could be leaking into groundwater but not showing signs at the surface. In addition, little information is known on the reasons for these leaking wells and therefore the model outputs cannot be validated directly against those wells showing fugitive gas migration.

Model validation approaches such as expert intuition, theoretical results and real system measurements are common techniques but all consist of disadvantages (Liu, 2015). Expert intuition is often the most suitable for fuzzy logic models as theoretical results provide crude validations with inconsistency in practise compared with theory, and real system measurements require significant data to compare modelled data with observed data (Liu, 2015). Expert intuition is subjective and can be ambiguous. However after testing the model on the 311 wells, the outputs can be used to adjust, improve and validate the model based on experience data and expert intuition. The actual experience with the model enables adjustments of the model parameters i.e. membership functions and inference rules (Shang and Hossen, 2013) (see Chapter 3).

Unlike heavily data-driven models, fuzzy logic models put less emphasis on experience data and validation. Often appropriate data will only be collected after the development and implementation of the fuzzy logic model and only at this point will revising of parameters, membership functions and inference rules be successful (Shang and Hossen, 2013). Therefore, fuzzy logic models can be expected to change and adapt with increasing information and hence validation should be an on-going process.

6.4 MODEL DEVELOPMENT AND CONSTRUCTION

6.4.1 Framework

The aim of a risk assessment framework within the scope of this research is to construct a model which calculates the probability of groundwater contamination occurring. The focus of this chapter is to understand the potential for fugitive gas migration within a wellbore to lead to groundwater contamination via SCP-induced gas migration. The chapter explores a mathematical understanding of SCP build-up and combines this with fuzzy logic analysis using a Mamdani inference system.

The framework for the proposed methodology is indicated in Figure 6.5. There are three main components which make up the risk assessment: (1) a literature analysis and data collection, (2) model development using fuzzy sets, and (3) model validation. Data collection helps determine where crisp values can be used directly for the numerical model and where fuzzy functions must be created. Model development uses the inputs from the mathematical equations which lack data and converts them into fuzzy inputs and outputs. The Mamdani FIS is applied to develop 'IF-THEN' rules between the input and output fuzzy functions. The model is run combining the fuzzy system with a numerical model and model validation allows adjustments to be applied to the functions where results seem incorrect based on expert judgement and literature.

The final model outputs the probability of SCP-induced gas migration for a range of horizontal wells in Canada. This probability is determined using fuzzy logic where gas flow and time taken are inputs and probability is the output.

6.4.2 Fuzzy logic application

The mud column length is vital information for understanding the construction of a well. Knowing the surface casing depth and mud column length determines which construction the well takes in Figure 6.2. As described in Section 6.2, the only way for gas migration to occur along a vertical well annulus is if the formation pressure at the location of the leak is greater than the combined annulus pressure:

$$p_f > p + g\rho_m L_m \tag{6.9}$$

To understand the differences in pressure, the hydrostatic pressure of the mud column is required ($g\rho_m L_m$). Mud column length and mud density are not measured or not available within the selected data sets (Table 6.1) so fuzzy logic is applied to estimate the hydrostatic pressure of the mud column.

Identify sources and gas migration pathways

Event tree construction

Select pathway and develop mathematical equations

Data collection

Available data

Unavailable data

Crisp input values

Apply fuzzy logic

MODEL DEVELOPMENT

Select data sets

Create membership functions
Are the data uniform?

No

Yes

Select alternative method

Apply box plot method

Mamdani inference system

Produce input and output functions

Produce inference rules

MODEL VALIDATION

Select data sets

Adjust functions

Run model

Sensitivity analysis

FIGURE 6.5: Framework for developing a risk analysis using fuzzy logic and the Mamdani system for a hydraulically fractured well during the production stage.

To determine an estimate for the final probability, gas flow and time are used which are also uncertain variables. Both are calculated in the model and the probability is determined using fuzzy logic.

6.4.2.1 Fuzzy membership functions

There are several methods available for constructing fuzzy membership functions, as detailed in Chapter 3, but the methods either require qualitative expert knowledge or sufficient input and output data to produce training and validation sets for machine learning techniques. This research has applied a box plot technique demonstrated by Asanka and Perera (2017) to create trapezoidal membership functions. The technique has only emerged recently but is a way of producing membership functions from data rather than solely relying on expert decisions; bridging the gap between only qualitative or only quantitative information. A flow chart to indicate the box plot method and its criteria is shown in Figure 6.6.
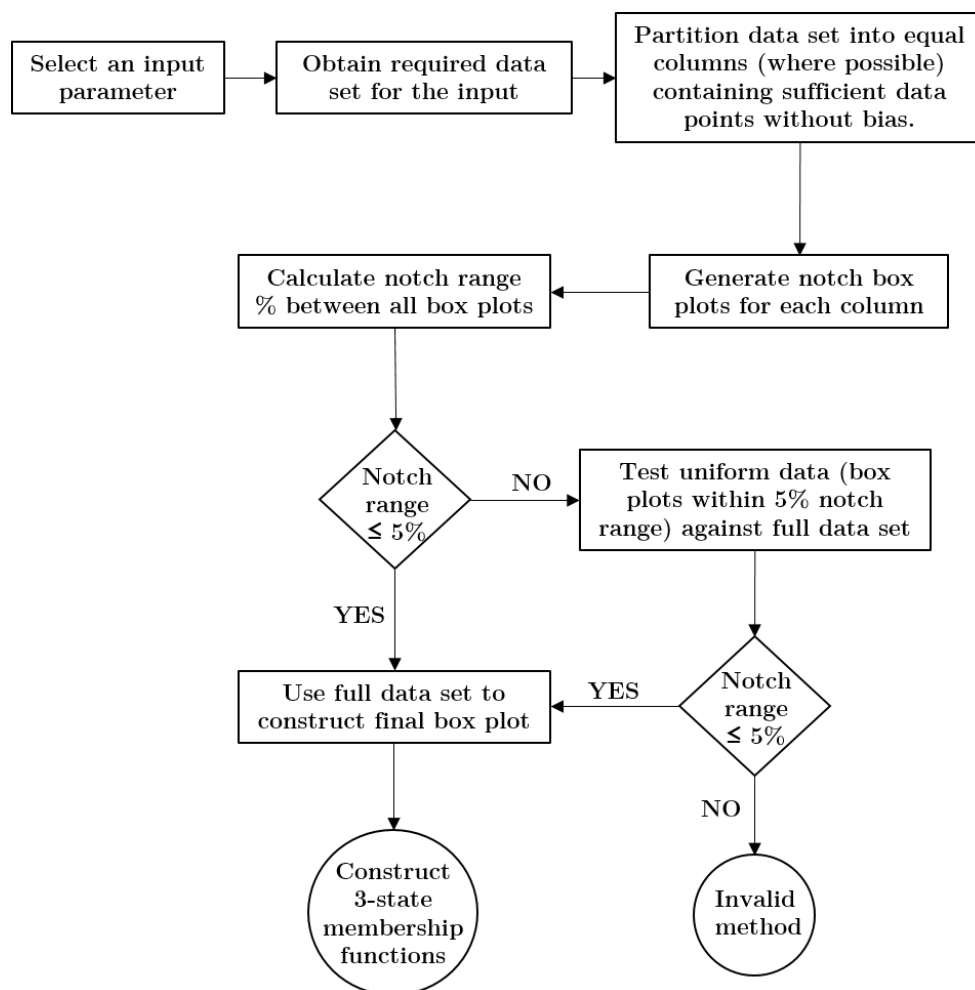
FIGURE 6.6: A flow chart indicating the steps required to apply the box plot technique.

As indicated in Figure 6.6, the constraints of the method require uniform data sets to be most effective. These data sets are tested for uniformity using notched box plots where the notch range must be within 5%. To demonstrate this, Figure 6.7 shows the construction and elements of a standard and notched box plot. A standard box plot involves the maximum, minimum, Lower Quartile (LQ), Upper Quartile (UQ) and median of a data set. These elements themselves can make up a fuzzy membership function. Notched box plots are useful in judging the 95% confidence interval between different sample medians, given by $m_-^+\frac{1.58\times IQR}{\sqrt{n}}$, where m is median, IQR is Interquartile Range and n is the number of sample points (Krzywinski and Altman, 2014). This method can be used to determine if the data used is uniform. If the range of the notches is within 5%, it can generally be assumed the data is uniform if the sample size is large enough (Krzywinski and Altman, 2014). The data used to create the fuzzy membership functions consists of almost 1000 sample points for each fuzzy input and therefore is considered suitable for this method.
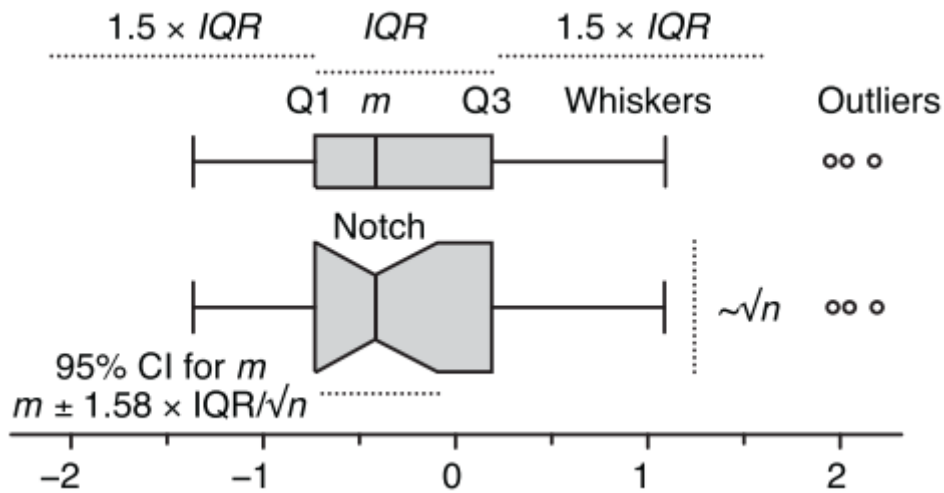
FIGURE 6.7: Construction of a standard and notched box plot (Krzywinski and Altman, 2014). The whiskers can either illustrate the maximum and minimum data points or Tukey-style whiskers extend to a maximum of $1.5 \times IQR$ beyond the box. The box might be scaled by $\sqrt{n}$, open circles are sample data points and the dotted lines indicate the lengths and widths of annotated features (Krzywinski and Altman, 2014).

For this work, trapezoidal membership functions are most appropriate as often it is a challenge to determine an exact value at which the membership function fully exists in the universe, so a triangular function is harder to construct. A trapezoidal function allows a range of values at which for any element x of universe X, the membership function $\mu_{\underset{\sim}{A}}(x) = 1$. The functions are created based on the maximum and minimum outliers, Tukey-whiskers and the lower and upper quartiles. The 3-state trapezoidal function is described by the equations below and is illustrated in Figure 6.8.
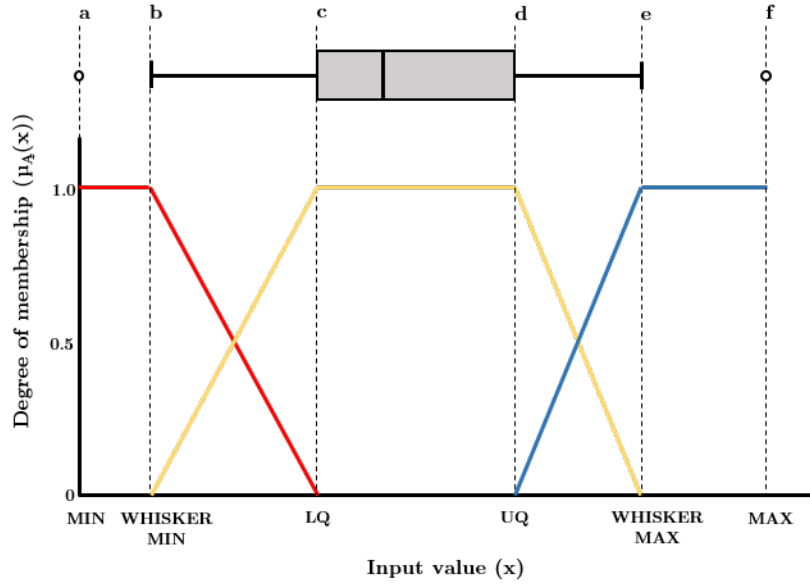
FIGURE 6.8: Applying the standard box plot elements to a 3-state trapezoidal membership function. The open circle represents minimum and maximum outliers. LQ: Lower Quartile, UQ: Upper Quartile. Whiskers represent the Tukey-whiskers at $1.5 \times IQR$. Occasionally, the minimum will be greater than the whisker minimum and the maximum will be lower than the whisker maximum. In this situation the minimum and whisker minimum, and maximum and whisker maximum will switch around.

$$
\mu_{\underset{\sim}{A}}(x : a, b, c) = \begin{cases} 1 & a \leq x \leq b \\ \frac{c-x}{c-b} & b \leq x \leq c \\ 0 & x > c \end{cases}
$$

$$
\mu_{\underset{\sim}{A}}(x : b, c, d, e) = \begin{cases} 0 & x < b \\ \frac{x-b}{c-b} & b \leq x \leq c \\ 1 & c \leq x \leq d \\ \frac{e-x}{e-d} & d \leq x \leq e \\ 0 & e \leq x \end{cases} \tag{6.10}
$$

$$
\mu_{\underset{\sim}{A}}(x : d, e, f) = \begin{cases} 0 & x < d \\ \frac{x-d}{e-d} & d \leq x \leq e \\ 1 & x > f \end{cases}
$$

6.4.2.2 Membership function data sets

The final conceptual model applied to support the data set used is shown in Figure 6.9. The unavailable, but required, data is highlighted in green and the parameters used to create fuzzy functions are denoted with a *. Table 6.2 illustrates each fuzzy membership function and the method used to develop it. Surface casing depth, hydrocarbon depth, MD, mud density at TVD and gas flow all use a data set to create box plots as their membership functions (Table 6.2).
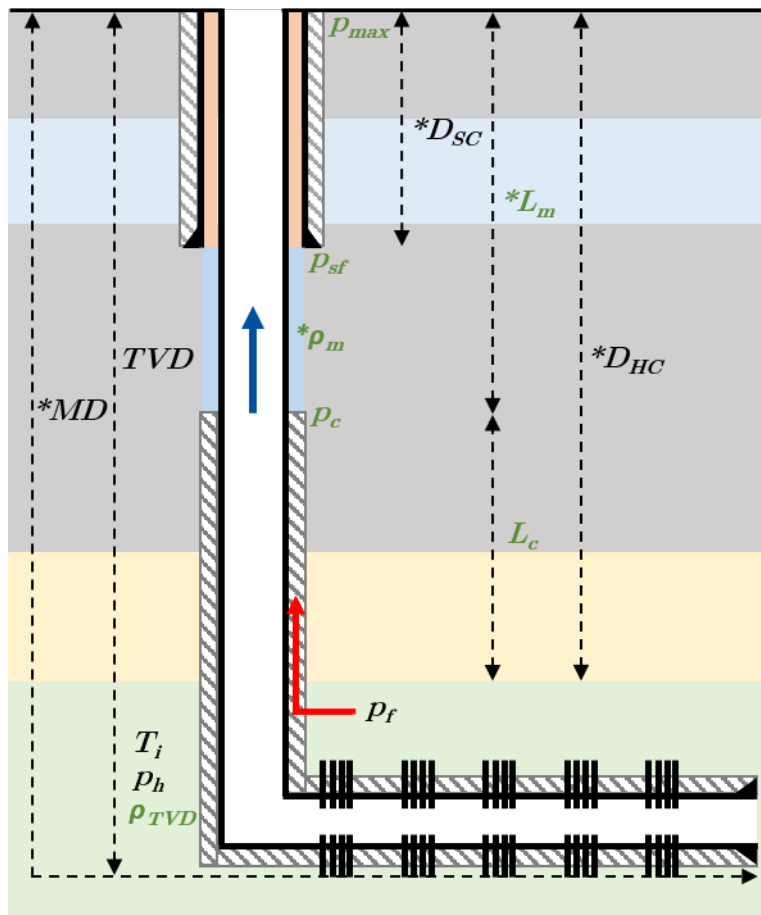
FIGURE 6.9: Final data measurements from a wellbore used as crisp values or for the development of fuzzy membership functions. The parameters highlighted in green represent unavailable data but which are required for model development and those with a * are used to create fuzzy functions.

MD: measured depth, TVD: total vertical well depth, T_i: reservoir temperature, p_h: hydrostatic pressure at TVD, ρ_{TVD}: mud density at TVD, p_f: reservoir formation pressure, p_c: cement top pressure, ρ_m: mud column density, p_{sf}: shallow hydrostatic formation pressure (critical casing pressure), p_{max}: maximum casinghead pressure, D_{SC}: surface casing depth, L_m: mud column length, L_c: cement column length, D_{HC}: hydrocarbon depth.

However, before the data sets can be used to create the fuzzy membership functions, they required manipulating to ensure the correct data was used for each parameter. The data

TABLE 6.2: Development of each fuzzy membership function.

Fuzzy functions	Type	Method
Surface casing depth (D_{SC})	Input	Box plot
Hydrocarbon depth (D_{HC})	Input	Box plot
Measured Depth (MD) (MD)	Input	Box plot
Mud density at TVD (ρ_{TVD})	Output	Box plot
Geology factor	Intermediate	Expert judgement
Mud column length (L_m)	Intermediate	Expert judgement
Gas flow (Q_{sc})	Input	Box plot
Time (t)	Input	Expert judgement
Probability	Output	Expert judgement

used for creating the membership functions for surface casing depth, hydrocarbon depth, MD, mud density and gas flow came from the BCOGC. The data set consisted of all wells whose rig release date was between 09/2008 - 12/2017. All wells were horizontally drilled into the Montney or Doig target formations. In total this database consisted of 1,236 individual wells but not all well ID's contained the required data. Wells were selected which contained data on surface casing depth, target reservoir depth and MD. Surface casing depth required all wells which had casing diameters of 177.8 mm, 193.7 mm, 219.1 mm, 244.5 mm and 339.7 mm. These are standard diameters for surface casings and highlighted in the data set as surface casings. Wells were filtered to contain those which had data on upper target reservoir depth and MD. After these eliminations, 915 individual wells were selected for producing the fuzzy membership functions for surface casing depth, hydrocarbon depth and MD.

The data sets for mud density and gas flow to create the fuzzy functions required different manipulations and different numbers of data points. The methods for adjusting these two data sets are described below.

Mud density

Mud density was not provided for each individual well and therefore had to be calculated before creating the fuzzy membership function. Mud density is estimated by using the pressure gradient at the measured pressure depth for each well and divided by gravity. This is a standard hydrostatic pressure calculation within a well annulus:

$$p_h \left(gradient \right) = \frac{p_h}{TVD} \tag{6.11}$$

$$\rho_{TVD} = \frac{p_h \left(gradient \right)}{g} \tag{6.12}$$

where $p_h \left(gradient \right)$ is the hydrostatic pressure gradient (Pa m^{-1}), p_h is the hydrostatic pressure (Pa), TVD is the Total Vertical Depth to the pressure measurement (m), ρ_{TVD} is the mud density at the TVD (kg m^{-3}) and g is gravity (9.81 m s^{-2}).

Once this column has been added to the data set of 915 wells, all wells which do not contain mud density measurements are removed and densities which are below 900 kg m^{-3} or above 1999 kg m^{-3} are removed. Mud densities are expected to range between 1000-1600 kg m^{-3} demonstrated by a few mud weight values from drilling documents from two specific wells and from input parameters for oil and gas wells used by Rocha-Valadez et al. (2014). This range is extended to cover slightly abnormal target formations with lower or higher than expected pressure values. After these eliminations, 337 individual wells were selected for producing the fuzzy membership function for mud density at TVD.

Gas flow

Gas flow data was only available in wells which were tested and showed signs for SCVF at the wellhead. The membership function for gas flow was created using this data set from the BCOGC. Although this gas flow represents surface emissions, it is assumed the range of values are similar to those seen in subsurface gas migration. From this data set, 154 wells demonstrating gas migration were selected for producing the fuzzy membership for gas flow rate.

6.4.2.3 Membership degrees for parameters

The data sets chosen for each parameter are tested for uniformity to ensure the box plot method is valid (Figure 6.6). The results to test for uniformity on each data set are summarised in Table 6.3. The individual box plots for each partitioned column for each input function are shown in Figure 6.10. The horizontal lines on the plots help to visualise the notch overlaps and the partitioned columns were divided into a sensible number to ensure each box plot contained sufficient data points.

TABLE 6.3: Results from partitioning each data set and determining uniformity across the data. Uniform box plots are those which demonstrated a notch overlap across the 7 or 10 box plots for each input function. Complete notch overlaps enables a full data set to be used.

Input function	No. of data points	No. of partitioned columns	Notch overlaps?	Final data set used
Aquifer depth (Surface casing depth)	915	10	YES	Full data set
Hydrocarbon depth	915	10	YES	Full data set
MD	915	10	YES	Full data set
Mud density	337	10	YES	Full data set
Gas flow rate	154	7	YES	Full data set
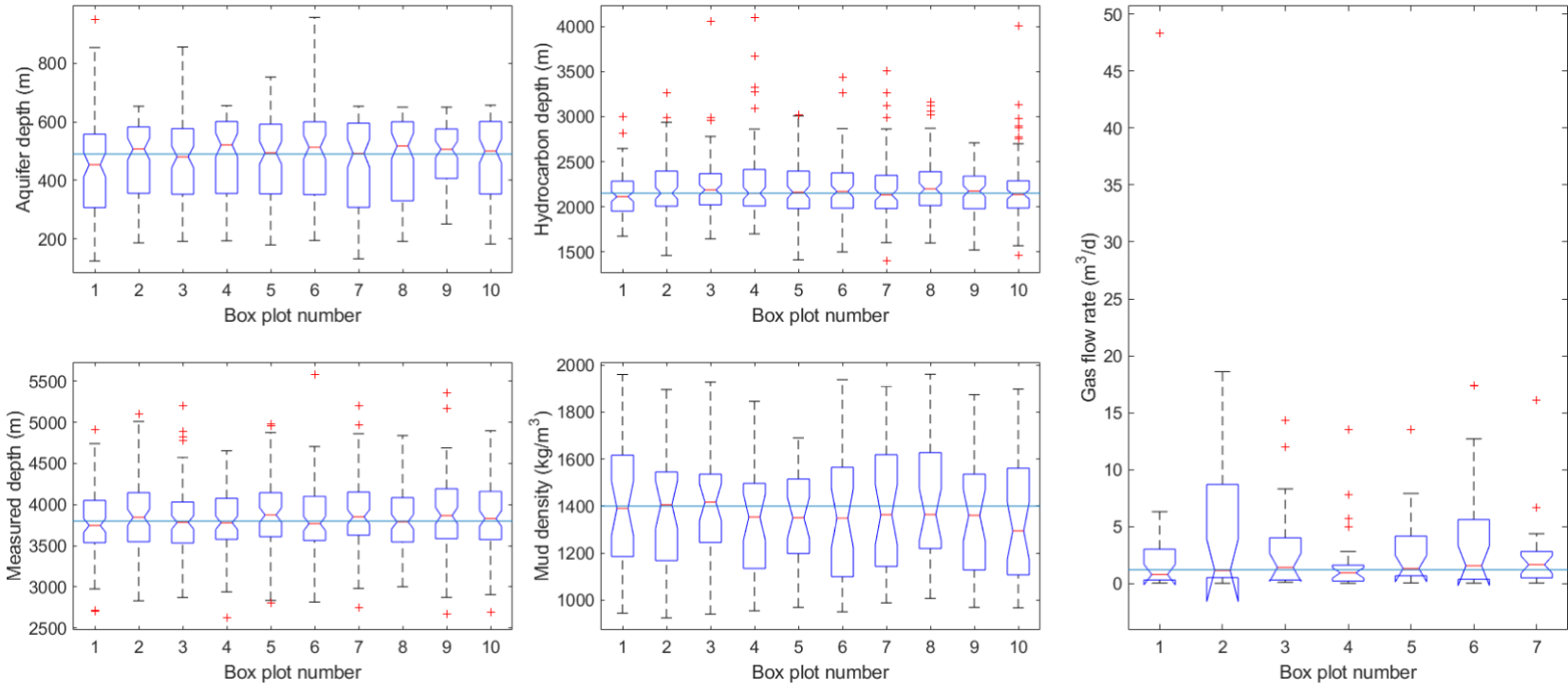
FIGURE 6.10: Notch box plots for partitioned data sets for all five input functions. Horizontal blue lines indicate the box plots whose notch ranges overlap to demonstrate uniformity.

As all data indicated uniformity (Table 6.3), the full data sets for all input functions are used to plot the final box plots. These box plots are shown in Figure 6.11.
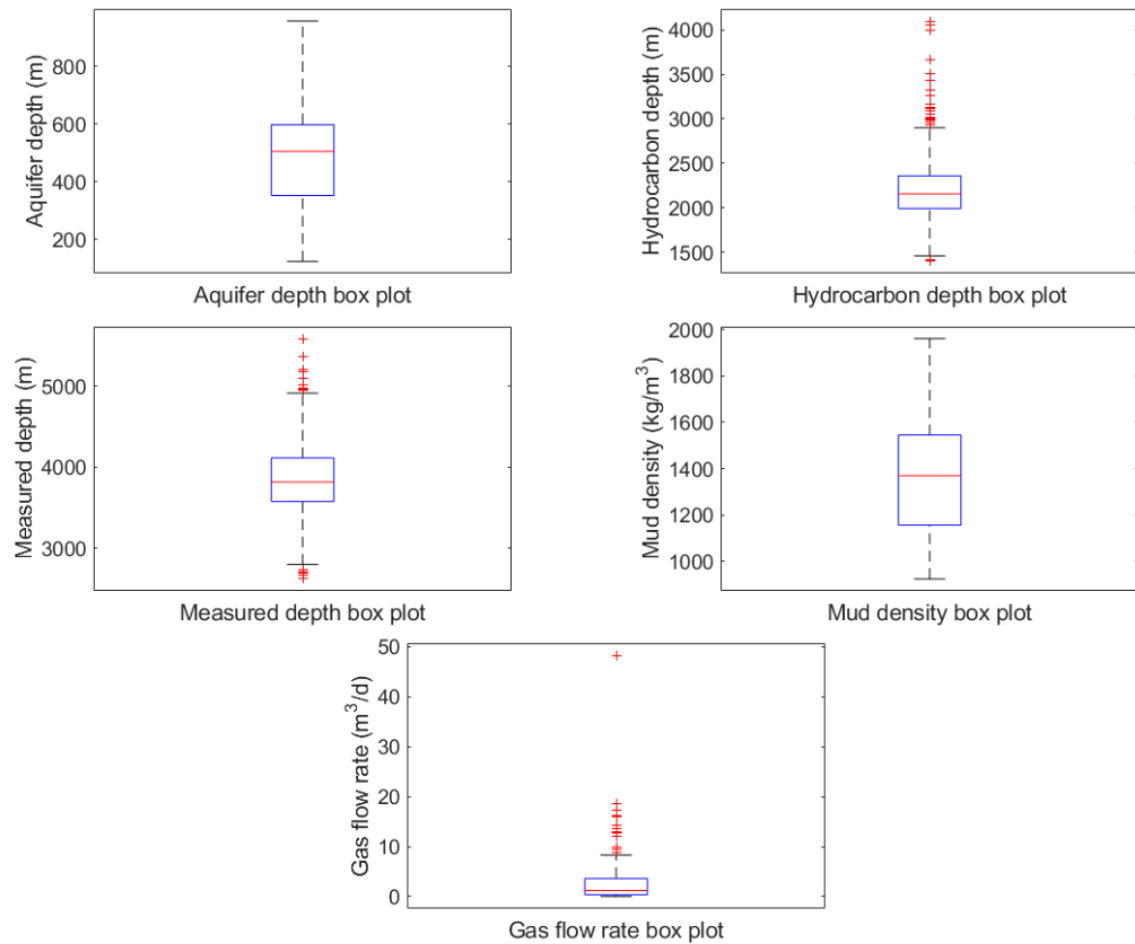
FIGURE 6.11: Final box plots using the full uniform data sets to create the fuzzy membership functions for aquifer depth, hydrocarbon depth, MD, mud density and gas flow rate.

The box plots showing the full data sets for all five input functions (Figure 6.11) are used to create the fuzzy membership functions as shown in Figure 6.8 and equation 6.10. The values to construct these membership functions are shown in Table 6.4.

As demonstrated in Table 6.2, five membership functions are created using the box plot method and four are created using expert judgement. The fuzzy membership functions for those with the box plot method have been created as described above but the linguistic reasoning behind all these functions and the construction of the FIS is described in more detail below. The final membership functions for all parameters in Table 6.2 are shown in Figures 6.12 and 6.13.

TABLE 6.4: Final values from each developed box plot to create the fuzzy membership functions for aquifer depth, hydrocarbon depth, MD, mud density and gas flow rate. LQ: Lower Quartile, UQ: Upper Quartile.

Input function	Min	Whisker min	LQ	UQ	Whisker max	Max
Aquifer depth (m) (Surface casing depth)	0^a	124^a	352	598	957^b	966^b
Hydrocarbon depth (m)	1400	1444	1993	2360	2910	4099
MD (m)	2622	2773	3578	4114	4919	5585
Mud density ($kg\,m^{-3}$)	573^c	924^c	1156	1545	1961^c	2128^c
Gas flow rate ($m^3\,d^{-1}$)	-4.5^d	0.01^d	0.36	3.6	8.46	48.3

[a] Aquifer depth had a minimum value of 124 making the whisker minimum value -16. An aquifer depth cannot be below 0 so the minimum was given a value of 0 and the whisker minimum a value of 124.
[b] Aquifer depth had a maximum value smaller than the whisker maximum. Both were switched around to suit the membership function.
[c] Mud density had a minimum value greater than the whisker minimum and a maximum value smaller than the whisker maximum. Both were switched around to suit the membership function.
[d] Gas flow rate had a minimum value greater than the whisker minimum. Both were switched around to suit the membership function.

Surface casing depth

Surface casing depth is used as a fuzzy input to estimate the potential depth of a shallow aquifer. Surface casings are required to protect sources of groundwater and are therefore built to the depth of the aquifer (Zoback et al., 2010; Wood et al., 2011; The Royal Society, 2012; Fleckenstein et al., 2015). As no data exists for the depth of groundwater intersecting the wells, the surface casing depth is used as an estimate and is therefore equivalent to aquifer depth (D_{AQ}). A fuzzy membership function has been developed as shown in Figure 6.12. Qualitative grades of 'high', 'medium' and 'low' are given. 'Low' represents a deep aquifer less likely to be usable groundwater so less of a consideration in construction and cementing practises. 'High' represents a shallow aquifer likely to be used as a water source so more of a consideration during well construction and cementing.

Hydrocarbon depth

The depth of a hydrocarbon-bearing formation where leaks could occur (in this case, the target formation) is developed as a fuzzy membership function as shown in Figure 6.12. The depth of this formation is vital for engineers during construction and drilling, in particular in relation to its distance from potential groundwater sources. Qualitative grades of 'high', 'medium' and 'low' are given to represent the depth of the formation with respect to its affect on cementing. 'High' represents a shallow formation as it could be closer to an aquifer and much less further for fugitive gas to travel. 'Low' represents a deep formation where fugitive gas flow times up the well will be much longer and cementing practises might be less of a concern.

Measured depth

The MD of the well covers the vertical section plus the horizontal section and any deviations along the wellbore (Figure 6.9). A fuzzy membership function for MD is developed and shown in Figure 6.12. The membership function is similar to hydrocarbon depth with qualitative descriptors of 'high', 'medium' and 'low' representing the depth of the well with respect to its affect on cementing. 'High' represents a less deep well and 'low' represents a very deep well.

Mud density at TVD

Mud density is not an available data set so had to be calculated using gravity and hydrostatic pressure at TVD, as explained above. These calculations enabled a fuzzy membership function to be produced for mud density as shown in Figure 6.12. Qualitative descriptors of 'low', 'medium' and 'high' are used to demonstrate the variation in mud densities which could exist in the annulus of a well. The final mud density (ρ_m) is determined by the mud column length using a set of rules illustrated in Section 6.4.2.4.

Geology factor

Geology factor is an intermediate fuzzy membership function used to determine how much the aquifer depth, hydrocarbon formation depth and MD affect the drillers decision on placement of the top of the cement and hence the mud column length. The membership function is shown in Figure 6.12. Five qualitative descriptors are used, 'very low', 'low', 'medium', 'high' and 'very high'. A 'very low/low' geology factor suggests there is little influence from the surrounding geology on where the top of the production cement should be. The geology is at a low risk of causing contamination during production so the mud column length could be very long. A 'high/very high' geology factor suggests the opposite where the geology could encourage a higher production cement top and hence a shorter mud column length.

Mud column length

Mud column length is an intermediate fuzzy membership function where aquifer depth, hydrocarbon depth and MD are used to predict the mud column length. Mud column length is not a standard measurement without knowing if the top of the production cement has returned to the surface. However, it is estimated based on the geology (aquifer and hydrocarbon formation depth) and the MD of the well. Five qualitative descriptors are used, 'very short', 'short', 'medium', 'long' and 'very long'. These represent the final length of the mud column.

Gas flow

Gas flow is an input fuzzy membership function used to determine the probability of SCP-induced migration. It has three qualitative descriptors, 'low', 'medium' and 'high' which represent the volume of gas flowing into the well per day. A low flow rate indicates a lower probability and a higher flow rate, a higher probability.
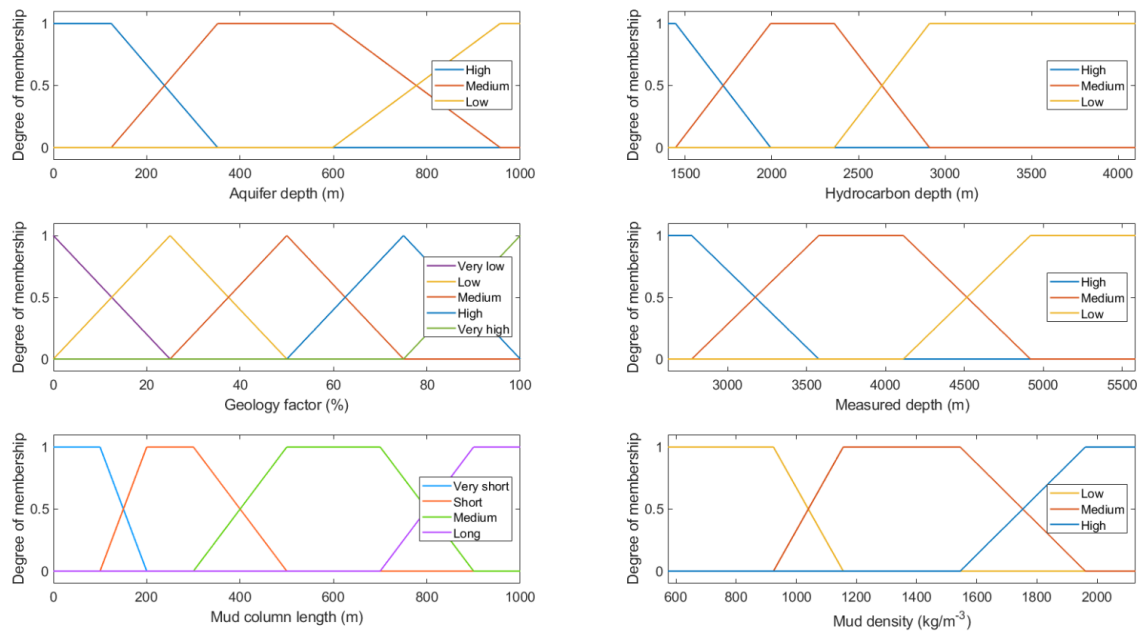
FIGURE 6.12: Membership functions for inputs aquifer depth (trapezoidal), hydro-carbon depth (trapezoidal) and MD (trapezoidal). Intermediates are geology factor (triangular) and mud column length (trapezoidal). Output is mud density (trapezoidal).

Time

Time is an input fuzzy membership function also used to determine probability. It has five qualitative descriptors, 'very short', 'short', 'medium', 'long' and 'very long' which represent the time taken for gas to reach the critical point in the annulus before flowing into groundwater. A short time indicates a higher probability and a long time indicates a lower probability.

Probability

Probability is an output fuzzy membership function created in the same way as geology factor. Five qualitative descriptors are used, 'very low', 'low', 'medium', 'high' and 'very high' to determine the probability of SCP-induced gas migration occurring based on gas flow rate out of the annulus and the time taken.

6.4.2.4 Fuzzy inference system

In order to combine the fuzzified inputs, intermediates and outputs, rule bases are used to produce different outcomes related to the parameters which control SCP potential. These rules are created using 'IF-THEN' statements to relate inputs to appropriate output results. Figures 6.14 and 6.15 illustrates the connection between inputs, intermediates and outputs and the four rule bases required within the system. These rules are based on engineering judgement and fuzzy logic and are shown in Appendix C.
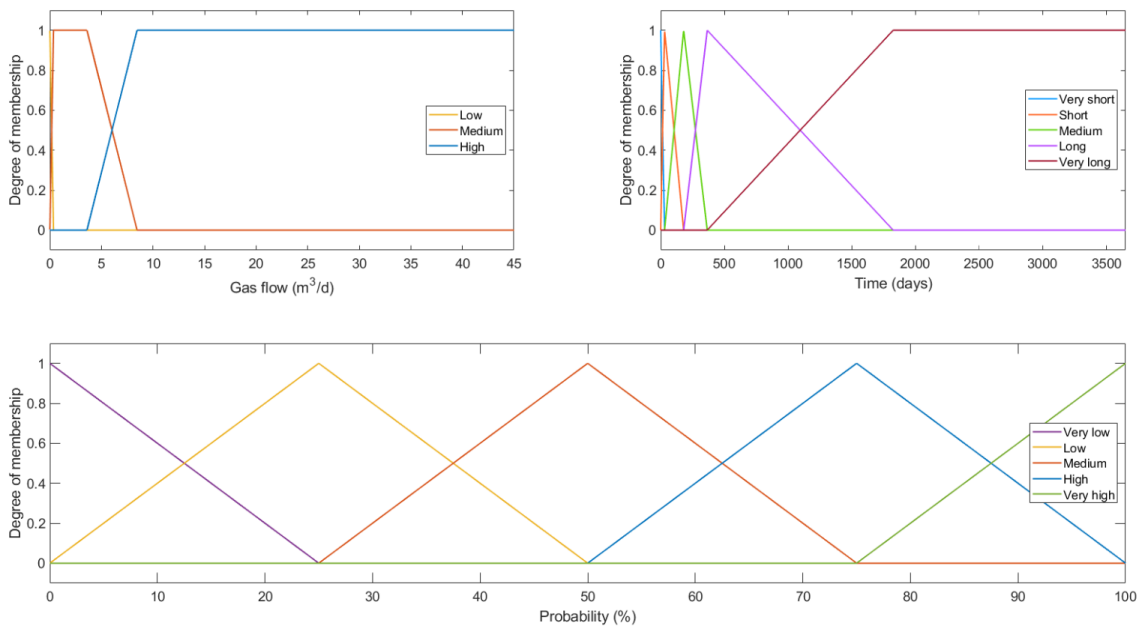
FIGURE 6.13: Membership functions for inputs gas flow (trapezoidal) and time (triangular) and output probability (triangular).

Once the rules have been created, a FIS is required. The Mamdani method is used here where both inputs and outputs are fuzzy functions. As indicated in Chapter 3, fuzzy operators, an implication operator and aggregation operator are used to form the FIS. Rule bases 1, 2 (Figure 6.14) and 4 (Figure 6.15) use the conjunction operator (AND) as indicated in Appendix C. The implication operator used here is the intersection minimum and the aggregation operator is the union maximum.

Defuzzification converts the aggregated outputs into crisp values using the centroid method. An output crisp value is obtained from the intermediate functions geology factor and mud column length, as these values can be used as an input for rule bases 2 and 3, respectively (Figure 6.14).

According to equation 6.9, mud column length, mud density and gravity must be multiplied together to obtain a value for hydrostatic pressure in the mud column, used as an input in the numerical model (Figure 6.15). As both the mud column length and mud density are fuzzy membership functions, fuzzy arithmetic using the DSW algorithm was used to multiply these two functions (Figure 6.14). As described in Chapter 3, the fuzarith function was used in MATLAB for fuzzy arithmetic. This function conducts the interval analysis over 100 α cuts and requires both input membership functions ($\underset{\sim}{A}$ and $\underset{\sim}{B}$) to be convex and to be of the same universe. In many cases, the universe of $\underset{\sim}{A}$ and $\underset{\sim}{B}$ is not the same so the function was adjusted to allow evaluation over two different universes. After defuzzification, hydrostatic pressure is subtracted from the formation pressure to obtain the maximum casing head pressure, also using the DSW algorithm.
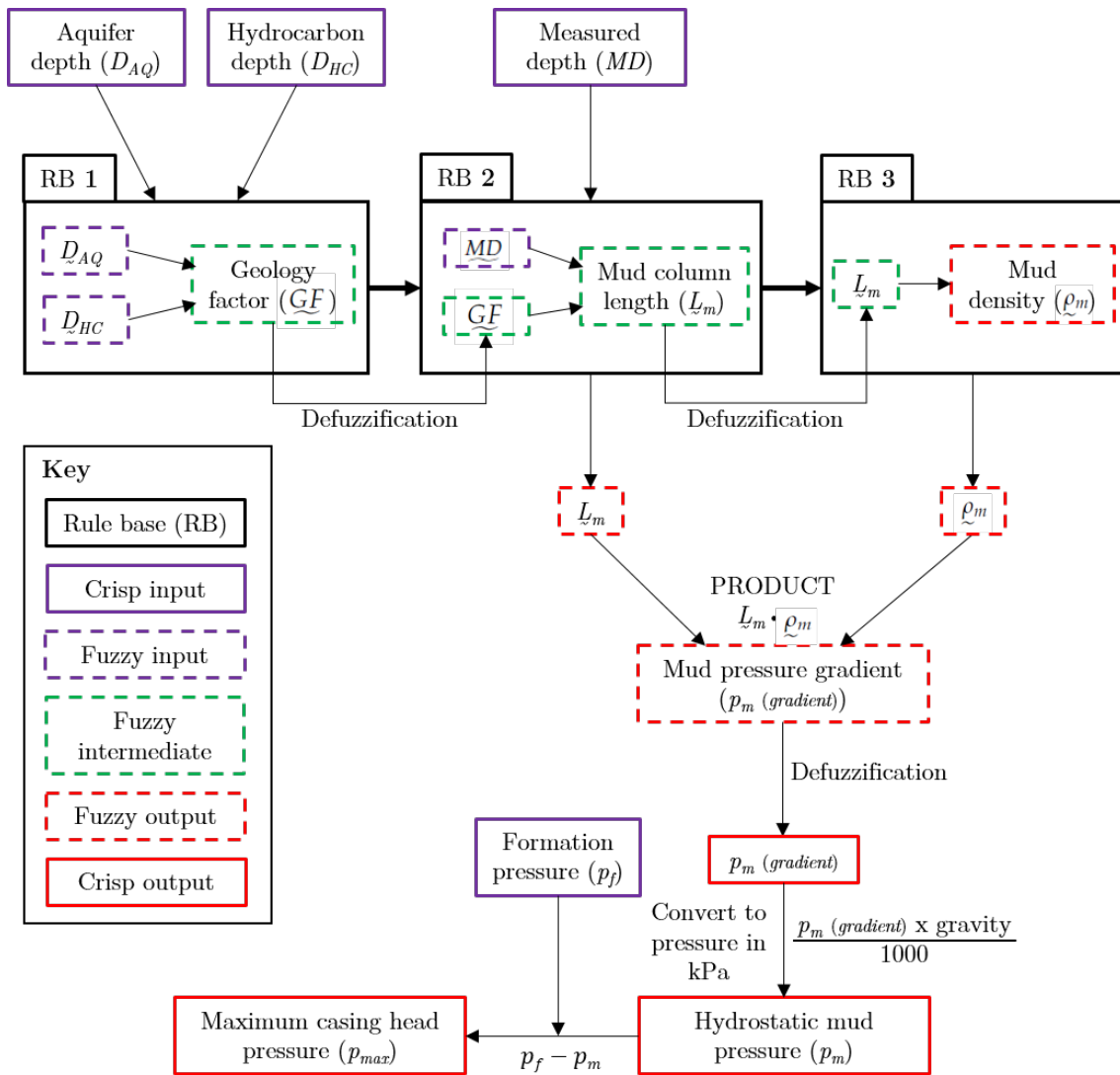
FIGURE 6.14: Fuzzy model construction using rule bases to obtain fuzzy membership functions for mud column length and mud density and converting these fuzzy functions to a final output for hydrostatic mud pressure and maximum casing head pressure.

6.4.3 Numerical model

The development of the fuzzy model (Figure 6.14) was required to produce input parameters which did not exist in the data set. Hydrostatic mud pressure and mud column length were both inputs which were developed from the fuzzy model and have been used in the numerical model to calculate gas flow and time (Figure 6.15). Mud column length is also required to determine whether an annulus is closed or open and hence can be used to determine the probability of this occurring for event 4 in the cement failure event tree (Figure 6.4). The final output for the model utilised the FIS with a fourth rule base to determine the final probability for event 6 in the cement failure event tree.

The numerical model requires parameters (Table 6.5) which are kept constant in this
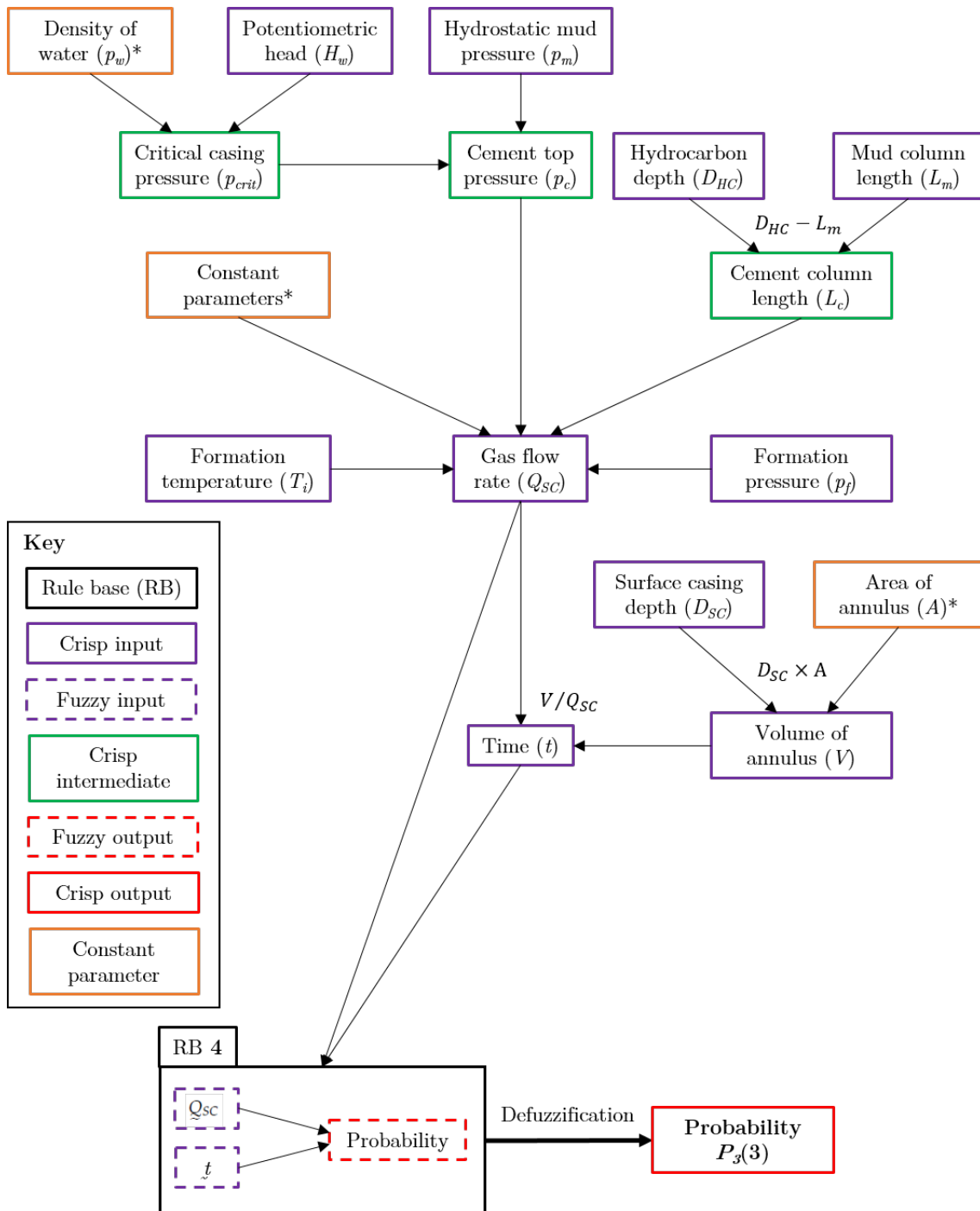
FIGURE 6.15: Numerical model construction to obtain the final gas flow and time taken using a FIS to determine the final probability.
*These parameters are detailed in Table 6.5

research. The area of the annulus might differ between wells depending on the inner diameter of the annulus. However, there is no data or information for the diameter of the cement annulus so the inner diameter is assumed to match that of a standard gas well stated by Rocha-Valadez et al. (2014). All other parameters are considered constants.

TABLE 6.5: Input parameters for an open annulus well to calculate gas flow from a leak.

Parameter	Value	Reference
Cement permeability (k), m^2	$1.48E^{-15}$	Rocha-Valadez et al. (2014)
Cross-sectional area of annulus (A), m^2	0.0294	Rocha-Valadez et al. (2014)
Gas viscosity (μ), Pa s	$1.5E^{-5}$	Rocha-Valadez et al. (2014)
Standard temperature (T_{sc}), K	273.15	-
Z-factor (Z)	0.92	Rocha-Valadez et al. (2014)
Standard pressure (p_{sc}), Pa	$1E^5$	-
Water density (p_w), kg m^{-3}	1000	Lackey et al. (2017)

6.5 SENSITIVITY ANALYSIS AND VALIDATION

Sensitivity analysis focuses on adjustments in the fuzzy model using a OAT approach. The membership functions for each input, output and intermediate functions are altered from their original membership function (base case) individually, whilst all others are kept at their original base case. The most important outputs which affect the decisions in the model are mud column length and probability. The percentage change in each model output for mud column length and probability with respect to the base case are calculated for each simulation.

Determining the upper and lower bound changes to be made to each membership function from its original function is a challenge as the parameter is a vector and not a crisp value and there is more than one function for each fuzzy input. Additionally, the membership functions are created based on engineering judgement and the box plot technique so there are no well-defined ranges which each function could be. Therefore, the variation in each function is determined based on a system defined by Reichert and Vanrolleghem (2001) (Table 6.6) and has been used in future sensitivity and uncertainty analyses (Rousseau et al., 2001; Benedetti et al., 2008; Sweetapple et al., 2013).

TABLE 6.6: Uncertainty classes to determine upper and lower bounds of each parameter. Adapted from Sweetapple et al. (2013).

Class	Description	Uncertainty (%)	Parameters
1	Accurately known parameters (correct full data set)	5	Hydrocarbon depth, MD, gas flow
2	Intermediate (data set partially available)	20	Aquifer depth, mud density
3	Very poorly known parameters (data not available)	50	Mud column length, time

Each fuzzy function has three or more membership functions. To adjust the parameter as indicated in Table 6.6, each vertex on each of these membership functions is adjusted simultaneously. For example, aquifer depth has three membership functions, 'high', 'medium' and 'low' in a trapezoidal shape i.e. with four vertices (Figure 6.12). This means adjusting these vertices by 20% up and down simultaneously would give 81 different combinations (3^4). Some of these combinations might produce incorrect functions which are not trapezoidal, convex functions. Where this occurs, these functions are removed from the simulations. Table 6.7 shows the number of combinations available for each fuzzy parameter and the number chosen within a suitable range to satisfy fuzzy function rules. Geology factor was only adjusted once by altering the shape of the membership functions from triangular to trapezoidal to demonstrate the sensitivity of its shape.

TABLE 6.7: The final number of simulations conducted for each well changing each parameter individually using OAT sensitivity analysis.

Parameter	Class	No. of potential combinations	No. of simulations
Aquifer depth	2	81	81
Hydrocarbon depth	1	81	81
MD	1	81	81
Mud column length	3	256	66
Mud density	2	81	55
Gas flow	1	81	81
Time	3	243	216

6.5.1 Mud column length

The percentage change was calculated from each simulation for both mud column length and probability. Mud column length is an essential part of the model as it determines the construction of the annulus as shown in Figure 6.3. The annulus could be fully cemented and closed (a), partially cemented and closed (b), partially cemented above a hydrocarbon-bearing formation and open (c), or partially cemented below a hydrocarbon-bearing formation and open (d). In the case of this model, the distinction is between (b) or (c) where the cement either sits above the surface casing shoe or does not reach the surface casing shoe. Some of the wells analysed are known to have their production cement above the surface casing shoe. This information was used to help calibrate and validate the model. Of the full data set (337 wells), 256 had data to show the wells have a closed annulus (Figure 6.3a/b) and the model predicted 93% of those wells correctly. For those wells which did not have data to demonstrate their construction (81 wells), the model calculated 8 wells which showed a construction with an open annulus as in Figure 6.3c with the rest representing wells with a closed annulus. This demonstrates 2.4% of horizontal wells drilled in the Montney formation between 2008 and 2017 were drilled with an open annulus and therefore have the potential to demonstrate SCP-induced gas

migration into groundwater. According to Lackey et al. (2017), horizontal wells drilled in the Wattenberg test zone between 2006-2014 demonstrated 90% casing cement coverage, i.e. 10% could demonstrate open annuli. This is higher than the model in the Montney formation predicts, but regulations within the Colorado state are less tight on production casing cement than in BC (Lackey et al., 2017) (Chapter 4). Therefore, the output from this model of 2.4% is expected due to tougher regulations in BC compared with Colorado so less wells will be drilled with open annuli.

Mud column length is determined based on four fuzzy functions; aquifer depth, hydrocarbon depth, geology factor and MD. OAT sensitivity analysis was conducted on these four functions to determine which has the largest impact on determining the mud column length. Across all simulations run for each parameter (Table 6.7), the upper and lower bounds from each run per well were calculated and the percentage change was plotted with respect to the base case to produce tornado graphs for aquifer depth, hydrocarbon depth and MD (Figure 6.16). The wells which demonstrated the largest change were plotted at the top. As geology factor was only adjusted once, there was no upper or lower bound to demonstrate the sensitivity of the function so a comparison between the two shapes has been made using box plots (Figure 6.17).
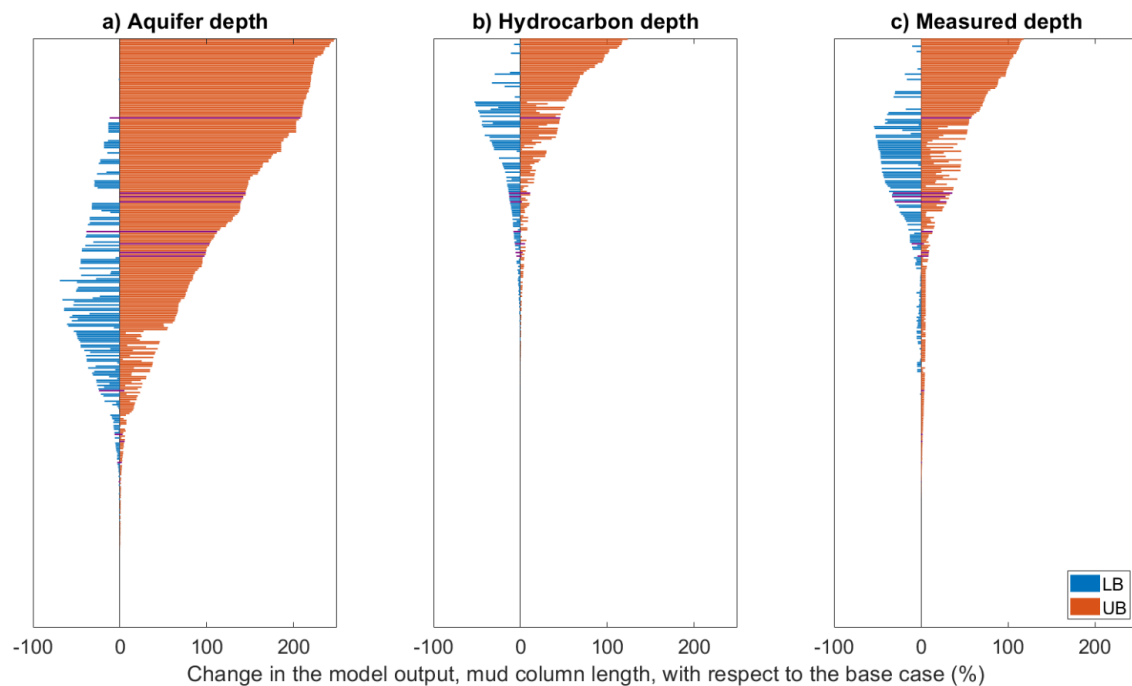
FIGURE 6.16: Tornado graphs indicating the percentage change in mud column length across 337 different wells whilst individually changing three different fuzzy functions, (a) aquifer depth, (b) hydrocarbon depth, and (c) MD.
The y-axis corresponds to each well but has been left out for clarity. The purple highlighted bars correspond to the open annulus wells 14, 24, 37, 51 and 52.
LB: Lower Bound, UB: Upper Bound

Across the three fuzzy inputs, changing the aquifer depth membership functions impacted the largest number of wells, with hydrocarbon depth impacting the least number of wells. Mud column length is considered the most sensitive to the change in aquifer depth with some wells changing their mud column length by up to 250% based on a different membership function. This is expected within the model as the presence of an aquifer is the biggest driver to ensuring suitable cementing practises (Fretwell et al., 2012).

The upper bound is significantly more sensitive than the lower bound for all three parameters suggesting the model has a tendency to increase the mud column length much more than decreasing it. This could affect the model by predicting a mud column length which is much longer and hence shifting the well from being a closed annulus to an open annulus. Well number 244 has the highest positive percentage change in mud column length when altering aquifer depth (246%) but on analysis of closed versus open annulus from the new data set, the number of open annulus wells increased from only 25 to 32, suggesting this large percentage change has not affected the mud column length substantially.
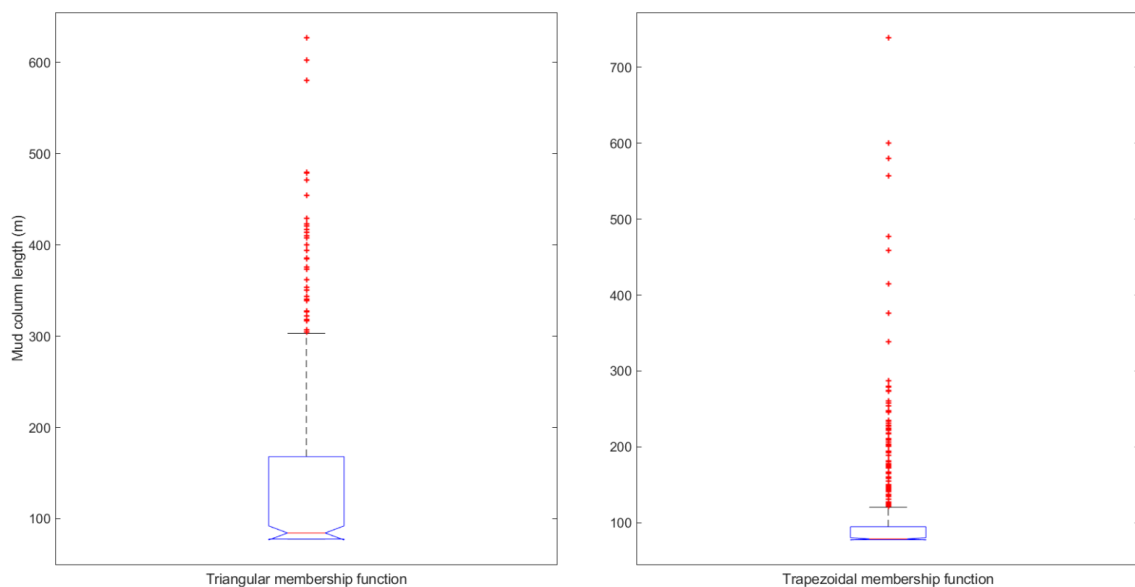
FIGURE 6.17: Box plots indicating the change in distribution of output mud column length when changing the shape of the geology factor membership function.
Triangular: median = 84.4, LQ = 77.7, UQ = 168.1
Trapezoidal: median = 78.8, LQ = 77.6, UQ = 94.9

Altering the shape of the geology factor membership function from triangular to trapezoidal has increased the skew of the data and introduced more outliers. The median values on both are similar and on plotting a notched box plot, the notches do overlap suggesting with a 95% confidence interval that the true medians do not differ. The lower 25% of the data has very little change whereas the upper 75% has changed significantly with the UQ shifting from 168.1 to 94.9. The changes in these two output data sets suggests a trapezoidal membership function will produce very similar values across the data set (78-95 m) but with a significant number of outliers and a much greater range of outliers,

whereas the triangular membership produces a more even spread of variability across a greater range (78-168 m) but with fewer outliers. The trapezoidal membership function increases the accuracy of the model to 98% for predicting closed annuli, but reduces the number of wells which did not have construction data to only two with an open annuli, demonstrating the change in the function could be very sensitive to the prediction of open or closed annuli. The lack of construction data demonstrating wells with an open annuli prevents further understanding as to whether this change improves or worsens the model outcome.

6.5.2 Probability

After mud column length has been calculated, the wells which demonstrate an open annulus are used to determine the potential for SCP-induced gas migration. It has been assumed based on the event tree in Figure 6.4 that once a well with an open annulus demonstrates SCP, eventually SCP-induced gas migration will occur either into a shallow aquifer by the surface casing shoe or dissolution into deep groundwater cross flows. The potential to which this could occur is demonstrated by the probability. Only eight wells represented an open annulus from the model but only five were used to determine the SCP-induced gas migration potential as three did not contain reservoir temperature data. These five are well numbers 14, 24, 37, 51 and 52.

The potential for SCP-induced gas migration is determined based on eight fuzzy functions; aquifer depth, hydrocarbon depth, geology factor, MD, mud column length, mud density, time and gas flow. The sensitivity analysis for seven of these for each open annulus well are plotted as a tornado graph in Figure 6.18. Similarly to mud column length, geology factor was changed once from a triangular membership function to a trapezoidal function and a box plot was produced to demonstrate any differences in the change (Figure 6.19).

As only five wells were analysed for probability of gas migration, the upper and lower bounds of each parameter could be shown for each individual well (Figure 6.18). All wells demonstrate very similar outcomes to the sensitivity of all seven parameters with no parameters showing high sensitivity. This confirms that accurate calibration of the model with respect to mud column length is much more important than probability.

Time is the most sensitive parameter which is expected as it has one of the highest impacts on the probability outcome. However, gas flow indicates no sensitivity but should also have a high impact on the probability outcome. This difference will be due to a poorly known parameter class used for time compared to an accurately known parameter class for gas flow (Table 6.7). The uncertainty in gas flow could be increased to see if the parameter becomes more sensitive. Probability is very insensitive to both hydrocarbon depth and aquifer depth, likely due to their less direct influence at the point gas flow and time are calculated. Hydrocarbon depth and aquifer depth are used earlier on in the

model to determine the mud column length. Mud column length is generally the next most sensitive after time as this value directly affects the gas flow rate up the cement column.
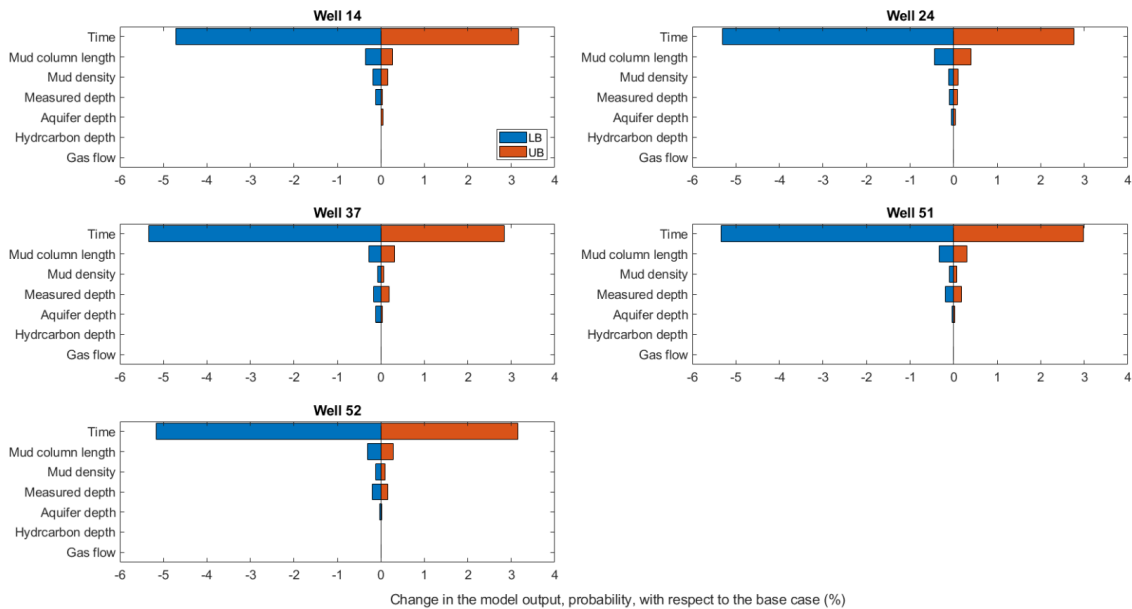
FIGURE 6.18: Tornado graphs indicating the percentage change in probability across five open annulus wells whilst individually changing seven different fuzzy functions. LB: Lower Bound, UB: Upper Bound

The geology factor has been changed from a triangular to a trapezoidal membership function where Figure 6.19 indicates very little effect on the outcome of the probability based on this change. The notched plots indicate a very clear overlap of the notches suggesting with a 95% confidence interval that the medians are the same. There are only five data points to develop the box plot but other than a slight increase in the range for the triangular membership function compared to trapezoidal, geology factor appears to be very insensitive to the probability outcome.

It is clear from the model the uncertainty lies heavily on the mud column length so further accuracy for this parameter can improve the outcome of the model substantially. Sensitivity analysis can also be conducted on the parameters used to calculate gas flow (Table 6.5) particularly if the cement permeability and annulus area could vary significantly across different wells. This has not been conducted here as the focus has been on the sensitivity of the fuzzy model.

6.6   RESULTS AND DISCUSSION

A fuzzy logic model was built in combination with a numerical model to assess the potential for SCP-induced gas migration on open annulus wells in the Montney formation.
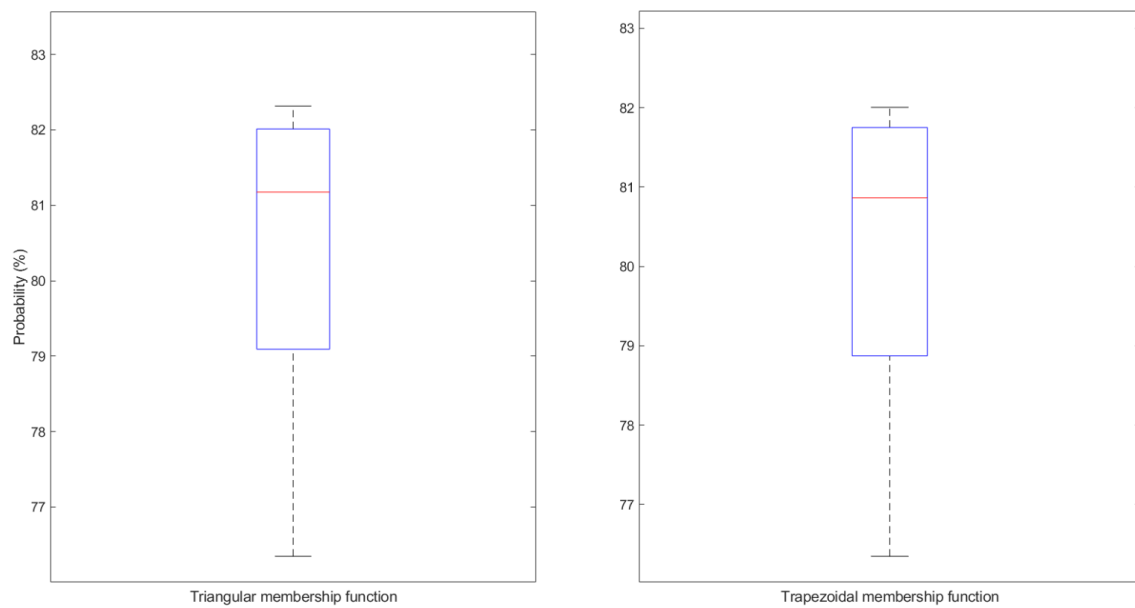
FIGURE 6.19: Box plots indicating the change in distribution of output probability when changing the shape of the geology factor membership function.
Triangular: median = 81.2, LQ = 79.1, UQ = 82.0
Trapezoidal: median = 80.9, LQ = 78.9, UQ = 81.8

The construction of wells, in particular the height of production cement or outer annulus cement is often unknown within a data set and is therefore hard to determine whether a well has a closed or open annulus. The fuzzy model was developed to use judgement and engineering knowledge to estimate the length of a mud column and hence the height at which the outer annulus cement (production cement) reaches.

The first part of the model developed the mud column length and selected which wells present a closed annulus and which present an open annulus (Figure 6.20). The numerical model for critical SCP and gas flow was developed based on an open annulus so the results focused on the five wells which represented an open annulus from the data set. These five wells all have the potential to develop SCP-induced gas migration over time where a shallow aquifer is present and where the surface casing vent valve is kept closed. The results are shown in Table 6.8 to represent the values for the fuzzy model and Table 6.9 to represent the values for the numerical model, used to calculate gas flow rate and time.

The final potential for SCP-induced gas migration is determined based on the gas flow rate out of the well once the gas reaches the bottom of the surface casing (Figure 6.20, open annulus), and the time taken for the gas to build-up to the point of critical casing pressure just before it leaks into the surrounding formation. The results indicate all five open annulus wells have a high probability of leading to SCP-induced gas migration once gas has leaked into the annulus. This high result is expected as once the gas has leaked into the annulus, the only further movement is out of a casing vent if left open or moving
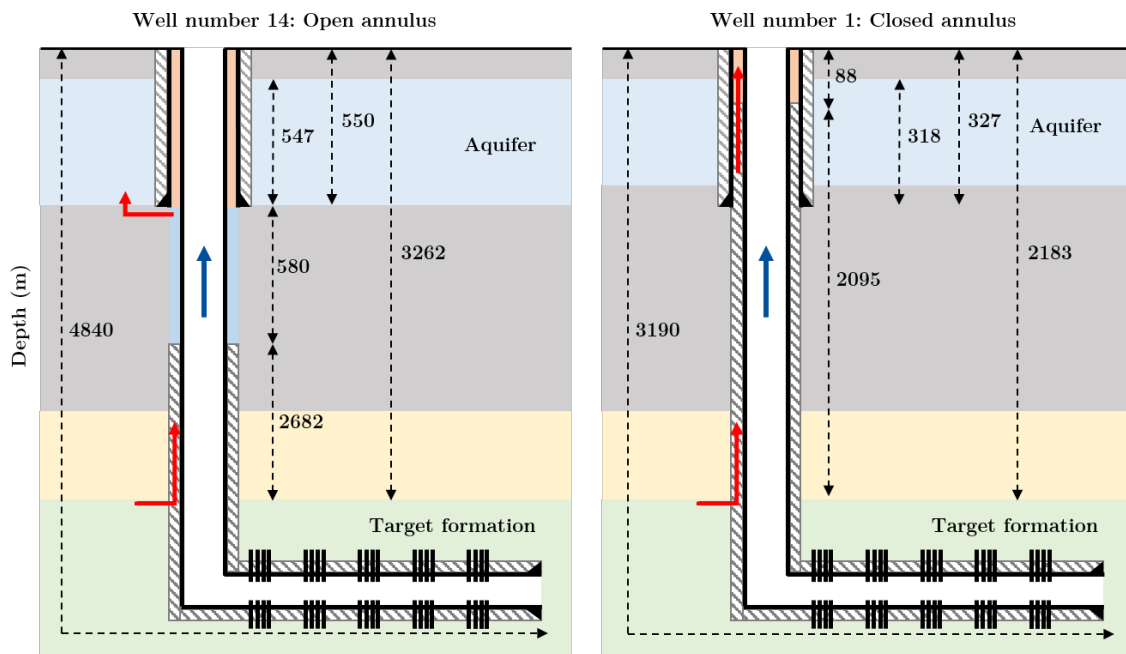
FIGURE 6.20: Representation of two horizontal wells in the Montney formation with measurements from the data set and fuzzy model outputs indicating an open and closed annulus. The red arrow indicates the leak from the target formation as determined in the model with the open annulus demonstrating SCP-induced gas migration and the closed annulus demonstrating a build-up of SCP within the annulus.

out where there is a lower pressure zone, if the vent is closed. This lower pressure zone will exist at a shallower formation, for example at the surface casing shoe, or where deeper groundwater is present and will almost always be exceeded over time if the leak is not repaired.

OAT sensitivity analysis demonstrated the sensitivity of the fuzzy membership functions aquifer depth, hydrocarbon depth and MD with respect to the mud column length although the final probability was not hugely affected by the mud column length. However, it is worth noting the importance for accurate mud column length for the representation of closed and open annuli. In addition, there were a total of 337 wells analysed and these were ordered and numbered according to their rig release date which could have an effect on their construction. Older wells often represented poorer constructions due to regulations getting tighter over time. Tables 6.8 and 6.9 show the five wells the model predicted with open annuli and due to their lower well numbers (<50) are older wells compared to the higher well numbers with closed annuli.

The probability determined from the fuzzy and numerical model does not represent the probability that any well drilled will lead to SCP-induced gas migration. An estimate for this probability is represented by the third failure pathway on Figure 6.4, $P_3(3)$. Each event probability is determined along the branch and multiplied together to obtain a final failure probability outcome. These probabilities are shown in Table 6.10. Event 4 and event 5

TABLE 6.8: Inputs for the fuzzy model to determine the probability of SCP-induced gas migration for five open annulus wells.

Well number	Surface casing depth (m)	Hydrocarbon depth (m)	MD (m)	Mud column length (m)	Mud density $(\mathrm{kg\,m^{-3}})$	Gas flow rate $(\mathrm{m^3\,d^{-1}})$	Time (days)	Probability of GM %	Probability
14	550	3262	4840	580	1403	0.81	18	76	High
24	254	2649	4560	414	1418	0.99	7	82	High
37	191	2622	4195	267	1403	0.69	7	82	High
51	253	2705	4230	317	1406	0.82	8	81	High
52	254	2645	4240	318	1406	0.68	10	80	High

GM: Gas Migration

TABLE 6.9: Inputs for the numerical model to determine the probability of SCP-induced gas migration for five open annulus wells.

Well number	Height of potentiometric surface (m)	Cement top pressure (kPa)	Cement column length (m)	Formation pressure (kPa)	Formation temperature (K)	Volume $(\mathrm{m^3})$	Probability of GM %	Probability
14	547	14421	2682	47842	355	16.17	76	High
24	237	9853	2235	46335	345	7.47	82	High
37	174	6861	2355	39520	344	5.62	82	High
51	236	8297	2388	43431	346	7.44	81	High
52	237	8318	2327	39237	344	7.47	80	High

GM: Gas Migration

are both calculated in this chapter using the model and event 2 is assumed to be 100% during production. Due to the depth of unconventional formations and the requirement of gas to flow from the target formation into the well, the pressure must be higher outside the well compared to inside the annulus. Event 1 was determined in Chapter 5 using Fuzzy Fault Tree Analysis (FFTA) and expert judgement but the value is slightly different due to different probabilities of failure between the injection stage and production stage. The same fault tree for vertical cement failure is used as in Chapter 5 but with different quantified probabilities, detailed in Appendix D. The final value for vertical cement failure during production is shown in Table 6.10.

These results estimate that for a horizontal, hydraulically fractured well, the probability of SCP-induced gas migration into shallow groundwater with a leak occurring into the cement at the target formation is approximately 0.02%. This represents a value for wells in BC if the surface casing vent valves were left closed (outcome 3 on Figure 6.4a) but would change depending on regulations within the country or province.

Event trees were developed for two scenarios of gas migration during a production well where a leak either occurred from the surrounding formation through the cement or from inside the annulus through the production casing and into the cement (scenarios 3 and 4, respectively). The framework and models developed in this chapter can be applied to other branches in both event trees. For vertical cement failure in a closed well annulus (outcomes 1 or 2, Figure 6.4a), the same model can be applied but the gas flow out of the well by gas circumvention requires an adjusted numerical model to consider the movement of gas out of a cemented annulus rather than a hydrostatic mud column. This would include the calculation for horizontal cement failure which was determined in

TABLE 6.10: Final results for each event in the event tree in Figure 6.4 to obtain a final probability for the third failure branch, SCP-induced gas migration.

Well number	[a]Event 1 Vertical cement failure	[b]Event 2 Pressure change	Event 3 Surface casing vent valve	Event 4 Annulus	Event 5 SCP-induced GM	Final probability (%) $P_3(3)$
14	$1.00E^{-2}$	FP>AP 1.00	Closed	Open 0.024	0.76	0.018
24	$1.00E^{-2}$	FP>AP 1.00	Closed	Open 0.024	0.82	0.020
37	$1.00E^{-2}$	FP>AP 1.00	Closed	Open 0.024	0.82	0.020
51	$1.00E^{-2}$	FP>AP 1.00	Closed	Open 0.024	0.81	0.019
52	$1.00E^{-2}$	FP>AP 1.00	Closed	Open 0.024	0.80	0.019

FP: Formation Pressure
AP: Annulus Pressure
GM: Gas Migration
[a] Value calculated using method in Chapter 5 and results in Appendix D.
[b] Assumed 100% probability as the formation pressure should always be greater than the annulus pressure during production.

Chapter 5. In addition, in an annulus which is fully closed the build-up of SCP within the failed cement column would require an alternative numerical model to that described in Section 6.2.

A leak occurring from inside the well annulus to the cement annulus through a casing failure (Figure 6.4b) follows the same migration pathways as a leak occurring from an outside formation into the cement annulus. This means the same model can be applied to the event tree branches but the pressure changes between the production annulus and cement column would need to be determined to see the probability of event 3 occurring in Figure 6.4b. It is assumed in this model the pressure would always be greater in the surrounding formations compared to inside the annuli (Table 6.10; event 2 = 1.00), but this assumption cannot necessarily be made when a failure occurs in the production casing. However, once this has been determined the model can be applied directly to the rest of the event tree branches.

6.7 CONCLUSION

This chapter successfully assessed the risk of contaminating shallow groundwater by fugitive gas migration of a production well under certain constructions. A risk assessment framework is developed using ETA to focus on the gas migrating pathways from source to receptor (groundwater). The methods by which gas migration occur in a production well, mainly SCP, are well known and sometimes tested in situ, but they are poorly quantified in the literature in terms of analysing the risk to groundwater. The theory of gas migration is complex and requires significant data which is often unavailable in the oil and gas industry. The model developed in this chapter successfully combines fuzzy methods to handle the lack of data and various or vague parameters with an analytical model to

predict the likelihood of SCP-induced gas migration in hydraulically fractured production wells in the Montney formation in BC, Canada.

The theory behind SCP demonstrated higher risk well constructions have open annuli rather than closed due to the ability for gas to migrate into groundwater once the annulus overcomes the external formation pressures. The length of this annulus compared to the depth of the surface casing was estimated for all chosen wells in the BC data set in order to apply the analytical model. With a lack of data on well constructions in the oil and gas industry, a fuzzy model incorporating fuzzy membership functions was successfully developed using engineering judgement and available data sets. The fuzzy model was calibrated against known closed annuli within the data set and demonstrated a 93% accuracy. From this, the model predicted 2.4% of wells in the Montney formation have open annuli and this was validated against wells in Colorado which demonstrated 10% with open annuli; the difference due to less tight regulations in Colorado compared with BC. The outcome from this fuzzy model produced the mud column length which was a vital parameter for the analytical model.

To demonstrate the validity of the fuzzy model and to understand the sensitivity of each fuzzy membership function with respect to mud column length and probability, sensitivity analysis was conducted using the OAT approach. This demonstrated the need to ensure accuracy for the mud column length parameter to improve the outcome and reduce uncertainty in the model.

The analytical model was used to determine the gas flow rate into an annulus when a leak occurs and the time taken for the gas to reach groundwater. This model had been developed by Rocha-Valadez et al. (2014) but had not been utilised to assess risk to groundwater from SCP-induced gas migration. In this research, the time and gas flow outputs from the five open annuli wells were successfully converted into fuzzy membership functions and the fuzzy model was used to determine the potential for SCP-induced gas migration, given a leak has occurred. Sensitivity analysis on this part of the fuzzy model indicated time was the most sensitive parameter and improvements on data collection for gas migration in the field would improve the gas flow membership function. The results from the fuzzy model demonstrated a high potential for SCP-induced gas migration for the five wells with open annuli, around 80%. This was expected considering once gas starts building up in an annulus, the pressure will eventually breach the well integrity barrier if there are no interventions.

Finally, the probability for well integrity failure during production was obtained using ETA where quantification used the fuzzy and analytical models from this chapter and the cement failure models from Chapter 5. Once the results from all three models were applied to the event tree, a final overall probability of gas migration to groundwater during well production was around 0.02% for all five wells. Given production occurs over a very long

period of time (20-30 years), it would be expected this value would be much greater than for an injection well as there is a much longer period of time for a well to fail.

The models developed in this chapter have provided a framework for assessing the risk of gas migration for open well annuli during production. With a few adjustments, the framework can be applied for wells with alternative constructions such as closed annuli and differing surrounding geological formations. The next chapter focuses on applying the methods in Chapters 5 and 6 to an onshore hydraulically fractured well in the UK, where well constructions and geological formations are likely to be quite different.

CHAPTER 7

DISCUSSION AND APPLICATION TO THE UK

7.1   INTRODUCTION

As previously discussed in Chapter 4, the UK unconventional onshore industry is still in its infancy and exploratory stage. The country is facing political, economical and social turmoil over whether exploiting shale gas resources would be beneficial or exacerbate environmental degradation (Cotton et al., 2014; Andersson-Hudson et al., 2019; Acquah-Andoh et al., 2019). The biggest concerns the UK shale gas industry faces, to date, are contaminating groundwater resources, induced seismicity and increasing contributions to climate change (Cotton et al., 2014; Stamford and Azapagic, 2014; Prpich et al., 2015).

This research has focused solely on the implications of onshore hydraulic fracturing on groundwater resources, particularly as the UK utilises an average of 31% of groundwater for water usage, with some areas in the southeast using up to 100% (Loveless et al., 2018b). Whether utilised for drinking or agricultural purposes, groundwater protection is essential in any area where the subsurface is exploited for hydrocarbons and has demonstrated degradation in countries where it has not been so carefully protected (Llewellyn et al., 2015; Hammond, 2016; Sherwood et al., 2016).

This chapter will bring together the information, knowledge, model results and discussions seen in Chapters 4, 5 and 6 and apply it within a UK context. A lack of data and experience in the UK onshore industry makes it difficult to quantitatively assess risk, as has been done for the Canadian case study. However, applying the model where possible allows further discussions on locating where information is present and must be used, and where gaps require substantially more information for improved research and a successful risk assessment for the future industry.

There are essentially three models within this research developed based on knowledge from Canada which could be applied to the UK: (1) cement failure, (2) integrity failure during injection, and (3) integrity failure during production. This chapter will discuss the application of these three models to the UK, illustrating their strengths and limitations and where further work is required.

7.2 CEMENT FAILURE

The development of fault trees to illustrate the vertical and horizontal failure of cement were conducted in Chapter 5 but can be applied to many well integrity situations. Cement failure was determined from literature review analysis and expert discussions, enabling more generic quantitative outcomes. Cement failure was constructed and applied to a Canadian model using experts in different fields, but the cement failure probabilities shown in Table 7.1 can also be applied to UK onshore wells.

TABLE 7.1: Cement failure probabilities during injection and production using Fuzzy Fault Tree Analysis (FFTA).

	Probability (%)	
	Vertical failure	Horizontal failure
Well injection stage	$3.4E^{-2}$	$8.4E^{-3}$
Well production stage*	$1.0E^{-2}$	$2.5E^{-3}$

*These values are calculated in Appendix D.

Despite their generic application, elements of the fault trees development should be improved before assuming the failure risk for UK wells. Suggestions for improvement to a UK scenario are discussed below.

1. To quantify the cement failure fault trees, only a few experts presented their opinions and they are likely to have come from biased backgrounds. Although every effort is made to reduce bias from experts, often there is limited choice and time. The experts used for the fault trees were mainly located in Canada so their decisions are influenced by their experiences in Canada. Obtaining new or more experts with an understanding of UK onshore well integrity could improve the accuracy of cement failure probability.

2. In addition to improving quantification of the basic events, discussions on the fault tree development with more suitable experts in the UK could improve their construction based on issues surrounding UK onshore well integrity.

3. An important point to note is the difference in onshore well development between the UK and other countries. Although the UK has around 2000 onshore hydrocarbon

wells, these have mainly targeted conventional reservoirs (Davies et al., 2014) but there is a difference of cement failure between conventional drilling and hydraulic fracturing (Ingraffea et al., 2014). Increased pressures, particularly during injection makes hydraulic fracturing potentially more susceptible to cement failure (Dusseault et al., 2000; Jackson et al., 2014). Therefore, the required experts for fault tree quantification in the UK should have a good understanding of the differences between conventional and unconventional techniques on cement failure in order to account for the differences in risk. Experts within the field of offshore hydrocarbon development in the UK Continental Shelf (UKCS) could provide relevant information where unconventional resources have been targeted.

7.3   PRESTON NEW ROAD WELL SITE

As discussed in Chapters 2 and 4, the UK is only in its infancy in developing a hydraulic fracturing industry and future plans for national production of shale gas is still undecided by the UK government (Acquah-Andoh et al., 2019). Licenses have been granted to Cuadrilla by the Environment Agency (EA) for exploratory drilling and more recently horizontal exploration wells have been drilled in Lancashire and are currently operating. These wells are based at the Preston New Road site; PNR1, PNR1z and PNR2. These three wells are from the same well pad i.e. their surface locations are all identical. PNR1 is a pilot well drilled vertically into the Lower Bowland Shale, PNR1z has the same vertical well section but turns horizontal at the top of the Lower Bowland Shale, and PNR2 is the most recent horizontal well drilled into the Upper Bowland Shale. The application in this chapter focuses on PNR1z. The geology and construction of this well is shown in Figure 7.1. The well is deviated in the vertical section from about 290 m at an average of 16° before reaching the horizontal section at approximately 90° in the Lower Bowland Shale.

The well is drilled through several formations which all have individual characteristics. These are described in Table 7.2. These characteristics are very similar to those seen during model development in Chapters 5 and 6 and therefore the models can be applied in a similar way. In this case, the Sherwood Sandstone, Mercia Mudstone and superficial deposits could all be considered aquifers given they contain water which might require protecting. However, the superficial deposit contains potable water and is the only aquifer which is monitored by the EA to protect groundwater resources (Cuadrilla Bowland Limited, 2016). The Sherwood Sandstone and Mercia Mudstone can be treated as aquifers or permeable formations for transporting gas to the secondary aquifer.

This well diagram and its characteristics are applied to both models discussed in Chapters 5 and 6, where possible.
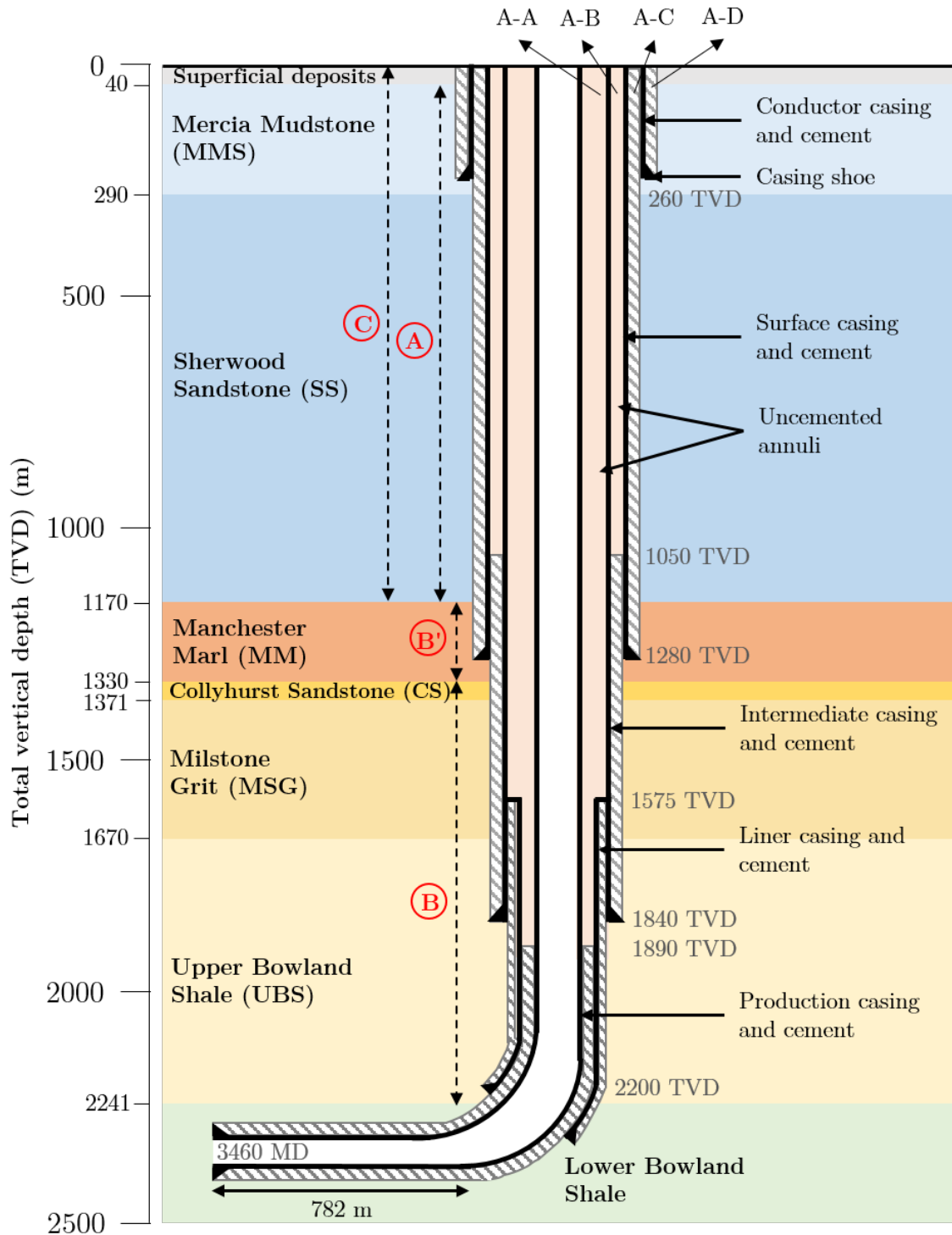
FIGURE 7.1: Detailed conceptual model of the Preston New Road horizontal well (PNR1z) drilled into the Lower Bowland Shale. The well deviation in the vertical section is not shown for simplicity. Details of the formations including the corresponding letters are shown in Table 7.2. Both the Sherwood Sandstone and Mercia Mudstone contain water but the superficial deposits is the monitored aquifer.
A-A: Annulus A, A-B: Annulus B, A-C: Annulus C, A-D: Annulus-D.

TABLE 7.2: Information on the formations intersected by the PNR1z horizontal well. Adapted from Cuadrilla Bowland Limited (2017) and Cuadrilla Bowland Limited (2018).

Formation	Top of formation TVD (m)	Description	Geological zone
Superficial deposits	10	-Shallow secondary aquifer. -Monitored from a groundwater well. -No gas present.	C
MMS	40	-Shallow artesian water flow seen at 19 m. -Fresh water, possibly brine. -No gas present.	A/C
SS	290	-Saline aquifer (brine). -No gas present.	A/C
MM	1170	-Low permeability. Forms a regional seal above the Collyhurst Sandstone. -Acts as a barrier to isolate gases or fluids below from reaching groundwater zones.	B′
CS	1330	-Both are likely to contain hydrocarbons (gases present).	B
MSG	1371	-Expected over-pressurised formations.	B
UBS	1670	-Both very tight formations.	B
LBS	2241	-For PNR1z, 69,000 kPa is required to fracture the formation and drilled with a mud weight of $1007 \, \text{kg m}^{-3}$.	-

TVD: Total Vertical Depth
A: Normal pressurised formation which might contain saline water.
B: Over-pressurised formation containing gas.
B′: Extremely tight formation acting as a seal for upward migrating fluids.
C: Groundwater zone of high permeability and porosity.

7.4   WELL INJECTION MODEL

The well stimulation model produced in Chapter 5 was developed from two different event trees based on the construction of the well for injection. Figure 7.1 illustrates a current horizontal well setup in the UK and corresponds similarly to the conceptual model for scenario 2 (Chapter 5, Figure 5.2b).

7.4.1   Event tree adjustments

There are differences between these two well constructions which must be considered. In Figure 7.1, an added casing string is used (intermediate casing) to protect the over-pressurised Collyhurst Sandstone and Milstone Grit formations. In addition, the annuli are not all cemented to the surface of the well. Both the intermediate casing and production casing/liner are only cemented above a previous casing shoe. The event tree created in Chapter 5 (Figure 5.6b) must be adjusted to account for the added casing string and uncemented regions of the well (Figure 7.2). This situation was not modelled in Chapter 5 but is quantified and discussed here, highlighting any further data or work required. Table 7.3 covers the data required to quantify each event in the event tree.

TABLE 7.3: Inputs for each failure event resulting in the loss of contaminants through well barriers.

	Component	Failure probability	Reference
	Packer	$1.04E^{-5}$	WellMaster database
	Tubing	$4.07E^{-5}$	WellMaster database
	Annulus	$1.29E^{-9}$	Chapter 5
Casing	Production casing	$7.59E^{-4}$	WellMaster database
	Intermediate casing	$3.89E^{-4}$	Estimated based on the failure rate for production casing and surface casing.
	Surface casing	$1.69E^{-5}$	Rish (2005)
	Conductor casing	$1.00E^{-6}$	Estimated based on the failure rate for surface casing.
Leak location	C1	0.003	Chapter 7
	U1	0.997	Chapter 7
	C2	0.007	Chapter 7
	U2	0.993	Chapter 7
	C3	0.09[a]	Chapter 7
	C4	0.71[a]	Chapter 7
	C5	0.2[a]	Chapter 7
Cement	Horizontal migration	$8.36E^{-3}$	Chapter 5
	Vertical migration	$3.42E^{-2}$	Chapter 5

[a] C3, C4 and C5 all represent sections of the surface casing which is fully cemented to the surface. As there is no uncemented section, the probability of failure at a particular location is dependent only on the length.

It is unclear from UK documents if a tubing and packer were used during the injection stage. Cuadrilla highlighted a tubing assembly was used during hydraulic fracturing operations to open the multi-frac sleeves for injection. Therefore, here it is assumed a tubing/packer construction was used (Cuadrilla Bowland Limited, 2019b).

The event tree constructed in Figure 7.2 has been adjusted according to an added casing string and differing cemented and uncemented casing sections. Given a leak has occurred somewhere along a casing string, the probability of where that leak occurs is dependent upon whether the section of a casing is cemented or uncemented and the length of that section. Uncemented casing plays a large role in gas migration and casing failure (Watson and Bachu, 2009) as they are at a much higher risk of failing compared to the cemented sections. A ratio between the proportion of the length and a cement index value is used to consider the probability of a cemented or uncemented section failing. Zulqarnain et al. (2017) determined a cement index for wellbore leakage during CO_2 geological sequestration which is the proportion of leakage in cased-cemented (0.01) and cased-uncemented wells (0.72). Assume a casing is 84% uncemented at a failure rate of 72% and 16% cemented at a failure rate of 1%, the proportion of failure of uncemented to cemented would be 0.6 : 0.0016. To ensure the proportion of failure equates to unity, the ratio of uncemented to cemented failure would be 0.997 : 0.003. This is a reasonable assumption given the cemented section is much smaller than uncemented and the majority of casing failures are due to poor or no cement in the annulus (Watson and Bachu, 2009).

EVENT TREE X

Event 1	Event 2	Event 3	
Packer or tubing	Annulus	Production casing	Outcome

Annulus pressure < injection pressure — Leak — X
No leak — ○
Leak — Annulus pressure > injection pressure — ○

EVENT TREE Y

Event 3	Event 4	Event 5	Event 6	
Production casing	Leak location	Production cement	Intermediate casing	Outcome

Cemented region (C1) — No horizontal migration — ○
Horizontal migration — Leak — Y1
No leak — ○
Leak — Uncemented region (U1) — Leak — Y2
No leak — ○

EVENT TREE Z

Event 6	Event 7	Event 8	Event 9	
Intermediate casing	Leak location	Intermediate cement	Surface casing	Outcome

Cemented region (C2) — No horizontal migration — ○
Horizontal migration — Leak — Z1
No leak — ○
Leak — Uncemented region (U2) — Leak — Z2
No leak — ○

EVENT TREE FINAL

Event 9	Event 10	Event 11	Event 12	Event 13	
Surface casing	Leak location	Surface cement	Conductor casing	Conductor cement	Final outcome

Cemented in B' zone (C3) — No migration — ○
Vertical migration to A/C then horizontal — ⊗ F1
Vertical migration to above CCS — No leak — ○
Leak — No horizontal migration — ○
Horizontal migration — ⊗ F2
Leak — Cemented below CCS, above B' (C4) — No migration — ○
Horizontal migration — ⊗ F3
Cemented above CCS (C5) — No migration — ○
Horizontal migration — No leak — ○
Leak — No horizontal migration — ○
Horizontal migration — ⊗ F4

FIGURE 7.2: An event tree divided into individual trees for clarity for the probability of groundwater contamination from a packer or tubing leak during injection. The C1 and U1 regions are along the production casing, C2 and U2 along the intermediate casing and C3, C4 and C5 along the surface casing. F1, F2, F3 and F4 are the final failure outcomes. 32 failure outcomes are possible when combining the four sub-event trees.

7.4.2   Results

Four individual event trees are illustrated in Figure 7.2. The additional casing strings and a variation of cemented and uncemented sections in the well (Figure 7.1) presents a more complex possibilities of failure pathways, producing a much larger event tree. This event tree has been divided up for simplicity and to indicate the failures after each casing string. Although the final event tree (Figure 7.2; FINAL) identifies four failures of probability, the multiple failure outcomes in event tree Y and Z and the initial failure of a packer or tubing in event tree X produces the potential for 32 different failures leading to groundwater contamination. The results for each event tree outcome and the cumulative failure probabilities are shown in Table 7.4.

As discussed earlier, it is unclear whether a tubing and packer are used in the PNR1z well. It is assumed for this application they are used. However, they can be easily removed from the event tree if they are not used. Event tree X can be ignored so the movement of gas starts at event tree Y. It should be noted the column for event tree Y in Table 7.4 does not include the production casing leak as it was included in the previous event tree (event tree X). This should therefore be included when removing the first event tree, so a re-calculation of event tree Y to include the production casing leak would be required.

The final results for the PNR1z well during injection demonstrate an extremely low probability of contamination during injection for all scenarios, whether a packer or tubing leak occurred. This probability would be considered negligible, even if the risks presumed to be additive and all leakage pathways occurred (packer failure: 10^{-26}, tubing failure: 10^{-25}).

As discussed in Chapter 5, there exists very little literature on single barrier and full well integrity failure during the well injection stage of hydraulically fractured wells. It is clear the more single barriers between the injection pressure and aquifer or surrounding formations, the substantially lower the risk of groundwater contamination. Although the Canada model demonstrated a very low probability of contamination during injection (0.0006%), the UK model with an added cemented casing string and protection of the tubing and pressurised annulus illustrates an extremely low probability at an estimated magnitude of 10^{-26}%.

The pressurised annulus between the tubing and production casing provides a critical barrier for gas migration and also allows performance monitoring to reduce the risk even further of a breached annulus (fault tree; Chapter 5, Figure 5.7). Casing sections of cemented regions are the next critical element to reducing the risk of barrier failure. Uncemented casing sections are much more likely to fail (given a failure occurs along a casing string) and without the cement after a failed casing string, the risk of barrier failure increases by a factor of approximately 10,000 (Table 7.4.).

TABLE 7.4: Final results for each failure outcome in the event tree shown in Figure 7.2.

Event Tree X	Event Tree Y	Event Tree Z	Event Tree FINAL	Probability (%)
	Y1	Z1	F1	$2.53E^{-37}$
	Y1	Z1	F2	$2.53E^{-43}$
	Y1	Z1	F3	$5.85E^{-35}$
	Y1	Z1	F4	$1.38E^{-43}$
	Y1	Z2	F1	$4.30E^{-33}$
	Y1	Z2	F2	$4.30E^{-39}$
	Y1	Z2	F3	$9.93E^{-31}$
	Y1	Z2	F4	$2.34E^{-39}$
Packer $(1.02E^{-17})$	Y2	Z1	F1	$1.01E^{-32}$
	Y2	Z1	F2	$1.01E^{-38}$
	Y2	Z1	F3	$2.32E^{-30}$
	Y2	Z1	F4	$5.48E^{-39}$
	Y2	Z2	F1	$1.71E^{-28}$
	Y2	Z2	F2	$1.71E^{-34}$
	Y2	Z2	F3	$3.95E^{-26}$
	Y2	Z2	F4	$9.31E^{-35}$
	Y1	Z1	F1	$9.87E^{-37}$
	Y1	Z1	F2	$9.87E^{-43}$
	Y1	Z1	F3	$2.28E^{-34}$
	Y1	Z1	F4	$5.38E^{-43}$
	Y1	Z2	F1	$1.68E^{-32}$
	Y1	Z2	F2	$1.68E^{-38}$
	Y1	Z2	F3	$3.88E^{-30}$
Tubing $(3.98E^{-17})$	Y1	Z2	F4	$9.14E^{-39}$
	Y2	Z1	F1	$3.93E^{-32}$
	Y2	Z1	F2	$3.93E^{-38}$
	Y2	Z1	F3	$9.07E^{-30}$
	Y2	Z1	F4	$2.14E^{-38}$
	Y2	Z2	F1	$6.67E^{-28}$
	Y2	Z2	F2	$6.67E^{-34}$
	Y2	Z2	F3	$1.54E^{-25}$
	Y2	Z2	F4	$3.63E^{-34}$

Y1: $9.76E^{-9}$, Y2: $3.88E^{-4}$
Z1: $9.89E^{-10}$, Z2: $1.68E^{-5}$
F1: $2.57E^{-5}$, F2: $2.57E^{-11}$, F3: $5.94E^{-3}$, F4: $1.40E^{-11}$

Although the results from applying this model to the PNR1z well in the UK indicate potentially negligible effects on groundwater, it is important to highlight the areas of highest risk and where only a few barrier failures could escalate to full integrity failure. Injecting down a tubing significantly reduces the risk of well integrity failure as does fully

cementing all annuli. Fully cemented annuli would reduce the number of potential failure pathways which in turn reduces the possibilities of failures. When dealing with a new industry which is yet to make considerable profit, future work should focus on comparing the risks of partially cemented annuli and fully cemented annuli and altering the numbers of casing strings against the economic costs of the process.

7.4.3 Assumptions and limitations

Using the data given in Table 7.3, the branches can be quantified to obtain all possible failures of probability for the UK well. However, several assumptions have been made to enable quantification suggesting more accurate data collection is required.

Assumptions:

1. The production casing has the same failure value regardless of whether a tubing and packer are present. Technically, the pressure exerted on a production casing is much higher when injection does not occur down a tubing and corrosive substances will come into direct contact with a production casing.

2. Using results from Zulqarnain et al. (2017), it is assumed a cemented casing allows wellbore leakage 1% of the time and an uncemented casing allows wellbore leakage 72% of the time. Although these values are determined based on injection into a storage zone (similar to injection during hydraulic fracturing), the model focused on leakage volume rates to determine the cement index under different geological scenarios compared to this work. In addition, the deeper a casing is set the higher the pressure exerted on that casing increasing the risk of failure, but this was not considered when determining the probability of failure as the increase in risk was assumed to be too small to make a significant impact.

3. Once a leak has occurred at an uncemented casing section, it is assumed gas will always move into this uncemented annuli. There must be a pressure gradient to ensure the gas migrates but it is assumed where gas has been allowed to flow across a leakage pathway, almost immediately the pressure will now be greater in that annuli compared to its outer neighbour.

4. There is no intermediate casing failure data on the WellMaster offshore database so it is assumed the failure sits between the failure of production and surface casing.

5. There is no conductor casing failure data on the WellMaster offshore database so the failure is assumed to be less than the surface casing.

6. For horizontal and vertical cement failure, it is assumed a complete pathway is created between one barrier to another. When a crack forms in cement, it propagates in the horizontal or vertical direction leading to an immediate release of a contaminant.

Data or modelling requirements:

1. Independent failure values for production casing when a tubing is used and when it is not used. Alternatively, where data collection is unreasonable or requires significant time for accurate failures, Fault Tree Analysis (FTA) can be used to identify specific basic failure events with respect to casings under different scenarios and can be quantified using expert knowledge and fuzzy logic.

2. There is little well-defined quantitative information on the differences between cemented and uncemented casing failure during injection of a hydraulically fractured well. More work is required to reduce this uncertainty and to eliminate the use of results from alternative engineering fields which might not produce an accurate representation.

3. The assumption gas will move between neighbouring uncemented annuli almost immediately (where there is a leakage pathway) is not unreasonable as you would expect there to be a pressure gradient. However, this could be dependent upon the timing of an event. The migration of gas across uncemented annuli might only happen after time t, at which pressure has built up enough to be greater than the neighbouring annuli. Failure location, timing of individual events and data collection on pressures of individual annuli would reduce the uncertainty of this assumption.

4. Intermediate casings are not as commonly used compared to surface and production casings so failure rates are harder to obtain. The WellMaster offshore database only has four records of offshore wells using intermediate casing, none of which failed. Four records is not substantial enough to determine a statistically valid failure rate for an intermediate casing string, even if at least one failed. More data is required to improve this value.

5. Conductor casing failure data is highly unlikely to be prevalent in an offshore database as conductor casing is more common for onshore wells. As a general improvement tool across this whole research and for this UK application, obtaining onshore failure rates would improve the accuracy of the application.

6. The assumption for vertical cement failure leading to propagation is supported by Dusseault et al. (2000) as an increase pressure at the leading tip of the crack due to gas build-up encourages an increase in the vertical height. However, the rate at which this occurs could be limited based on stiffness and geometry (Dusseault et al., 2000). Further work is required based on the duration and length at which a vertical crack propagates to improve the accuracy of vertical cement failure leading to barrier failure. Additionally, horizontal failure and the interaction between horizontal and vertical failure in cement requires further understanding. It is more likely horizontal failure immediately creates a pathway between two barriers than vertical due to

a smaller distance to fail and the reasons for horizontal failure (Bonett and Pafitis, 1996), but its application in gas migration is still very poorly understood.

7.5 WELL PRODUCTION MODEL

In Chapter 6, the model was developed based on a high risk well construction with an open annulus, closed vent valve system and only two casing strings: production casing and surface casing. The UK well construction indicated in Figure 7.1 is considered a low risk construction for gas migration into groundwater. There are uncemented annuli: the production annulus and intermediate annulus, but the cemented sections of the intermediate and production casings extend above the base of the surface casing shoe. This model corresponds similarly to that in Chapter 6, Figure 6.3a and 6.3b. The surface casing is cemented to the surface but Surface Casing Pressure (SCP) is possible within the two partly uncemented annuli. This is further examined in Section 7.5.2.

7.5.1 Fuzzy logic model

The initial part of the model in Chapter 6 uses a Fuzzy Logic System (FLS) to determine the mud column length of a well and later the potential for SCP-induced gas migration using gas flow rate and time. The mud column length, particularly for older wells is often not found in gas well databases or not properly noted. This was particularly the case for the onshore wells in British Columbia (BC), Canada. In newer wells, if the annulus has been cemented to the top this is generally noted but if it has been left partly uncemented the cement top is generally unknown.

Due to high public concerns and EA regulations, information has recently been detailed and made public on the few wells which Cuadrilla are drilling in Lancashire (Environment Agency, 2017b). The mud column lengths are already known for all annuli, as indicated in Figure 7.1 and therefore the initial part of the FLS to determine mud length is not required.

The FLS for predicting mud column length assumes only a production and surface casing construction where the production cement is the only barrier between surrounding formations and the production casing. The PNR1z well also contains a partly cemented intermediate casing to protect certain surrounding formations, which will alter the decisions drillers make on cement height. Therefore, the fuzzy logic component of this model to predict the mud column length in the A-A or A-B annuli cannot be used due to the differences in construction.

Where mud column length might not be known in the A-A or A-B annuli (not in this case) the fuzzy logic inputs can be altered. Currently, the decision of production cement is governed by the depth of the aquifer (the deeper the aquifer the less requirement for

cement), the depth of hydrocarbon-bearing formations (cement only needs to go just above the top) and the measured depth of the well (a shallower well might require a higher cement column). In the case of the PNR1z well setup, the decision for production cement height is dependent upon the depth of cemented intermediate casing, depth of cemented surface casing and presence of over-pressurised formations. The production cement height in the UK well is very low due to the presence of a cemented liner and deep cemented intermediate casing. Additionally, the A-B annulus is partly uncemented (also can be predicted using the framework of the fuzzy logic model) due to the depth of the cemented surface casing, presence of the tight Manchester Marl seal and the deep Sherwood Sandstone aquifer. Suggestions for fuzzy inputs could include:

- Aquifer depth

- Importance for aquifer protection

- Country regulations

- Depth of shallowest and deepest over-pressurised, gas-bearing formations

- Number of casing strings (surface, intermediate, production, liner)

- Depth of cemented casing strings

- Measured Depth (MD) of the well

As mentioned above, the final part of the fuzzy model in Chapter 6 predicts the potential for SCP-induced gas migration using gas flow rate and time. This can still be applied in the case of the PNR1z well and is described in more detail in Section 7.5.2.

7.5.2   Numerical model

The second part of the model estimates a probability of gas migration out of the well into a surrounding formation (with the assumption it reaches groundwater) during the production stage of the well. In Chapter 6, this quantification is conducted based on a closed vent valve causing the build-up of SCP in the open annulus and exceeding the surrounding pressure formation, allowing gas to migrate into groundwater. The PNR1z well has uncemented sections but does not have an open annulus to the surrounding formations. The well was constructed to protect the Sherwood Sandstone aquifer formation and prevent the migration of gas into annuli from the gas-containing Collyhurst Sandstone, Milstone Grit and Bowland Shale formations. Unlike the well represented in Chapter 6, the UK well has been built to protect vital formations and to reduce the potential for groundwater contamination, inevitably reducing the risk to groundwater.

Despite all measures to eliminate SCP and gas migration to groundwater, well integrity failure is still a possibility. Pathways can still develop within the cement-casing annuli

and build-up of pressures in an area can encourage pressure gradients and movement of gas. The event trees in Chapter 6 (Figure 6.4) include simplified pathways for wells with closed annuli and their outcomes (P_3 (1), P_3 (2), P_4 (1), P_4 (2)). The focus for this application is the movement of gas from the external formation along poorly cemented annuli to shallower formations, Figure 6.4a (Chapter 6). Therefore only pathways P_3 (1) and P_3 (2) are considered.

Pathways P_3 (1) and P_3 (2) presume once gas has entered into an external faulty cement column, SCP occurs and can lead to gas circumvention where high quality cement overlies poor quality cement, forcing the gas into external formations. This often happens underneath a casing shoe and would require the gas to leave at a lower pressurised formation compared to the annulus (Lackey and Rajaram, 2019). In the case of the PNR1z well, gas can enter anywhere within location B, Figure 7.1, as these are all considered gas-bearing formations so likely to be higher pressured than a well annuli. However if the gas entered into the intermediate cement annulus (Figure 7.1, A-B), gas circumvention could not occur as the surface casing shoe is set into the Manchester Marl formation, a tight impermeable formation which acts as a seal from migrating gases. It can be assumed gas would not be able to escape at location B'. If the gas entered into the liner/production cement annulus (A-A), gas circumvention also could not occur due to the extra casing string (intermediate casing) and depth of the liner and production casing shoes. Gas will only migrate out of the annuli if casing strings failed, SCP was high enough to migrate into the next annulus and the surface casing cement failed, allowing a higher pressure to escape into the lower pressure shallow formations (Sherwood Sandstone and Mercia Mudstone). Alternatively, if casings or cement did not fail and the casing vent valves were kept closed, the SCP could build-up enough to match that of the pressure at the leak, eliminating the pressure gradient and essentially healing the leak. The event tree for vertical cement failure from Chapter 6 (Figure 6.4a) has been applied more specifically to the PNR1z well, indicated in Figure 7.3.

Events 2 and 4 are dependent upon pressure gradients between formations and annuli. The required pressures are detailed in Table 7.5. Event 2 assumes gas will always flow into the A-B annulus from the over-pressurised formations (Figure 7.1, location B) as the hydrostatic pressure of the A-B mud column is always less than the formation pore pressures (Table 7.5). If a vertical cement failure occurred at a shallower formation in the surface casing cement, the initial pressure inside the annulus must be measured to determine a pressure gradient; no measurements are available for this study in the A-C or A-D annuli (Table 7.5).

When gas enters the cement annuli, either gas will escape at the surface if the vent is open (Surface Casing Vent Flow, SCVF) or gas will build-up in the annulus (SCP). In event 4, gas migration out of a specific location is dependent upon the build-up of gas in the annulus and the surrounding shallow formation pressure. SCP depends upon the flow into the
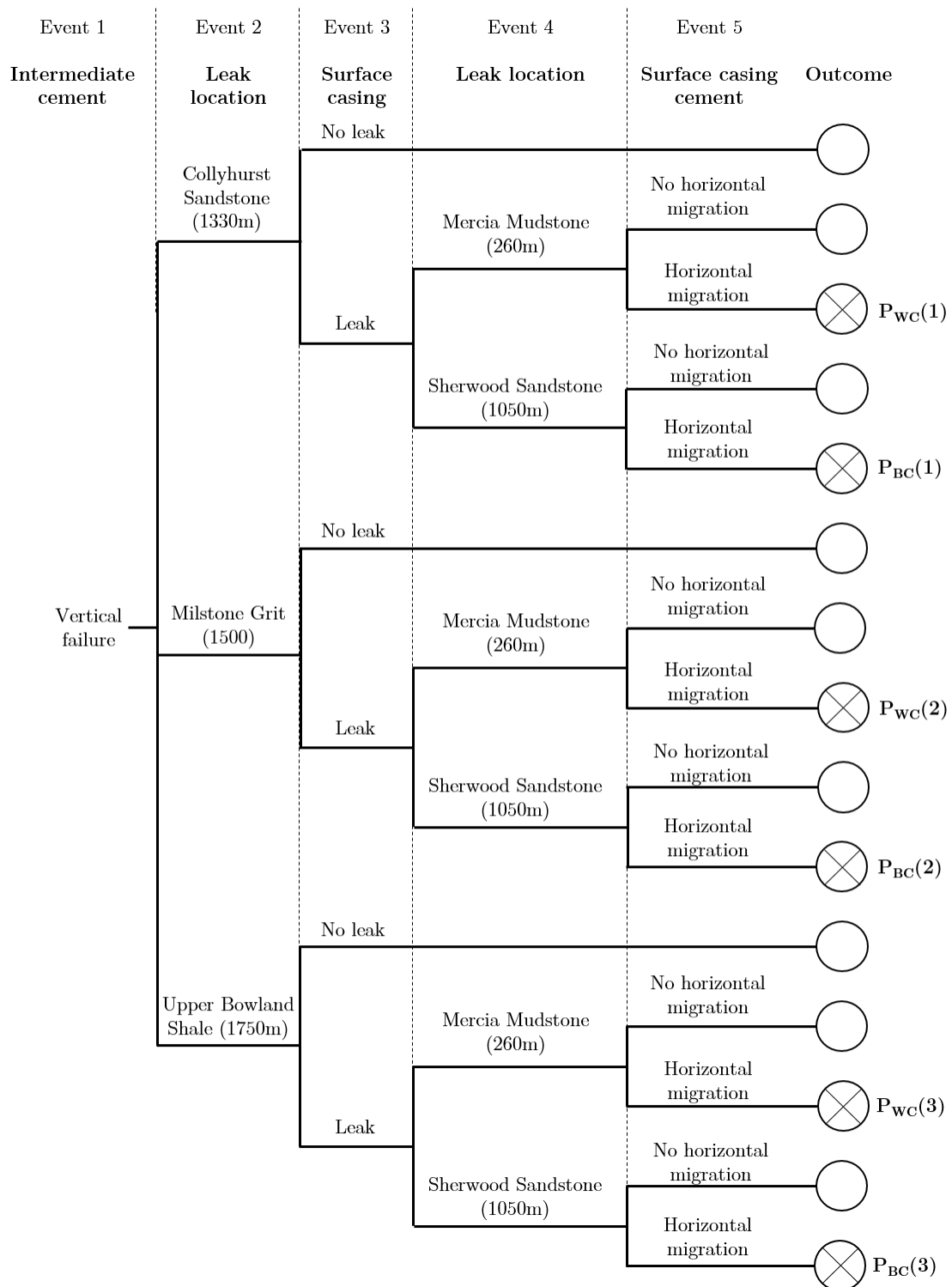
FIGURE 7.3: An event tree for the probability of groundwater contamination from the failure of intermediate cement during production. Event 2 is the inflow of gas from an over-pressurised formation and event 4 is the outflow of gas into a shallower formation. The failure outcomes are defined as three worst-case scenarios ($P_{WC}(y)$) and three best-case scenarios ($P_{BC}(y)$).

TABLE 7.5: Estimated values of formation pore pressures using a pressure profile (Cuadrilla Bowland Limited, 2017) and calculated hydrostatic annulus and formation pressures.

		TVD (m)	Pore pressure (kPa)	Potentiometric head above TVD[a] (m)	Formation fluid density (kg m^{-3})	Hydrostatic pressure (kPa)
	MMS	260	2070	243.5	Fresh water 1000	2389
Formation	SS	1050	10,000	1033.5	Brine 1034[b]	10,483
	CS	1330	15,000	-	-	-
	MSG	1500	17,200	-	-	-
	UBS	1750	20,700	-	-	-
Annulus (Mud column)	A-A	1890	-	-	-	18,671[c]
	A-B	1050	-	-	-	10,373[c]
	A-C	0[d]	-	-	-	-
	A-D	0[d]	-	-	-	-

[a] Static water level for the potentiometric head is assumed to be 16.5 m (Chapter 4).
[b] Assuming 5 wt% NaCl.
[c] Mud density is assumed to be 1007 kg m^{-3} (Cuadrilla Bowland Limited, 2017).
[d] Annuli A-C and A-D are fully cemented and no pressure measurements exist for these annuli.
 Gravity is taken as 9.81 m s^{-2}.

annulus through the cement and the increasing casinghead pressure, using the equation explained in Chapter 6 (Rocha-Valadez et al., 2014):

$$Q_{sc} = \frac{kAT_{sc}\left(p_f^2 - (p + g\rho_m L_m)^2\right)}{2\mu_i Z_i T_i L_c p_{sc}} \tag{7.1}$$

Gas migration out of the annulus is dependent upon the hydrostatic pressure of the Sherwood Sandstone or Mercia Mudstone. The casinghead pressure of the annulus is critical when it reaches the hydrostatic pressure of the formation, as described in Chapter 6:

$$p_{crit} = g\rho_w H_w \tag{7.2}$$

where ρ_w is the density of the formation fluid, either freshwater or brine, and H_w is the potentiometric head above the TVD of the formation.

To estimate the potential for SCP build-up moving into the shallower formations, as conducted in Chapter 6, the flow of gas into the annulus and time taken to reach the critical pressure for which migration occurs is determined. To encourage migration, the hydrostatic pressure of the formation must be less than the built-up pressure of gas and under the assumption gas rises to the top of a mud column, the volume of gas must compress the mud column down to the point at which the leak occurs.

Given that the well integrity fails from a leak in the intermediate cement, there is a best- and worst-case scenario of SCP build-up in the A-B annulus. As shown in Figure 7.3, once the surface casing fails the gas could migrate anywhere from the bottom of the conductor casing shoe to the top of the Manchester Marl formation. The worst-case

scenario is considered as migration at the bottom of the conductor casing shoe (260 m). The hydrostatic pressure is at its lowest so less SCP is required to break the pressure gradient barrier. The best-case scenario is considered migration in the Sherwood Sandstone at the top of the intermediate cement (1050 m). According to Table 7.5, the casinghead pressure is critical when it reaches 2389 kPa in the worst-case scenario or 10,483 kPa in the best-case scenario.

7.5.3 Results

Applying the information above and using equation 7.1, the potential for SCP and gas migration into shallower formations for the PNR1z well can be determined. The probability of well integrity failure, given the intermediate cement fails, can then be determined using the event tree in Figure 7.3. To calculate the gas flow rate into the well at which the casinghead pressure has reached a critical point, equation 7.1 and details of inputs and parameters are used as shown in Table 7.6.

TABLE 7.6: Inputs and parameters for the numerical model to determine the probability of SCP build-up leading to migration at a shallower formation in the PNR1z well.

		Scenario	Formation of gas inflow/outflow	Value	Reference
Inputs	Formation pressure (p_f), kPa	- - -	CS MSG UBS	15,000 17,200 20,700	Table 7.5 Table 7.5 Table 7.5
	Casinghead pressure (p), kPa	Worst-case Best-case	MMS SS	2389 10,483	Table 7.5 Table 7.5
	Mud density (ρ_m), $\mathrm{kg\,m^{-3}}$	-	-	1007	Cuadrilla Bowland Limited (2017)
	Mud column length (L_m), m	Worst-case Best-case	- -	790 0	Figure 7.1 Figure 7.1
	Run depth temperature (T_i), K	-	-	350	Estimated - no data available
	Cement column length (L_c), m	-	-	790	Figure 7.1
Parameters	Cement permeability (k), m2			$1.48E^{-15}$	Rocha-Valadez et al. (2014)
	Area of intermediate annulus (A), m2			0.076	Cuadrilla Bowland Limited (2017)
	Gas viscosity (μ), Pa s			$1.5E^{-5}$	Rocha-Valadez et al. (2014)
	Standard temperature (T_{sc}), K			273.15	-
	Z-factor (Z)			0.92	Rocha-Valadez et al. (2014)
	Standard pressure (p_{SC}), Pa			$1E^5$	-

The gas flow rate into the well from an over-pressurised formation at critical casinghead pressure is calculated using inputs and parameters from Table 7.6. The volume of gas required to compress the top of the mud column to the location of the leak is determined and hence the time taken for the gas to reach this location is calculated. Table 7.7 shows these outputs and illustrates the probability of gas migration to either the Mercia Mudstone (MMS) or Sherwood Sandstone (SS) given SCP occurs in an annulus.

It is important to recognise the probability of failures indicated in Table 7.7 are the potential for SCP exceeding the shallow formation pressure and given all barriers fail, allowing the gas to migrate into the surrounding formations. Assuming SCP occurs in the A-B annulus, the best-case scenario illustrates a medium likelihood for gas reaching the Sherwood Sandstone formation and a high likelihood for the gas reaching the Mercia Mudstone. In comparison to the BC wells modelled in Chapter 6, the potential for gas migration is generally slightly lower in the PNR1z well. This is mainly due to a much larger volume of gas required to enter the annulus to compress the mud column down to a point where a leak is most likely. This indicates a much stronger construction in the PNR1z well as the surface casing is fully cemented at a depth at least twice that of the BC well construction with the conductor casing also deeply cemented to reduce very shallow gas migration.

TABLE 7.7: The values for the probability of gas migration from SCP build-up in the A-B annulus, given all preceding barriers fail.

Scenario	Formations		Gas flow rate ($m^3\,d^{-1}$)	Volume (m^3)	Time (days)	Probability of GM	
	Inflow	Outflow				%	Probability
Worst-case	CS		0.42		47	71	High
	MSG	MMS	0.67	19.76	30	75	High
	UBS		1.13		18	77	High
Best-case	CS		0.40		199	47	Medium
	MSG	SS	0.65	79.80	123	60	Medium
	UBS		1.11		72	67	High

Finally, the overall probability of well integrity failure from an intermediate cement leak during production is calculated using Figure 7.3, the probability values obtained in Table 7.7, casing failures from Chapter 5 and cement failures calculated in Appendix D. The values required for each branch on the event tree and the final probability values are demonstrated in Table 7.8.

The final probability values for well integrity failure from an intermediate casing leak are all very low, with the highest probability pathway at only 10^{-8}%. This outcome is supported by the conceptual model and risk assessment developed by Arup for the PNR1z site, where the probability of well integrity failure due to poor construction leading to the contamination of the Mercia Mudstone or Sherwood Sandstone is determined to be very low (Cuadrilla Bowland Limited, 2016). Similarly to the injection model in Section 7.4, the

TABLE 7.8: Final results for each event in the event tree in Figure 7.3 to obtain a final probability for each failure branch.

Failure pathway	[a]Event 1 Vertical cement failure	[b]Event 2 Location	[c]Event 3 Surface casing failure	Event 4		[a]Event 5 Horizontal cement failure	Final probability (%)
				[b]Location	Gas migration		
P_{WC} (1)	$1.00E^{-2}$	0.08	$1.69E^{-5}$	0.04	0.71	$2.50E^{-3}$	$9.60E^{-11}$
P_{BC} (1)	$1.00E^{-2}$	0.08	$1.69E^{-5}$	0.96	0.47	$2.50E^{-3}$	$1.53E^{-9}$
P_{WC} (2)	$1.00E^{-2}$	0.59	$1.69E^{-5}$	0.04	0.75	$2.50E^{-3}$	$7.48E^{-10}$
P_{BC} (2)	$1.00E^{-2}$	0.59	$1.69E^{-5}$	0.96	0.60	$2.50E^{-3}$	$1.44E^{-8}$
P_{WC} (3)	$1.00E^{-2}$	0.33	$1.69E^{-5}$	0.04	0.77	$2.50E^{-3}$	$4.29E^{-10}$
P_{BC} (3)	$1.00E^{-2}$	0.33	$1.69E^{-5}$	0.96	0.67	$2.50E^{-3}$	$8.97E^{-9}$

[a] Calculated using method in Chapter 5 and results in Appendix D.
[b] Calculated based on the proportion of each length where failure could occur.
[c] Chapter 5 or Chapter 7.
 WC: Worst-case, BC: Best-case

probability values are expected to be low due to the strict well construction regulations employed in the UK for onshore hydraulic fracturing. A failure at the surface casing cement above the conductor casing shoe has not been included in this event tree (Figure 7.3) as the risk would be so much lower due to the added requirement of failure in the conductor casing and cement.

7.5.4 Assumptions and limitations

Along with some of the assumptions already mentioned in Section 7.4, certain aspects of the numerical model have been assumed to allow for quantifiable results and to simplify the complexity of well integrity failure in the subsurface, with very little applicable experimental data. Suggestions for improvements in relation to application to the UK have been included.

Assumptions:

1. The improvements to apply the fuzzy logic aspect of the model to the UK has been already discussed in Section 7.5.1 but assumptions in the final fuzzy probability part of the model must be noted. The gas flow rate membership function was developed from data showing gas migration noticed at the surface of wells in BC. This data could be specific to BC wells so the function might require adjustment for UK wells.

2. The PNR1z well is deviated in the vertical section at an angle of approximately $16°$ after the conductor casing shoe before reaching the horizontal section in the Bowland Shale. For simplicity, this has not been accounted for in the TVD of the mud column within the A-B annulus.

3. To determine the required pressures to represent gas migration (Table 7.5) and gas flow rate (Table 7.6), certain assumptions had to be made:

(a) The static water level to calculate the potentiometric head was assumed to be 16.5 m based on one measurement in the monitored borehole for the secondary aquifer (superficial deposits).

(b) The formation fluid density of the Mercia Mudstone and Sherwood Sandstone are estimated based on basic descriptions (Cuadrilla Bowland Limited, 2017; Cuadrilla Bowland Limited, 2019c), although are not expected to change drastically across different salinities.

(c) It is assumed the pressure in fully cemented annuli is zero and therefore if a crack were to be formed, gas in the neighbouring annulus would always move into the failed cemented annulus.

(d) Assumed the run depth temperature at the initial leak is 350 K (Chapter 6) and the same for all three potential leak locations, due to a lack of data. In reality, the run depth temperature should increase slightly with increasing depth.

4. The time over which gas migration occurs from the initial cement leak through to SCP build-up and migration into a shallow formation is not properly executed in this model, due to the lack of available experimental data over time. The well has not been producing gas for very long and operations are often halted due to seismic issues (Pater and Baisch, 2011; Cuadrilla Bowland Limited, 2019a) so time-sensitive data on SCP is not available. Additionally, the two horizontal wells in Lancashire (PNR1z and PNR2) are the only wells producing data which presents further uncertainty for generic gas migration failures in the UK.

5. The depletion of the gas-bearing formation over time is not considered and therefore its change in pressure and overburden weight is also ignored.

Data or modelling requirements:

1. Despite the low number of wells, there have likely been gas migration/SCP/SCVF incidences in onshore wells in the UK. This data is vital for improving an understanding of gas migration potential from the formations in the UK, particularly as the UK geology is more complex compared with other countries (Loveless et al., 2018a).

2. Rocha-Valadez et al. (2014) incorporated a calculation for deviated sections of a well, such as the mud column, which can be applied to the model if well deviations are known:

$$L_m = \sum \left(\Delta z_i \cos \theta_i \right) \tag{7.3}$$

where L_m is the mud column TVD, Δz_i is the difference in the MD within a certain section i, with a deviation of θ_i from the vertical.

3. Improvements to pressure measurements/calculations:

(a) The groundwater level can vary substantially across different seasons/rainfall events, altering the hydrostatic pressure so more frequent monitoring is required of the water well. Additionally, boreholes and monitoring into the Mercia Mudstone and Sherwood Sandstone would reduce uncertainty in hydrostatic pressures.

(b) More accurate measurements for the salinity of the Mercia Mudstone and Sherwood Sandstone for improved calculation of the hydrostatic pressures.

(c) Pressure measurements for fully cemented annuli should be available or determined to reduce the uncertainty in gas migration between annuli.

(d) Run depth temperatures of the target formation should be determined during drilling and well stimulation, although temperatures at certain depths would need to be requested if these are required.

4. The model has high accuracy for early-time data but uncertainty in the outputs increases with time (Rocha-Valadez et al., 2014). Realistically, the higher the number of onshore hydraulically fractured wells drilled and producing, the more temporal information available to improve the understanding of SCP and gas migration in UK wells. Ideally, this understanding must be grasped before gas migration occurs in the UK. If the numerical model is applied during field data testing and analysis, the casing pressure rise over time and gas flow rate can be better quantified.

5. To reduce uncertainty in depleting gas reservoirs over time and hence gas flow rate into an annulus, the changes in reservoir pressure should be modelled over a period of time during which the well is producing.

7.6 CONCLUSION

Initially, it was expected the models developed in this research would be a challenge to apply to the UK due to the infancy of the industry, a lack of data and confidentiality requirements. Recently, further information has become available to the public on the UK onshore hydraulic fracturing industry to improve the trust between the industry and society. The three wells in Lancashire consist of a vertical pilot well (PNR1) and two horizontal wells (PNR1z and PNR2) with PNR2 only recently being drilled and explored. Data has become available for the PNR1z well, particularly to improve the understanding of seismicity incidences Cuadrilla are currently facing.

The data required for the models in this research has been extracted from the PNR1z well, where possible, to encourage application. Although the models in Chapters 5 and 6 have been developed based on very different constructions to the PNR1z well, adjustments have been successfully made in both models to account for these differences. Where

adjustments could not be made or assumptions were required, these were discussed along with improvements for data collection or modelling.

As expected for a well with multiple barrier layers, the outputs for both the injection well and production well were of significant low risk even in comparison with the BC wells. The probability surrounding the injection wells can be deemed insignificant, although further data collection on casing failures and modelling the propagation of a cement crack would improve the uncertainty in this output. The probability of failure during production was significantly higher although still low enough to not be of concern. Improvements require modelling of SCP over time during field-based analysis, particularly over long periods of time whilst the well is producing. Where annuli are only partly cemented, further reduction in the probability of well integrity failure can be executed by fully cementing all annuli. This should be weighed up against the economic and environmental benefits of partially or fully cemented annuli.

Strict environmental regulations, disclosure of information and collaboration between regulators and industries puts the UK in good stead for commercialisation for reducing environmental issues which have been faced by other countries. This statement does not adhere to support or not support hydraulic fracturing in the UK, but respects the potential for development and the issues faced, which must be of priority.

CHAPTER 8

CONCLUSION AND RECOMMENDATIONS

8.1 CONCLUSION

The aim of this research project was to develop a risk assessment framework for the onshore hydraulic fracturing UK industry to quantify the probability of groundwater contamination from well integrity failure during the injection and production stages of a well, incorporating data uncertainty methods. Eight objectives were set to meet this aim and the following section discusses the conclusions obtained from each of these objectives.

8.1.1 Individual objectives

Objective 1: Identify the risks to environmental receptors facing the onshore hydraulic fracturing industry globally and its future in the UK.

Chapter 2 introduces the historical background of hydraulic fracturing and shale gas. An understanding of the techniques used in hydraulic fracturing introduces questions on where risks to the environment could occur and the exposure pathways for potential contaminants. After reviewing the environmental issues which currently surround the industry, fugitive gas migration was highlighted as a prominent issue in the US and Canada (Osborn et al., 2011; Vengosh et al., 2014; Cahill et al., 2019). An understanding of the potential pathways for gas migration is well documented enabling conceptual model development, but a gap in the literature on quantifying these pathways, particularly with reference to groundwater as a receptor, was recognised. Even more so, almost all studies have been site-specific and commonly targeted in the US within similar shale gas plays, eliminating the applicability to the UK or other countries (Prpich et al., 2015).

Well integrity failure was positioned as one of the most significant pathways to gas migration and hence the main focus of this research (Dusseault and Jackson, 2014). Chapter

2 discussed the issues surrounding well barrier failure and well integrity failure, including the main culprits of fugitive gas migration: Surface Casing Vent Flow (SCVF) (emissions) and Surface Casing Pressure (SCP) (groundwater contamination or emissions). The importance of proper well construction and cementing practises were discussed along with an understanding of cement failure to enable quantification of this pathway later in the research.

An aspect of this research is to apply the outcomes of risk analysis from well integrity failure to the UK, an industry still in its infancy and rocked heavily by social and political debates. Chapter 2 concludes the review with the political debate facing hydraulic fracturing in the UK, where the industry currently stands in terms of exploratory drilling and the main concerns facing the industry. Chapter 4 extends this preliminary knowledge to highlight the present data and gaps in knowledge for model application to the UK. Information on the UK industry for model application, including current and missing data, focuses on the Bowland shale formation and UK groundwater and drilling regulations.

Objective 2: Identify the gaps in knowledge by evaluating the current literature surrounding risk assessment approaches in the oil and gas industry.

Chapter 3 introduces risk with the focus of this research on risk assessment as a part of risk analysis, quantifying the probability of groundwater contamination. Methodologies for assessing risk are reviewed and evaluated to illustrate the most suitable methods for this research: a deterministic approach using Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) to construct failure scenarios and either numerical or fuzzy logic approaches to quantify probability. The construction of a risk assessment within the context of this research is discussed, illustrating the Source-Pathway-Receptor (SPR) model and the four failure scenarios further developed in Chapters 5 and 6.

Chapter 3 completes this objective by reviewing current risk assessment methodologies in the oil and gas industry, incorporating offshore, onshore, conventional and unconventional industries. The majority of studies have conducted risk assessments for the offshore industry, focusing on decision-making for drilling locations, qualitative assessments for well integrity and drilling disasters such as blowouts (Chen and Fu, 2003; Aven et al., 2007; Vignes and Aadnoy, 2010; Skogdalen and Vinnem, 2012; Khakzad et al., 2013). Offshore drilling presents a different set of risks, particularly with the lack of interest in groundwater, so a gap is recognised in applying a variety of current risk assessment methodologies to the onshore industry where a new set of risks can be assessed.

Objective 3: Demonstrate the suitability of using fuzzy logic theory to fill literature gaps and handle data uncertainty in the hydraulic fracturing industry.

A challenge in the oil and gas industry, in particular onshore hydraulic fracturing, is the lack of data and confidence in modelling studies. The latter half of Chapter 3 introduces the concept of fuzzy logic to risk assessment applications to fill the gap of insufficient data, incomplete knowledge and a combination of human reasoning and imprecise data (Shang and Hossen, 2013). Fuzzy logic is a mathematical technique for modelling uncertainties, developed from ideas in classical sets (Mendel, 1995). The mathematical techniques on Fuzzy Set Theory (FST), Fuzzy Logic Systems (FLS) and fuzzy arithmetic are discussed to introduce the theory and methods applied in Chapters 5 and 6.

Chapter 3 concludes with the application of fuzzy logic risk assessments in the oil and gas industry to identify where this approach has been applied and what is lacking in the hydraulic fracturing industry. Fuzzy logic risk assessments have mainly focused on the offshore industry, so the approach to onshore hydraulic fracturing where data is inconsistent, insufficient or not yet available is a requirement, particularly for new industries. FTA and ETA in this research are responsible for developing failure scenarios. A method for quantifying these hybrid techniques can include fuzzy logic. Literature on Fuzzy FTA (FFTA) and Fuzzy ETA (FETA) is discussed with respect to the oil and gas industry and introduces the Similarity Aggregation Method (SAM), possibility to probability of failure conversion and sensitivity analysis, applied in Chapter 5. These methods have shown to successfully support the application of fuzzy logic to risk assessments and allowed a flexible approach to combine subjective and objective events.

Objective 4: Identify a suitable case study for model development and application.

Chapter 2 reviewed the hydraulic fracturing industry on a global scale to highlight important and interesting locations with less current research. Areas with significant development mainly consist of the US and Canada. Canada was chosen as the main focus for model development due to the collaborations made with the University of British Columbia (UBC), accessibility of data from the British Columbia Oil and Gas Commission (BCOGC) and little research on the shale gas plays compared with the US. This research has been conducted during a time of significant uncertainty with the shale gas industry in the UK. Therefore, the UK was chosen to illustrate model application and highlight current limitations or gaps in the UK industry.

Chapter 4 contributes to this objective and discusses the two chosen case studies for model development and application (Canada and UK, respectively). The focus of this research was on groundwater and well integrity failure. Data was obtained for both case studies on groundwater in the chosen locations, indicating lower vulnerability aquifers in Canada

compared with the UK, mainly due to a difference in population density in the surrounding areas. Uncertainty was faced in determining the potentiometric head of aquifers for both the UK and Canada as the water table is not often monitored. Additionally, the mapping of specific groundwater aquifers amongst hydraulically fractured wells in BC was a challenge and required more appropriate data of underlying rock formations at a particular well site. This was much easier obtained in the UK once the data was released, as shown in Chapter 7, partly due to focusing on one specific well.

Data was also obtained on drilling regulations to understand the likely well constructions for both case studies. Both countries had clear regulations in place, although confirmation on construction during injection and production was often required from experts in industry, obtained from those based in Canada or Norway. For the UK, detailed information on the construction of the Preston New Road well (PNR1z) was only recently released (towards the end of this research) and therefore construction regulations were hypothetical up until application of the model. Contrarily, Canadian well constructions were estimated because available data was either incomplete or lacking sufficient detail to make certain decisions. The development of the two case studies in Chapter 4 presented clear areas where data was lacking and hence improved the development of the models in Chapters 5 and 6.

Objective 5: Assess the risk to groundwater contamination from well integrity failure during the well injection and production stages of an onshore hydraulically fractured well.

This objective focused on developing the fuzzy logic risk assessment models for groundwater contamination from gas migration during either the injection stage (Chapter 5) or the production stage (Chapter 6). Frameworks for both models included the development of conceptual models during injection and production to identify the well integrity pathways between the source (gas) and the receptor (groundwater). This allowed the construction of event trees of the four identified scenarios introduced in Chapter 3. Event tree construction has been an integral part of risk assessment in this research. Individual barriers must fail before well integrity failure occurs, even in those wells with very poor construction. Barrier failure depends upon casing strings, presence of cement annuli and pressure gradients which encourage gas migration. Constructing event trees enables a logical progression of individual failure pathways from the source to the receptor and prevents exclusion of vital barriers. By presenting success and failure outcomes, event trees can visualise where more barriers can reduce the probability of failure, or increase the probability of success. Dividing up the pathway between source and receptor improves the ability to analyse the probability of failure by analysing individual events with a variety of methods, depending upon available data.

Chapter 5 focuses on the loss of well integrity from inside the well mainly due to cement failure under high pressure injection. Cement failure is a common issue in the oil and gas industry but is poorly quantified due to its complexity and lack of real-time data (Dusseault et al., 2000; Dusseault and Jackson, 2014). This chapter achieved the first part of this objective by introducing FFTA to quantify cement failure, not currently done in the literature. The method for conducting FFTA was described and included experts to produce their opinions on vertical and horizontal cement failure. This allowed quantification of several individual events from the event trees. Pressure annulus failures used a fault tree and was quantified using probabilistic values from the literature (Rish, 2005) and FFTA with expert opinions. Finally, where components have failed, data from the offshore industry was used to obtain failure rates over the duration of the high pressure injection stage. These individual analysis methods were combined successfully to determine the overall probability of failure outcomes for groundwater contamination during injection.

Chapter 6 focuses on the failure of an external casing or cement annuli in contact with a gas-bearing formation to act as a conduit for gas migration to shallower groundwater formations during the production stage of a well. SCP, SCVF and SCP-induced gas migration are common issues for gas migration from well integrity failure, either to the atmosphere or to groundwater. This chapter achieved the second part of this objective by applying the combination of a numerical model for SCP and a fuzzy model for well construction and probability outcomes to quantify the event tree branches. Data gaps were discovered when developing the numerical model from theoretical principles, so FST and FLS were successfully applied to predict the mud column length, mud density and hence hydrostatic pressure of the mud column. Without this information, SCP can only be calculated hypothetically, or not determined at all. Additionally, the potential for gas contamination of groundwater is presented as fuzzy membership functions of time taken for the gas to start flowing out of the well and the rate at which it flows. Based on five wells determined to have open annuli from the BC data set, the final probability of groundwater contamination from gas migration was determined from the event tree. ETA required individual failure events on cement failure calculated in Chapter 5, probability of open annuli constructions determined from the fuzzy model output and probability of SCP-induced gas migration from the numerical and fuzzy models.

Objective 6: To test the accuracy of the implemented framework, evaluate and validate the fuzzy logic risk assessment methodologies.

Validation of fuzzy logic models can present a challenge when little data was available initially to produce the model (Shang and Hossen, 2013). Often appropriate data will only be collected after the development and implementation of the model due to the nature of a fuzzy logic model. At this point, revising of parameters, membership functions and

inference rules can be successful. Therefore, validation of fuzzy logic models should be an on-going process as they are expected to adapt and change with increasing information.

More commonly, sensitivity analysis is used to illustrate the robustness of the model and to understand the variation in the system and probabilities of failure. Chapter 5 applied sensitivity analysis to FFTA to identify the weakest components of the system and where improvements could be made to reduce the failure. Cement failure fault trees were analysed using failure probability rankings and Fuzzy Weighted Index (FWI) values. These methods both indicated premature gelation of cement contributed the most to the top event of horizontal cement failure and poor mud removal contributed the most to the top event of vertical cement failure. As quantifying cement failure has not been conducted in literature, only partial validation was possible for this method of quantification. A literature value for the formation of a vertical microannulus in cement was determined probabilistically by Rish (2005) and was loosely compared with the calculated failure for vertical cement from FFTA. The values differed quite significantly, however the literature value was determined from a Poisson distribution to describe random failures in a system with large bounds of uncertainty, whereas the FFTA value incorporated expert opinions on individual cement failures which combine to produce a more detailed analysis of vertical cement failure, potentially reducing the uncertainty in the output. In the literature, horizontal failure is considered less likely compared with vertical cement failure (Dusseault et al., 2000) and this was indicated in the cement failure results, $8.4E^{-3}$ and $3.4E^{-2}$, respectively.

A fault tree developed in the literature for pressure changes in the annulus during injection was also used to illustrate the suitability of the fuzzy logic methodology compared with the probabilistic method (Rish, 2005). The output between the fuzzy fault tree and conventional fault tree were equally low at $1.3E^{-9}$ and $6.5E^{-11}$, respectively. The difference between the two was attributed to the implementation of human error and expert judgement in the fuzzy model but lack of variation in the data on human influence in the probabilistic model. Sensitivity analysis on the pressure fuzzy fault tree was conducted to indicate the basic events with the highest influence on the system. The main areas of focus for pressure control in an annulus are preventing mechanical failure of the auto alarm system and ensuring operators are aware of potential errors in their practise.

The event trees illustrated in Chapter 5 represented a hypothetical UK construction (prior to data publication) and a typical BC construction. As the UK construction was only hypothetical, there was no available data to validate the outcome against. Data collected from the BCOGC included information on wells from the Montney formation which have shown fugitive gas migration at the surface and was used to compare against the value determined from the model in Chapter 5. However, the data was very sparse and did not specify when the leaks occurred, at what stage of the well or from where and only those leaks seen at the surface during monitoring were detected. Further leaks could

have occurred into groundwater due to a lack of monitoring. BC data from the Montney formation indicated 0.13% of wells demonstrated gas migration at the surface, whereas the model in Chapter 5 showed a probability of failure during injection at 0.0006%. It was concluded this low value in comparison to the data set is due to only two scenarios of failure being quantified during one stage across the life cycle of a well.

One-factor-at-a-time (OAT) sensitivity analysis was conducted on the fuzzy logic model in Chapter 6 to understand the uncertainty in the model, particularly the development of the fuzzy membership functions. Validation was partially achieved on the prediction of mud column length in the model. The BC data set containing 337 wells contained approximately 75% of wells with known closed annuli. Adjustments of the model allowed the model to predict 93% of those wells correctly; this suited as a validation for this part of the model. OAT sensitivity analysis was conducted on the mud column length whilst changing aquifer depth, hydrocarbon depth, geology factor and Measured Depth (MD) to illustrate the sensitivity in the model prediction and validation. Results illustrated low sensitivity in the model prediction, shifting the open annulus wells from 25 to 32, despite mud column length being most sensitive to a change in aquifer depth. However, altering the shape of the geology factor membership function improved the model prediction to 98% but a lack of data on open well annuli prevents a deeper understanding of the model accuracy as only the prediction of closed annuli can be validated.

Equally with mud column length, OAT sensitivity analysis was conducted on the probability fuzzy membership function whilst changing eight fuzzy functions, independently. A lack of probability data prevents validation for this part of the model but sensitivity analysis indicated probability demonstrated very low sensitivity to a change in all eight parameters. This confirms accurate calibration of the mud column length fuzzy membership function is a priority over the probability membership function, as a large portion of the uncertainty in the model lies in this parameter. All five wells with open annuli from the BC data set demonstrated a high probability of SCP-induced gas migration, given a leak occurs in the production cement and SCP builds up due to a closed surface casing vent valve. Given the known high risk of open annulus wells (Fleckenstein et al., 2015; Stone et al., 2019), this is not a surprising outcome. Incorporating the whole event tree, the probability of SCP-induced gas migration occurring in the Montney formation in BC is 0.02%.

Concluding results from Chapters 5 and 6 indicate very low probabilities of groundwater contamination at 0.0006% and 0.02%, respectively. In addition to the quantification of only a few failure pathways during injection and production, these low values are not surprising given the results from the small amount of literature on well integrity failures and well construction. Stone et al. (2019) indicated the low probability of groundwater contamination (catastrophic failure) from hydraulic fracturing, particularly for the most recently drilled wells. An important point to note is the reason for catastrophic failures

indicated by Stone et al. (2019). Although these were for vertical or deviated wells, catastrophic failures were often encountered from failure in the production casing, vertical migration along the casing to the aquifer, or the top of the production cement being set below a gas-bearing formation. All these elements have been of high importance in production of the models in Chapters 5 and 6.

Objective 7: To identify the models utilities and limitations, apply the model to a case study.

As discussed in objective 4, the UK is an interesting case study for application of the groundwater contamination model due to the infancy of the industry and limitations in the data available. The UK case study at Preston New Road (PNR1z well) is applied to cement failure, integrity failure during injection and integrity failure during production to test the models utility against alternative sites and recognise where further data or knowledge is required to reduce uncertainty.

The application of cement failure was discussed mainly with respect to improvements for the UK. This is due to the failure of cement quantified mainly using expert knowledge based in Canada or offshore petroleum experts. The fault trees for cement failure are suitable for generic application but employing appropriate experts without introducing bias is essential for accurate representations of cement failure in the desired location.

Applying the UK case study to both injection and production models required adjustments of the event trees, mainly to account for the unexpected differences between the hypothetical UK construction scenario and actual construction of the PNR1z well. These adjustments required adding an additional failure event for a partly cemented intermediate casing string. Additionally, given the detail provided by the Environment Agency (EA) and Cuadrilla, an improved representation of the location of failure along a casing string was included in the construction of the event trees for both models. The probability of failure for a cemented casing string should be much lower than that of an uncemented casing string (Watson and Bachu, 2009) and this proportion is calculated based on a 'cement index' determined by Zulqarnain et al. (2017). This added quantification in the risk analysis improves the accuracy of the location of a leak and hence the accuracy of probability of contamination.

The cumulative failure probability for an injection well under the PNR1z construction illustrates a negligible probability of groundwater contamination. This outcome matches the negligible probability of groundwater contamination estimated by Arup (Cuadrilla Bowland Limited, 2016). The low probability is related to the complex geology of the UK and hence the tight regulations to ensure all measurements are taken to protect groundwater, where possible. The PNR1z well was constructed with an added casing string to protect the deep Sherwood Sandstone aquifer from abundant gas-bearing formations, and

cement was added at a height in the production and intermediate annuli well above the base of the neighbouring casing shoe for added protection. These measures have all been taken to reduce the risk to groundwater, shown clearly by the outputs in the injection model.

The production well model in Chapter 6 focused on a well constructed very differently to that of the UK case study, but followed a similar failure path in the event trees constructed in the chapter. The event tree was adjusted to account for these differences but the presence of closed annuli compared with open (as in Chapter 6) added complications to the model application and required some further work to adjust the numerical model. On the other hand, due to the abundance of detailed data provided for the PNR1z well, the mud column lengths and mud densities in all annuli are already known (or assumed) and therefore do not require the use of the initial fuzzy model. The UK well can be used as a validation for the fuzzy model, but adjustments need to be made to the model as it only predicts mud column length based on the presence of a production casing and surface casing.

To predict SCP in annuli and eventual gas migration into groundwater, pore pressures and hydrostatic pressures were determined for the important formations (gas-bearing and aquifers) to understand the movement of gas once it has entered the intermediate cemented annuli. In Chapter 6, the gas would migrate out of the open annulus once it reached the base of the surface casing shoe. However, due to the closed annuli the gas could migrate anywhere along the casing string, depending on where the leak occurred and the pressure gradient between the surrounding formation and annulus. Therefore, a best- and worst-case scenario was determined for the SCP build-up leading to gas migration. Given all preceding barriers fail and SCP build-up occurs, the potential for gas migration into the surrounding aquifer ranged from 'medium' for the best-case scenario and 'high' for the worst-case scenario with almost all probabilities being lower than those calculated for the Canadian well. More importantly, the final probability of failure for gas migration to occur from a leak in the intermediate cement ranged from $1.4E^{-8}\%$ to $9.6E^{-11}\%$. These probabilities are extremely low failures, even compared with the Canadian well at 0.02% but as mentioned above, are expected due to the focus on protecting groundwater when constructing the PNR1z well.

The application of both models to the UK has demonstrated successful outcomes which could be equally applied to other site-specific locations. The application required some areas of further work including adjustments to the event trees but this was conducted in a few days using the original models. The PNR1z well is one of the most complex constructions when it comes to evaluating well integrity failure so the added model development illustrated in this application might only ever need to be simplified.

Application to the UK highlighted important limitations in the model and areas where work could be improved. The low probability of failures in both models contain elements of uncertainty. Although the injection well outcomes were deemed insignificant, further

data collection on casing failures and modelling of cement crack propagation would improve the uncertainty of this output. During production, modelling SCP over long time periods and during field analysis will improve the analysis of SCP build-up in annuli and the extent to which the well holds integrity during SCP.

Objective 8: Present recommendations for policy makers for practical application of the framework.

This current chapter corresponds to the outputs and conclusions of this objective and is therefore discussed in Section 8.2.

8.1.2   Contributions

The work presented in this thesis highlights a number of novel contributions to the field of risk assessment in the hydraulic fracturing industry. These are discussed below:

1. The main contribution of this research is the construction and quantification of a risk assessment framework which covers both the injection and production stages of an onshore hydraulically fractured well. Well integrity studies have either involved qualitative analysis or focused on modelling a small issue such as SCP for a specific scenario, especially for offshore or conventional formation studies. The development of this risk assessment has produced similar results to those seen in literature, supporting the fuzzy logic method. The results from the UK application are equally similar to those identified in industry.

2. Compared with other unconventional risk assessments in the literature, this research took a novel approach by assessing a formation in Canada with very little focus in the literature and a formation in the UK, a country inexperienced in the industry. This presented difficulties in data collection and certain aspects of model validation. Current literature studies often worked with areas containing historic data which meant the same sites were evaluated, ignoring those with newer industries. In studies facing poor quality data from the industry, either assumptions were made resulting in highly uncertain best- and worst-case scenarios or qualitative approaches were required. Within this research, fuzzy logic was applied where data was limited or missing. The application of fuzzy logic to risk assessments for hydraulic fracturing has not yet been utilised to date, and provided useful outcomes where previous areas would not have been quantified, such as the failure of cement.

3. This research successfully identified and implemented an alternative method for quantifying the failure of cement in wellbores. Cement failure is a common problem in well integrity failure and literature has identified the key elements which can encourage fluid or gas migration along a wellbore. Despite the current knowledge

on reasons for crack propagation pathways in cement, quantifying failure for proba-
bilistic analysis has not been conducted. This research has applied the known FTA
technique for simplifying the failure of cement into the key elements of pathway
development, and quantified the basic events using fuzzy logic methods and expert
judgement. The outputs from this application highlighted where experts feel more
work is required on preventing poor cementing practises and allowed a more ac-
curate representation of well integrity failure. Additionally, the fault trees can be
adjusted or adapted if cementing practises change or ideas become more complex
and adding more expert opinions from the specific area of drilling can improve the
uncertainty in the failure outcome.

4. Present risk assessments have been conducted for unconventional gas develop-
   ment either for the purpose of satisfying regulations or to identify where failure
   events have already occurred during a hydraulic fracturing operation. Current risk
   assessments provide qualitative analysis to enable a generic application and under-
   standing of the risks across the whole operation, or they involve model development
   and quantitative analysis but focus on a small individual risk with application to
   a specific site. Risk assessment development in this research has adopted a combi-
   nation of qualitative and quantitative approaches to take advantage of the variety
   of limited and accessible data and to enable the development of multiple failure
   events during hydraulic fracturing. Furthermore, the risk assessment framework has
   been developed using site-specific information in BC, Canada but has demonstrated
   a clear application to a case study in the UK despite significant differences in the
   geology, well construction and regulations. Important discussions on where model
   development or data limitations have prevented further application were made to
   highlight improvements for model applicability.

5. The risk assessment framework developed here is a useful tool for highlighting
   higher risk areas during the injection and production stages and can be applied
   before hydraulic fracturing operations are undertaken. This is particularly important
   for decision-makers where there lies significant uncertainty within an area for poten-
   tial contamination to groundwater. This can help decision-makers and engineers
   target suitable areas for hydraulic fracturing and encourages improved decisions on
   weighing up the costs and benefits of casings and cement placement.

8.2   RECOMMENDATIONS

8.2.1   Policy recommendations

Policy plays a significant role across the globe in the hydraulic fracturing industry so the
collaboration of scientific research with the decision-makers in government is essential

for a properly applied practice. To satisfy objective 8 in this thesis, the application of this framework to guide policy decisions has been discussed below in relation to global and UK expectations.

Global policy recommendations:

1. Risk assessments for hydraulic fracturing must be a priority prior to undertaking any operations. This includes decisions made for economic, social or environmental reasons. Without a solidified risk assessment tailored to the area of interest, significant high risk events could occur with little warning (e.g. blowouts, induced seismicity) or no warning (e.g. groundwater contamination, Greenhouse Gas (GHG) emissions, well integrity failure). Utilising the framework described in this research for all risk scenarios across individual stages highlights the areas for concern and enables advanced mitigation to reduce or eliminate the probability of occurrences.

2. All risks must be properly quantified and released to the public before decisions are made and operations begin. Risk assessments at an industry level often take a qualitative approach as first discussed in the point above. However, variation across locations is better compared and understood when the risks present numerical information. This research has identified certain risks to groundwater which are of high concern and quantified the outcomes across two different locations, representing clear distinctions between the risks to groundwater in a location in Canada compared with a location in the UK.

3. A significant outcome from this research is the clear reduction in risk to groundwater between differently constructed wells for both the injection and production stages. Cementing practises play a huge role in supporting well integrity thus the modelling of cement failure in this research is useful for highlighting those areas where insufficient or higher risk cementing might increase the risk of failure. Where gas production versus economic costs are a factor, particularly for the UK (or an equivalent new industry), weighing up the risk of groundwater contamination compared with financial gain for well construction will be essential for decision-makers and policy.

4. Groundwater monitoring surrounding hydraulically fractured wells in BC, Canada is currently unregulated with no strict requirements to monitor aquifers (Wisen et al., 2019). The model for groundwater contamination potential during production indicated of the 0.02% chance groundwater could be contaminated, a worst-case scenario showed only seven days before gas in a casing reaches critical pressure. This was shown for a well with an open annulus casing but indicates monitoring should be done of the surrounding aquifers, especially where less strict regulations are kept on well construction. Additionally, over time the depletion of the reservoir, changes in pressure and interaction of casings with gas production can erode or

alter the structural integrity of the well so consistent monitoring is vital during production.

UK policy recommendations:

1. Preliminary outputs from the model application have indicated a very low risk to groundwater, considered insignificant particularly during injection. Despite this, measures must always be taken to ensure groundwater and well integrity are monitored frequently, particularly during the production phase, to recognise signs of SCP before well integrity is breached. Outputs indicated the worst-case scenario would take eighteen days for the gas to reach critical pressure and best-case would take just over six months. Particularly for a new industry and usable groundwater, monitoring must be undertaken several times a year to cover the risk of a worst-case scenario. Equally, baseline groundwater monitoring prior to hydraulic fracturing in conjunction with monitoring during production indicates if any contaminants have reached groundwater, avoiding the confusion of naturally occurring methane. This was a problem particularly in the US and should not be ignored (Davies, 2011; Molofsky et al., 2011; Jackson et al., 2013b; Darrah et al., 2014).

2. The application to the UK in this research has indicated a low risk to groundwater, supported by Arup (Cuadrilla Bowland Limited, 2016), and appears to be a lower threat compared with that experienced by the US and Canada. This is due to the differences in well design and geological strata. In recent scientific and political news, induced seismicity has been the biggest problem in the UK from the exploratory wells at Preese Hall and Preston New Road (Cuadrilla Bowland Limited, 2019a; OGA, 2019). Further research on the risks for induced seismicity must be conducted and this research presents a framework which can equally be applied to issues surrounding induced seismicity. Additionally, consequences from induced seismicity such as well integrity failure from an event must be assessed.

3. There must be better risk communication between researchers, industry and decision-makers. Currently decisions are more heavily weighted towards public concerns and policy achieving their own objectives, but the validity of scientific research collaborated with industry experience must weigh much heavier on policy decisions. Clear risk assessment models which output understandable risks to the lay audience will help disseminate knowledge more effectively. In this research, clear pathways of risk scenarios are developed to ensure individual concerns are tackled and their quantification produces an output easily understood by researchers and industry for development and analysis.

4. Finally, significant data has recently been made public in the UK to reduce uncertainty and concern amongst local communities. However the documents are

extensive and poorly located, requiring only those with a strong technical under-standing to be made fully aware of the risks and their magnitude. Decision-makers who face criticism must ensure information is disseminated properly to the public with a well-defined risk analysis which can be interpreted easily without prerequisite knowledge.

8.2.2 Further research

Further research for improvements or application to other areas can be conducted to extend this work. The framework can be extended to apply to any stage of the well where an understanding of logical failure events exists. In the case of risk assessments, these events should be well-known in the industry. Suggestions for further work have been discussed below, particularly in relation to some of the limitations recognised in Chapter 7 when applying the model to the UK.

- In this thesis, risk is considered the probability of groundwater contamination occur-ring due to gas migration from well integrity failure. An engineering perspective considers risk a product of probability and consequence. With hydraulic fracturing, the decisions made with respect to the potential consequences of an event will also play a large economic factor. Therefore, future research can be conducted using sce-nario logic modelling, fuzzy logic modelling and numerical modelling to determine the consequences of groundwater contamination where economic outputs could also be incorporated to support policy decision-making.

- Currently, probability of failures have been determined independently across two different operational stages of a hydraulically fractured well. Potential cumulative failures to groundwater over the life cycle of the well which include spills and leaks, fracture propagation, induced seismicity and alternative well integrity failure pathways will improve risk prediction when deciding to drill in a particular area and highlight where or when high risk events could occur. This research framework can be applied to many of these potential scenarios for a more comprehensive understanding of risk.

- Induced seismicity is a recent concern in the UK during hydraulic fracturing opera-tions and therefore should be a focus for long-term effects on faults and surrounding infrastructure, as well as damage to well integrity leading to potential groundwater contamination. The framework in this research can be applied to tackle these risk events. The scenarios which can cause micro-seismic events during high pressure injection can be logically modelled using event trees and the consequences will most likely represent the magnitude of the seismic event or the long-term effects of seismic events, should these exist.

- The ETA and FTA consider all events independent of each other and the timing between each failure event is simultaneous and occurs before any interventions to prevent further failures. In reality, events might be dependent upon one another; if one cement column fails the probability for the neighbouring to also fail might increase if the job was conducted by the same person. Applying Bayesian networks allows consideration of conditional dependencies between initiating events, top events and failure outcomes to tackle this simplification in the future (Yang et al., 2018).

- To develop the fuzzy logic model in Chapter 6, fuzzy membership functions were constructed using either expert intuition or box plot analysis. However, implementing machine learning techniques for fuzzy membership development improves the outcome of the membership functions and rules by using well formulated training and validation data sets (Hong and Lee, 1996; Sun et al., 2007; Cintra et al., 2008). Machine learning techniques such as neural networks or genetic algorithms can significantly speed up the process of membership function development where appropriate data has been collected. The framework developed in this thesis indicates where increased data collection is required to incorporate machine learning.

- Currently, it is assumed as soon as the gas leaves an external well annulus it has contaminated groundwater (or has the potential for contaminating groundwater). Modelling the flow of gas once it has left the well from various formations across different strata can more accurately predict the probability of contamination. Currently, unless the gas leaves at an aquifer, the probability is over-estimated. The time it takes for the gas to reach an aquifer can also help determine the consequence once well integrity occurs.

Appendices

APPENDIX A

CEMENT TREE INSTRUCTIONS AND QUESTIONNAIRE

INSTRUCTIONS

The information in this appendix consists of the instructions and questionnaires sent out to each expert to quantify each basic event on the cement fault trees.

A brief context of the project

My project involves developing a risk assessment for hydraulic fracturing in the UK focusing on the risk towards contamination of groundwater. The work is taking a fuzzy logic approach which can deal well with high uncertainty, ambiguity and lack of data. Current work is looking at the risk for well integrity failure and how the design of the well can affect potential pathways for fluid or gas migration to aquifers. As cement is a big factor in the integrity of a well it is important to understand what could go wrong with the cement to allow for gas migration, and why, to help quantify the risks. Quantifying the probabilities of cement failure over the life time of a gas well is extremely difficult and requires substantial knowledge and expertise. Therefore, in order to account for the possibilities of cement failing and leading to gas/fluid migration, I am using a fuzzy logic approach which utilises the opinions of experts who work within this area (or similar) to quantify the probabilities.

A gas well will go through different stages with the longest being the production and abandonment stages. Generally, cement is present below the surface in some form during 3 stages of a gas well; well stimulation or injection, production and abandonment. The probabilities of the cement failing will vary depending on the stage at which the well is

at. Therefore, for this research quantifying cement failure will be required for the well construction and stimulation stage and production stage.

Fault trees explained

- Top-down approach to understand and deduce the failure of a system using Boolean logic.
- Can be used to understand the logic leading to the failure of an event/system.
- Their complexity can vary greatly depending on the top event.
- In this case, cement is the failure with the top event being either a horizontal pathway or a vertical pathway created in the cement for gas/fluid migration.
- They are created by starting with the top event (e.g. horizontal pathway in the cement) and working backwards, thinking about the ways in which each event might occur until you reach a basic event which cannot be further analysed.
- Most common symbols used for the events are:
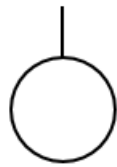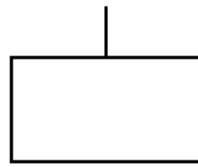
Basic event   Intermediate event

- Logic gates are used to describe the relationship between the inputs and outputs. Most common logic gates are:

OR gate: the output occurs   AND gate: the output occurs
if any input occurs.   only if all the inputs occur
                                   (inputs are independent).

Fault trees within cement failure context

The two fault trees produced below indicate the failure of cement to prevent gas migration either by the creating of horizontal pathways or vertical pathways.

The fault tree above is a basic logical way of explaining how horizontal pathways in the cement could form. To describe the tree: the horizontal pathway occurs due to either
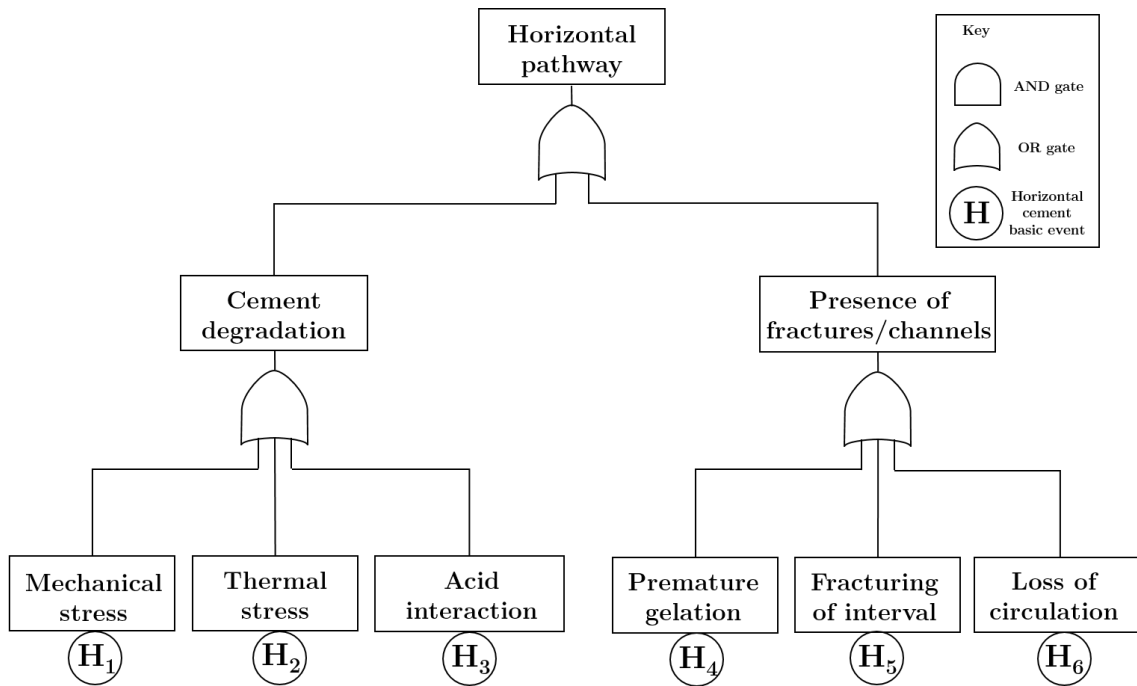
cement degradation OR the presence of fractures or channels in the cement. Cement degradation occurs due to either mechanical stresses (H1), thermal stresses (H2) OR acid interaction (H3) (all basic events). The presence of fractures/channels in the cement occur due to either premature gelation (H4), fracturing of an interval (H5) OR loss of circulation (H6) (all basic events).
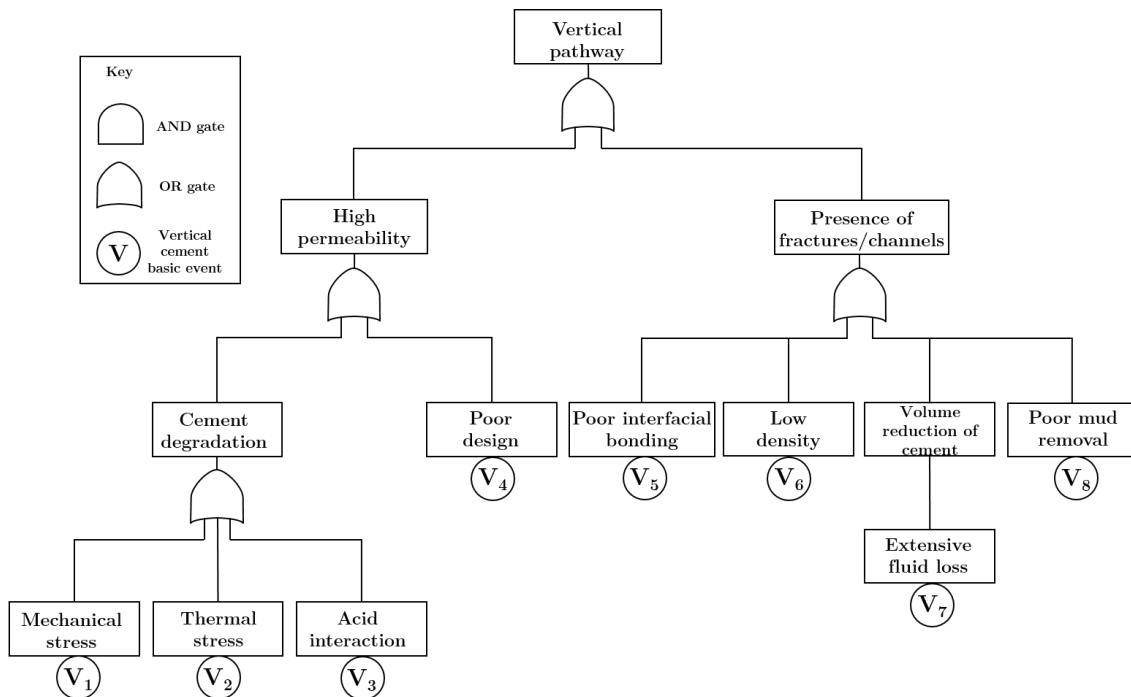
The fault tree above is a basic logical way of explaining how vertical pathways in the cement could form. To describe the tree: the vertical pathway occurs due to either high permeability OR the presence of fractures or channels in the cement. High permeability occurs due to either cement degradation OR poor design of the cement (V4). Cement degradation occurs due to either mechanical stresses (V1), thermal stresses (V2) OR acid interaction (V3). The presence of fractures/channels in the cement occur due to either poor interfacial bonding (V5), cement which has low density (V6), a reduction in volume of the cement due to extensive fluid loss (V7) OR poor mud removal during drilling (V8).

Method for expert judgements

In order to quantify the top event of these fault trees, values need to be put to each of the basic events described above. These are not events which can easily be measured so the values will be in a linguistic form of 'very high', 'high', 'medium', 'low', 'very low'; a probability of the basic event occurring. A description of each probability is shown in the table below. The fuzzy probability will be used by myself to quantify the decisions made by the experts for each basic event.

Category	Linguistic probability	Fuzzy probability
Very low	Rarely encountered, never reported or highly unlikely	$(0, 0, 0.1, 0.2)$
Low	Unlikely to occur/infrequent occurrences, but possible over the stage of the well	$(0.1, 0.25, 0.4)$
Medium	Likely to occur at some point during the stage of the well	$(0.3, 0.5, 0.7)$
High	Will occur several times during the stage of the well	$(0.6, 0.75, 0.9)$
Very high	Will occur very frequently during the stage of the well	$(0.8, 0.9, 1, 1)$

The questionnaire will ask for you to write one of the 5 categories above next to each basic event. There are 6 basic events for the horizontal pathway failure and 8 basic events for the vertical pathway failure. Every basic event for both pathway failures for each stage (3 stages) need to be quantified i.e. you will be giving a qualitative descriptor (category in the table above) to 42 different basic events.

As an example looking at the horizontal pathway fault tree, H1 is the first basic event; mechanical stress. So the question you will ask yourself is 'how likely will mechanical stress occur in cement during the well construction and stimulation stage of the well to lead to a potential gas migration pathway?'. If you think it is likely to occur at some point during that stage of the well, then you can put 'medium'.

Adjusting the fault trees

The fault trees produced above are developed from a relatively general basic understanding of the failure of cement. However, if there are some important aspects missing or the basic events can be simplified further or there are situations where several things must happen together for a failure to occur (e.g. mechanical AND thermal stress), then it is worth adjusting the fault trees first before the probabilities of the basic events are decided. I am very happy to have input from experts into the fault trees to improve them, if required, so please send through improvements/suggestions/ideas before completing the questionnaire. The fault trees will then be re-evaluated and sent out again and once they are satisfactory, the questionnaire can be fully filled out by the experts.

Questionnaire rules

- Fault trees can be discussed with others if needed to adjust changes in the inputs, outputs and logic gates.
- Once fault trees have been discussed and ideas sent through to myself, there cannot be any discussion on the probabilities of the basic events.
- Questionnaires must be completed individually and preferred to be anonymous, but the 'expert information' section is very important to the weighting of each answer, particularly as the questionnaires are anonymous.

QUESTIONNAIRE

Please do not collaborate with anyone else on your answers as it is important each opinion is individual to the expert.

Expert information

Professional position:

☐ Professor ☐ PostDoc/ Research scientist ☐ Graduate student ☐ Engineer ☐ Technician

Service time (years):

☐ ≥ 30 ☐ 20-29 ☐ 10-19 ☐ 6-9 ☐ ≤ 5

Highest current education level:

☐ PhD ☐ Masters ☐ Bachelors ☐ HND ☐ School level

Age:

☐ ≥ 50 ☐ 40-49 ☐ 30-39 ☐ 21-29 ☐ < 21

Expert opinion

For each basic event write if you think the probability of it occurring is 'very high', 'high', 'medium', 'low', 'very low'. The table for these qualitative definitions is shown below. Please refer to the instructions for more information, if required.

Category	Linguistic probability	Fuzzy probability
Very low	Rarely encountered, never reported or highly unlikely	$(0, 0, 0.1, 0.2)$
Low	Unlikely to occur/infrequent occurrences, but possible over the stage of the well	$(0.1, 0.25, 0.4)$
Medium	Likely to occur at some point during the stage of the well	$(0.3, 0.5, 0.7)$
High	Will occur several times during the stage of the well	$(0.6, 0.75, 0.9)$
Very high	Will occur very frequently during the stage of the well	$(0.8, 0.9, 1, 1)$

Stage A – Well Construction and Stimulation

Horizontal pathway fault tree:

H1 . . . .   H2 . . . .   H3 . . . .

H4 . . . .   H5 . . . .   H6 . . . .

Vertical pathway fault tree:

V1 . . . .   V2 . . . .   V3 . . . .

V4 . . . .   V5 . . . .   V6 . . . .

V7 . . . .   V8 . . . .

Stage B - Production

Horizontal pathway fault tree:

H1 . . . .   H2 . . . .   H3 . . . .

H4 . . . .   H5 . . . .   H6 . . . .

Vertical pathway fault tree:

V1 . . . .   V2 . . . .   V3 . . . .

V4 . . . .   V5 . . . .   V6 . . . .

V7 . . . .   V8 . . . .

APPENDIX B

PRESSURE TREE INSTRUCTIONS AND QUESTIONNAIRE

INSTRUCTIONS

The information in this appendix consists of the instructions and questionnaires sent out to each expert to quantify each basic event on the pressure fault tree.

A brief context of the project

My project involves developing a risk assessment for hydraulic fracturing in the UK focusing on the risk towards contamination of groundwater. The work is partly taking a fuzzy logic approach which can deal well with high uncertainty, ambiguity and lack of data. Current work is looking at the risk for well integrity failure and how the design of the well can affect potential pathways for fluid or gas migration to aquifers.

I have created a scenario for a well under stimulation in which a potential pathway could lead to eventual groundwater contamination. One of the first stages of this pathway is the likelihood the injection pressure exceeds the pressure in the annulus. This is not an easy probability to quantify and requires substantial knowledge and expertise. Therefore, in order to account for this probability occurring during well stimulation, I am using a fuzzy logic approach which utilises the opinions of experts who work within this area (or similar) to quantify the probabilities with linguistic descriptors.

Fault trees explained

- Top-down approach to understand and deduce the failure of a system using Boolean logic.

- Can be used to understand the logic leading to the failure of an event/system.
- Their complexity can vary greatly depending on the top event.
- In this case, the injection pressure exceeding the annulus pressure is the top event.
- They are created by starting with the top event (e.g. horizontal pathway in the cement) and working backwards, thinking about the ways in which each event might occur until you reach a basic event which cannot be further analysed.
- Most common symbols used for the events are:
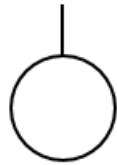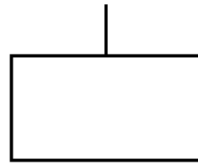
Basic event   Intermediate event

- Logic gates are used to describe the relationship between the inputs and outputs. Most common logic gates are:

OR gate: the output occurs   AND gate: the output occurs
if any input occurs.   only if all the inputs occur
                                                         (inputs are independent).

Fault trees within pressure failure context

The fault tree produced below indicates the failure of pressure and hence the 10 basic events which exist for the failure to occur (zoom up on word to see words more clearly).

The fault tree above is a logical way of explaining how the injection pressure into the well could exceed the annulus pressure. To describe the tree:

The pressure is exceeded due to the pressure difference being below the design criteria AND the pressure difference not being detected. The pressure difference is not detected if the auto alarm fails (Pr9) AND if the operator fails to detect or respond (Pr10).

The pressure difference being below the design criteria is either due to an under pressure annulus OR an over pressure injection. The over pressure injection will be due to either an injection pressure control system failure (Pr6) OR an operator error (Pr7) OR the loss of injection zone capacity (Pr8).
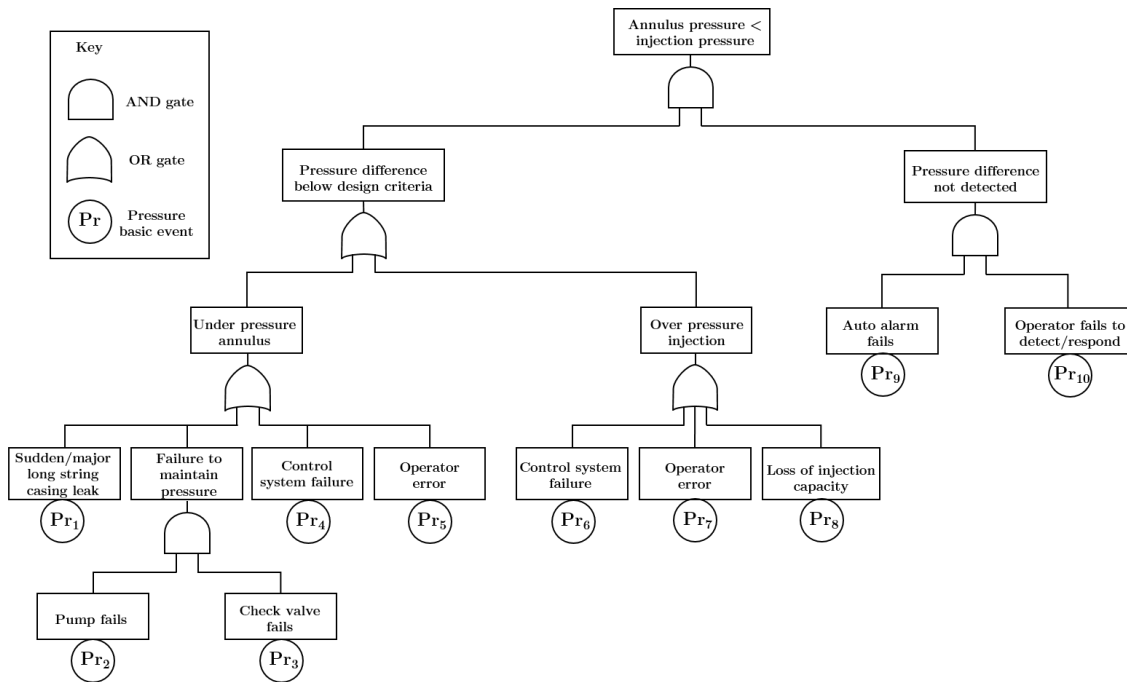
The under pressure annulus is due to either a sudden/major long string casing leak (Pr1) OR the failure to maintain pressure OR an annulus pressure control system failure (Pr4) OR an operator error (Pr5).

Finally, the failure to maintain pressure in the system will be due to an annulus pump failure (Pr2) AND an annulus check valve failure (Pr3).

Method for expert judgements

In order to quantify the top event of these fault trees, values need to be put to each of the basic events described above. These are not events which can easily be measured so the values will be in a linguistic form of 'very high', 'high', 'medium', 'low', 'very low'; a probability of the basic event occurring. A description of each probability is shown in the table below. The fuzzy probability will be used by myself to quantify the decisions made by the experts for each basic event.

The questionnaire will ask for you to write one of the 5 categories above next to each basic event. There are 10 basic events for the above fault tree. Each basic event needs to be quantified i.e. you will be giving a qualitative descriptor (category in the table above) to 10 different basic events.

As an example, Pr1 is the first basic event; sudden/major long string casing leak. So the question you will ask yourself is 'how likely will there be a sudden/major long string casing leak during well stimulation?'. If you think it is likely to occur at some point during well stimulation, then you can put 'medium'.

Category	Linguistic probability	Fuzzy probability
Very low	Rarely encountered, never reported or highly unlikely	$(0, 0, 0.1, 0.2)$
Low	Unlikely to occur/infrequent occurrences, but possible over the stage of the well	$(0.1, 0.25, 0.4)$
Medium	Likely to occur at some point during the stage of the well	$(0.3, 0.5, 0.7)$
High	Will occur several times during the stage of the well	$(0.6, 0.75, 0.9)$
Very high	Will occur very frequently during the stage of the well	$(0.8, 0.9, 1, 1)$

Questionnaire rules

- There cannot be any discussion on the probabilities of the basic events with other experts.
- Questionnaires must be completed individually and preferred to be anonymous, but the 'expert information' section is very important to the weighting of each answer, particularly as the questionnaires are anonymous.

QUESTIONNAIRE

Please do not collaborate with anyone else on your answers as it is important each opinion is individual to the expert.

Expert information

Professional position:

☐ Professor ☐ PostDoc/ Research scientist ☐ Graduate student ☐ Engineer ☐ Technician

Service time (years):

☐ ≥ 30 ☐ 20-29 ☐ 10-19 ☐ 6-9 ☐ ≤ 5

Highest current education level:

☐ PhD ☐ Masters ☐ Bachelors ☐ HND ☐ School level

Age:

☐ ≥ 50 ☐ 40-49 ☐ 30-39 ☐ 21-29 ☐ < 21

Expert opinion

For each basic event write if you think the probability of it occurring is 'very high', 'high', 'medium', 'low', 'very low'. The table for these qualitative definitions is shown below. Please refer to the instructions for more information, if required.

Category	Linguistic probability	Fuzzy probability
Very low	Rarely encountered, never reported or highly unlikely	$(0, 0, 0.1, 0.2)$
Low	Unlikely to occur/infrequent occurrences, but possible over the stage of the well	$(0.1, 0.25, 0.4)$
Medium	Likely to occur at some point during the stage of the well	$(0.3, 0.5, 0.7)$
High	Will occur several times during the stage of the well	$(0.6, 0.75, 0.9)$
Very high	Will occur very frequently during the stage of the well	$(0.8, 0.9, 1, 1)$

Pr1 .... Pr2 .... Pr3 ....

Pr4 .... Pr5 .... Pr6 ....

Pr7 .... Pr8 .... Pr9 ....

Pr10 ....

APPENDIX C

FUZZY RULE BASE

A fuzzy rule consists of a conditional statement in the form 'IF x is A THEN y is B', where x and y are linguistic variables and A and B are linguistic values. A conjunction or disjunction can also exist between two inputs: 'IF x is A AND/OR y is B THEN z is C'.

The fuzzy rule bases developed here use linguistic variables which are important factors that affect the construction of a well; most importantly the placement and height of production casing cement. The depth of an aquifer and the target formation and Measured Depth (MD) are all important factors in cement placement. Aquifer depth and hydrocarbon-bearing formation depth are both considered geological factors which have an important part in determining well construction; Table C.1. The MD along the wellbore (often the entire length of the production casing) and the geology factor play a final role in determining the placement of cement and hence the length of the mud column; Table C.2. Both fuzzy rule bases in Table C.1 and C.2 use the conjunction between the two inputs.

TABLE C.1: Fuzzy rule base 1 to obtain geology factor.

	IF		THEN
Aquifer depth	**AND**	**Hydrocarbon depth**	**Geology factor**
Low		Low	Very low
Low		Medium	Low
Low		High	Medium
Medium		Low	Medium
Medium		Medium	High
Medium		High	Very high
High		Low	Very high
High		Medium	Very high
High		High	Very high

The third rule base in the model is used to more accurately predict the mud density within the annulus column between the cement top and surface. The mud density is calculated

TABLE C.2: Fuzzy rule base 2 to obtain mud column length.

MD	AND	Geology factor	Mud column length
	IF		**THEN**
Low		Very low	Long
Low		Low	Long
Low		Medium	Medium
Low		High	Short
Low		Very high	Very short
Medium		Very low	Long
Medium		Low	Medium
Medium		Medium	Short
Medium		High	Very short
Medium		Very high	Very short
High		Very low	Medium
High		Low	Medium
High		Medium	Short
High		High	Very short
High		Very high	Very short

based on the depth and hydrostatic pressure at the Total Vertical Depth (TVD) of the well but the required mud density is for the mud column length. Therefore, rule base 3 adjusts the mud density according to the predicted mud column length; Table C.3.

TABLE C.3: Fuzzy rule base 3 to obtain mud density.

Mud column length	Mud density
IF	**THEN**
Very short	Low
Short	Medium
Medium	Medium
Long	High

The final rule base in the model is used to determine the output probability based on two inputs; gas flow out of the annulus and the time taken. These two inputs use the conjunction between them to produce the final output membership function, Table C.4.

TABLE C.4: Fuzzy rule base 4 to obtain probability.

	IF		THEN
Gas flow	**AND**	**Time**	**Probability**
Low		Very short	High
Low		Short	Medium
Low		Medium	Low
Low		Long	Very low
Low		Very long	Very low
Medium		Very short	Very high
Medium		Short	High
Medium		Medium	Medium
Medium		Long	Low
Medium		Very long	Very low
High		Very short	Very high
High		Short	Very high
High		Medium	High
High		Long	Medium
High		Very long	Low

APPENDIX D

CEMENT FAILURE DURING PRODUCTION

The failure of cement has been determined and used throughout this research as a new way of quantifying cement failure. However, the failure of each basic event in the fault tree will be slightly different between the injection and production stages due to changes in pressures and stresses between the two stages. Experts were asked to quantify the basic events independently for the well stimulation stage and production stage, as shown in Appendix A. The same experts were used for quantifying both stages.

VERTICAL CEMENT FAILURE

The vertical failure of cement has been used in the model for both Chapters 5 and 6. The expert decisions for the production stage for vertical failure are shown in Table D.1.

TABLE D.1: Expert decisions showing linguistic values and converted fuzzy numbers for all basic events in the vertical cement fault tree during production.

BE	Expert decision					Fuzzy number				
	E_1	E_2	E_3	E_4	E_5	E_1	E_2	E_3	E_4	E_5
V_1	L	VL	M	M	L	$(0.1, 0.25, 0.4)$	$(0, 0, 0.1, 0.2)$	$(0.3, 0.5, 0.7)$	$(0.3, 0.5, 0.7)$	$(0.1, 0.25, 0.4)$
V_2	L	VL	M	M	M	$(0.1, 0.25, 0.4)$	$(0, 0, 0.1, 0.2)$	$(0.3, 0.5, 0.7)$	$(0.3, 0.5, 0.7)$	$(0.3, 0.5, 0.7)$
V_3	VL	VL	L	L	M	$(0, 0, 0.1, 0.2)$	$(0, 0, 0.1, 0.2)$	$(0.1, 0.25, 0.4)$	$(0.1, 0.25, 0.4)$	$(0.3, 0.5, 0.7)$
V_4	L	L	L	L	M	$(0.1, 0.25, 0.4)$	$(0.1, 0.25, 0.4)$	$(0.1, 0.25, 0.4)$	$(0.1, 0.25, 0.4)$	$(0.3, 0.5, 0.7)$
V_5	M	VL	H	M	M	$(0.3, 0.5, 0.7)$	$(0, 0, 0.1, 0.2)$	$(0.6, 0.75, 0.9)$	$(0.3, 0.5, 0.7)$	$(0.3, 0.5, 0.7)$
V_6	VL	VL	L	VL	M	$(0, 0, 0.1, 0.2)$	$(0, 0, 0.1, 0.2)$	$(0.1, 0.25, 0.4)$	$(0, 0, 0.1, 0.2)$	$(0.3, 0.5, 0.7)$
V_7	VL	VL	L	VL	M	$(0, 0, 0.1, 0.2)$	$(0, 0, 0.1, 0.2)$	$(0.1, 0.25, 0.4)$	$(0, 0, 0.1, 0.2)$	$(0.3, 0.5, 0.7)$
V_8	L	VL	M	M	M	$(0.1, 0.25, 0.4)$	$(0, 0, 0.1, 0.2)$	$(0.3, 0.5, 0.7)$	$(0.3, 0.5, 0.7)$	$(0.3, 0.5, 0.7)$

BE: Basic Event

The calculated possibilities, final failure probabilities and ranking of the vertical cement failure are indicated in Table D.2. The final probability of failure value for vertical cement failure is $1.00E^{-2}$.

TABLE D.2: Calculated aggregated values from fuzzy numbers and the final failure probability rank for vertical cement failure during the production stage.

BE	Aggregated possibilities	FPS	Failure probability	Rank
V_1	$(0.1520, 0.2906, 0.3106, 0.4692)$	0.3070	$9.59E^{-4}$	3
V_2	$(0.1983, 0.3495, 0.3687, 0.5391)$	0.3653	$1.71E^{-3}$	2
V_3	$(0.0939, 0.1876, 0.2319, 0.3699)$	0.2235	$3.27E^{-4}$	5
V_4	$(0.1382, 0.2983, 0.2983, 0.4585)$	0.2983	$8.71E^{-4}$	4
V_5	$(0.3009, 0.4569, 0.4750, 0.6490)$	0.4718	$4.08E^{-3}$	1
V_6	$(0.0740, 0.1393, 0.2023, 0.3307)$	0.1898	$1.85E^{-4}$	6
V_7	$(0.0740, 0.1393, 0.2023, 0.3307)$	0.1898	$1.85E^{-4}$	6
V_8	$(0.1983, 0.3495, 0.3687, 0.5391)$	0.3653	$1.71E^{-3}$	2

BE: Basic Event
FPS: Fuzzy Possibility Score

HORIZONTAL CEMENT FAILURE

The horizontal failure of cement has been used in the model for Chapter 5 and is required for Chapter 7 where further casing strings might be required. The expert decisions for the production stage for horizontal failure are shown in Table D.3.

TABLE D.3: Expert decisions showing linguistic values and converted fuzzy numbers for all basic events in the horizontal cement fault tree during production.

BE	Expert decision					Fuzzy number				
	E_1	E_2	E_3	E_4	E_5	E_1	E_2	E_3	E_4	E_5
H_1	L	VL	L	L	L	$(0.1, 0.25, 0.4)$	$(0, 0, 0.1, 0.2)$	$(0.1, 0.25, 0.4)$	$(0.1, 0.25, 0.4)$	$(0.1, 0.25, 0.4)$
H_2	L	VL	L	L	L	$(0.1, 0.25, 0.4)$	$(0, 0, 0.1, 0.2)$	$(0.1, 0.25, 0.4)$	$(0.1, 0.25, 0.4)$	$(0.1, 0.25, 0.4)$
H_3	VL	VL	M	L	M	$(0, 0, 0.1, 0.2)$	$(0, 0, 0.1, 0.2)$	$(0.3, 0.5, 0.7)$	$(0.1, 0.25, 0.4)$	$(0.3, 0.5, 0.7)$
H_4	VL	VL	L	L	M	$(0, 0, 0.1, 0.2)$	$(0, 0, 0.1, 0.2)$	$(0.1, 0.25, 0.4)$	$(0.1, 0.25, 0.4)$	$(0.3, 0.5, 0.7)$
H_5	L	VL	L	L	M	$(0.1, 0.25, 0.4)$	$(0, 0, 0.1, 0.2)$	$(0.1, 0.25, 0.4)$	$(0.1, 0.25, 0.4)$	$(0.3, 0.5, 0.7)$
H_6	VL	VL	L	L	M	$(0, 0, 0.1, 0.2)$	$(0, 0, 0.1, 0.2)$	$(0.1, 0.25, 0.4)$	$(0.1, 0.25, 0.4)$	$(0.3, 0.5, 0.7)$

BE: Basic Event

The calculated possibilities, final failure probabilities and ranking of the horizontal cement failure are indicated in Table D.4. The final probability of failure value for horizontal cement failure is $2.50E^{-3}$.

TABLE D.4: Calculated aggregated values from fuzzy numbers and the final failure probability rank for horizontal cement failure during the production stage.

BE	Aggregated possibilities	FPS	Failure probability	Rank
H_1	$(0.0806, 0.2016, 0.2214, 0.3623)$	0.2179	$3.00E^{-4}$	4
H_2	$(0.0806, 0.2016, 0.2214, 0.3623)$	0.2179	$3.00E^{-4}$	4
H_3	$(0.1345, 0.2387, 0.2827, 0.4310)$	0.2744	$6.58E^{-4}$	1
H_4	$(0.0939, 0.1876, 0.2319, 0.3699)$	0.2235	$3.27E^{-4}$	3
H_5	$(0.1183, 0.2483, 0.2685, 0.4187)$	0.2649	$5.84E^{-4}$	2
H_6	$(0.0939, 0.1876, 0.2319, 0.3699)$	0.2235	$3.27E^{-4}$	3

BE: Basic Event
FPS: Fuzzy Possibility Score

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