APPENDIX I
Review of Issues Related to Air Quality and Land Impacts Assessment, Waste Management, and Site Restoration

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EXECUTIVE SUMMARY

Due to environmental and public concerns, hydraulic fracturing (HF) is currently on a moratorium in Newfoundland; however, a panel was formulated to study various impacts associated with HF operations and to make a recommendation on the future of the HF in the province. In order to facilitate the panel's decision, this report presents potential issues due to HF operations that are related to air quality, land, waste management, and site restoration in the Western Newfoundland context. Relevant regulations, best management practices (BMPs), and mitigation measures are also included.

Air-Quality Impacts

Although state-of-the-art technologies are employed in current HF operations, these technologies are not without any environmental footprint, including that on air quality. The main sources of air-quality pollutants during HF operations are emissions from trucks and heavy machinery, flowback and produced water, gas flaring venting activities, compressor stations, and separators and condensate tanks. The primary pollutants are particulate matter (PM), nitrogen compounds, volatile organic compounds (VOCs), and benzene, toluene, ethylbenenze, and xylene (BTEX), which are harmful to humans as well as to flora and fauna. Thousands of tons of these pollutants are known to be released due to HF activities. Methane (CH_4) which is one of the potent greenhouse gases (GHGs) may be leaked due to improperly drilled wells. Dispersion of pollutants depends largely on the meteorology of the area. Average summer temperatures in the area were in the range of 20-25°C while winters are below zero. The wind blows predominantly from west as geographically this area is located in westerlies, however due to the influence of ocean currents the wind direction varies highly in certain areas. The emissions of criteria pollutant per well were estimated based on EPA emission factors. Using these emissions, a preliminary air dispersion study of selected criterial pollutants were conducted in two domains. The first domain was a large area covering south-west NL, and the second one a small and high resolution area covering Port au Port peninsula. The modelling exercise revealed that the peak concentrations of NO_2 were relatively high while other pollutants were predicted very low. All modelled pollutants were below NL ambient air quality standards however, relative high concentrations of NO_2 is a cause of concern due to its health impact as well as its role in the formation of Ozone (O_3). Therefore, a detailed photochemical modelling is highly recommended to study the regional ozone formation in addition to detailed dispersion study for other criteria pollutants including BTEX which is an occupational health hazard. Appropriate air quality mitigation measures include avoiding venting, taking measures to reduce greenhouse gases, and conducting periodic site-specific air-quality monitoring.

Land Impacts

Activities such as the construction of access roads, well pads, work camps, the storage and handling of additives, and waste processing facilities require the reclamation of land. The land requirement for a HF drilling pad and supporting facilities is not large; however, constructing an access road might necessitate the reclamation of a considerable area of land. As many areas in Western Newfoundland are not currently connected by roads, the construction of access roads is needed if drilling is to be performed in those areas. Land clearance and gravel quarrying generally destroy the existing vegetation and disturb regional fauna. The impact on flora results from an increase in soil erosion, sedimentation, and habitat fragmentation. Many areas in Western Newfoundland are rich in flora and fauna, if HF activities are undertaken in the vicinity of such areas, flora and fauna might get disturbed or even destroyed. Several ecological reserves and protected areas exist in this region, including Gros Morne National Park, which is a UNESCO heritage site. These reserves are host to many threatened plant and animal species. Considering its impacts on land, recommendations are strictly adhered to, particularly avoiding ecological reserves and areas containing threatened animal and plant species.

Waste Management

Despite their small quantity in fracturing fluids, chemical additives play critical roles in improving the performance of HF operations. Considering that some additives are toxic and might be hazardous to the environment, it is important to rationally select the type of additives and control their quantities while preparing fracturing fluids. For the specific-site conditions in Western Newfoundland, sea water might be the water supply of choice for operation locations near the coast, especially when the clay content of the subsurface profile is low; the addition of no or low-dosage clay stabilizers is recommended.

HF could lead to a wide range of environmental concerns if it is not properly managed. Particularly, flowback water as one of the main streams of fracturing waste poses potential environmental risks. Because it contains some of the original chemical additives of fracturing fluids, flowback water exhibits detrimental effects on surface and subsurface environments. Potential risks might originate from surface spills, subsurface leakages, and disposals. General risk mitigation plans such as adequate training, using more environmentally friendly chemicals, strengthening storage facilities, properly insulating injection wells, and monitoring and inspecting regularly also apply to HF operations in Western Newfoundland. It is also recommended that site-specific spill prevention and responding plans be prepared.

Site Restoration

When drilling activities have been completed, the areas surrounding the well pad must be restored as closely as possible to their pre-drilling conditions. This generally involves landscaping and contouring the property, removal of infrastructure, assessment of soil, remediation, if necessary, and long-term monitoring at the site. Well-established regulations and BMPs are in place with respect to activities associated with site restoration, such as well decommissioning and infrastructural removal. These regulations and BMPs are also applicable to the Western Newfoundland region. Innovative and proven soil assessment and remediation technologies (e.g., bioremediation) particularly for harsh climates are available in the province and can conveniently be applied if the need arises when site-restoration activities are undertaken.

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INTRODUCTION

Depending on the characteristics of the rock, hydrocarbon reservoirs are classified as either conventional or unconventional (GNLDNR, 2014 a). In conventional reservoirs, layers of sandstone and fluid typically allow oil or natural gas to flow readily into wellbores. On the other hand, in unconventional reservoirs, due to the low permeability of the rock formation, the hydrocarbon cannot easily flow out unless a path is created artificially, for example, by hydraulic fracturing (HF), which is linked with the horizontal drilling of wells (GNLDNR, 2014 a).

Historically, oil and gas (O&G) have been largely extracted from the ground by drilling a vertical well into a hydrocarbon reservoir, called conventional reservoirs, and allowing the oil or gas to flow into the well by natural pressures (GNLDNR, 2014 a). As conventional resources become limited, the exploitation of unconventional resources such as shales, tight sands, and coalbed methane is gaining recognition. Tapping shale reserves is not economically feasible for producing O&G without sophisticated technologies. To resolve this issue, research and innovation by O&G industries have produced advanced techniques for extracting the O&G trapped in shale formations. A key technology for accessing unconventional hydrocarbon resources is hydraulic fracturing, or fracking. HF involves pumping a mixture of water, sand, and chemicals into shale at a high pressure to create fissures or fractures in a tight rock formation (PTAC, 2012). These fractures lead to an increase in the flow of natural gas and other hydrocarbons from the formation to the well. Fracking has gained popularity due to its capability to increase the exploration and production of shale O&G (PTAC, 2012). However, this expansion of fracking has also increased concerns from federal, provincial, and local agencies, including the public, about its associated potential environmental impacts on land, water, and air. Scientific research and investigations continue to look for an environmentally friendly use of HF. The HF operation consumes significant energy, which also brings new environmental management challenges for the O&G industry.

Due to the presence of potential HF reserves in Western Newfoundland, there has been an increased interest in exploring these reserves. However, in November 2013, the government of Newfoundland and Labrador enacted a moratorium on HF and adopted a “go slow” approach due to associated environmental concerns. Consequently, an independent panel was appointed by the Minister of Natural Resources in October 2014 to conduct a public review of the socio-economic and environmental implications of HF in Western Newfoundland. The mandate of the panel is also to make recommendations on whether or not HF should be undertaken. To make an informed decision on this subject, the panel divided the scope covering the different aspects of impacts due to HF activities and opinions were sought from experts in these respective areas.

The team at Memorial University of Newfoundland’s Environmental Engineering department undertook a study to investigate the impacts on the air quality, land, and soil, waste management, and site-restoration aspects of HF in the Western Newfoundland context.

This report addresses the issues related to air emissions, land reclamation, soil contamination, waste management, and site restoration due to HF operations and their potential impact on the environment. This report also provides recommendations for improving environmental management efforts through proper regulations and best management practices (BMPs) to reduce these impacts. The report is comprised of the following sections:

HF – Western Newfoundland Context: This section briefly describes the geology of Western Newfoundland in the context of HF. It also gives an overview, and a brief description, of the potential hydrocarbon areas.

Overview of HF Operations: This section provides an overview of the HF operating procedure, equipment, and fracturing fluids and its potential risks to the environment. It also gives a brief overview of the regulatory framework.

Potential Risks to Air Quality: This section summarizes the state of knowledge about the potential risks to air quality resulting from HF operations.

Potential Risks to Land: This section summarizes the state of knowledge about the potential risks to land environment, especially the impact on flora, fauna, and soil contamination, due to HF operations.

Waste Management: This section summarizes the types of fracturing fluids and groups of additives typically used in HF operations. The potential environmental impact risks associated with flowback water, as well as its management options, are also addressed.

Site Restoration: This section covers the issues related to site restoration such as site decommissioning, post-operation monitoring requirements, and potential remediation technologies.

Conclusion and Recommendations: This section summarizes the findings and provides recommendations on HF activities.

Appendix A: This appendix presents a compilation of Canadian and international regulations that apply to HF.

Appendix B: This section summarizes BMPs for HF activities.

2.0 HYDRAULIC FRACTURING – WESTERN NEWFOUNDLAND CONTEXT

The Western region of the island of Newfoundland stretches 750 kilometres from Channel-Port aux Basques on the southwest corner to the Viking site of L'Anse aux Meadows at the tip of the Great Northern Peninsula. The geology of Western Newfoundland developed as the result of many Earth processes acting over long periods of geological time (GNLDNR, 2014 a). Geologically, the island of Newfoundland is divided into three zones: Western (Humber), Central, and Eastern (Figure 2.1).

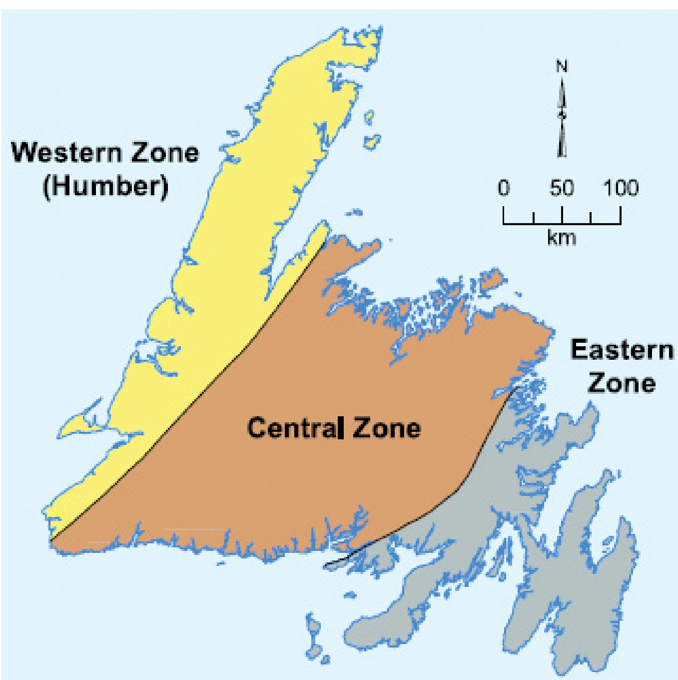

Figure 2.1. Tectonic zones of Newfoundland (adapted from GNLDNR, 2014 a).

On the island, the Western Zone contains the oldest rocks, which have the unique geological history of being at least a billion years old. As part of the Canadian Shield, they form the continental basement, or foundation, upon which all other rocks of the region rest (GNLDNR, 2014 a). Hydrocarbon exploration in Newfoundland dates to the early 1800s and oil exploration has been ongoing periodically for about a hundred years (GNLDNR, 2014 a). According to one report (GNLDNR, 2014 b), Western Newfoundland has four sedimentary basins capable of generating hydrocarbons (Figure 2.2).

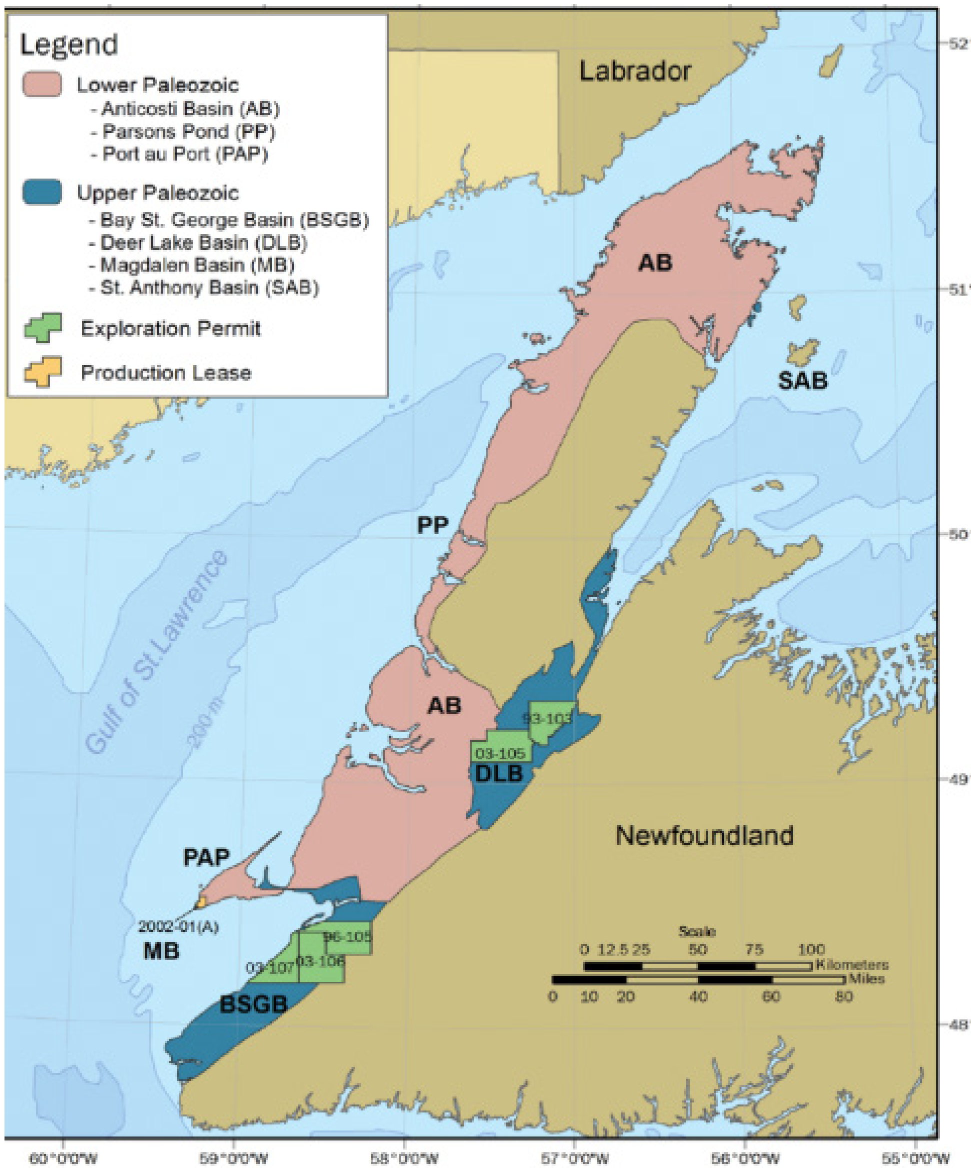

Figure 2.2. Sedimentary basins in Western Newfoundland (adapted from GNLDNR, 2014 b).

According to GNLDNR (2014 a), the distribution of seep oil and show O&G reservoirs are mostly on shoal lines; only one is an inland reservoir, as shown in Figure 2.3 (GNLDNR, 2014 b). Geologically, these reservoirs can be divided into two areas: Lower Paleozoic, including Anticosti Basin (AB), Parsons Pond (PP), and Port au Port (PAP); and Upper Paleozoic, including Bay St. George Basin (BSGB), Deer Lake Basin (DLB), Magdalen Basin (MB), and St. Anthony Basin (SAB), as shown in Figure 2.2. Among the others, the Lower Paleozoic Anticosti Basin is the largest, at approximately 13,000 square kilometres. Several towns and communities are close to these reservoirs, such as Port au Port and Stephenville in BSGB; Deer Lake in DLB; and Rocky Harbour, Sally's Cove, and Daniel's Harbour in AB. Some of these reservoirs are described in subsequent sections.

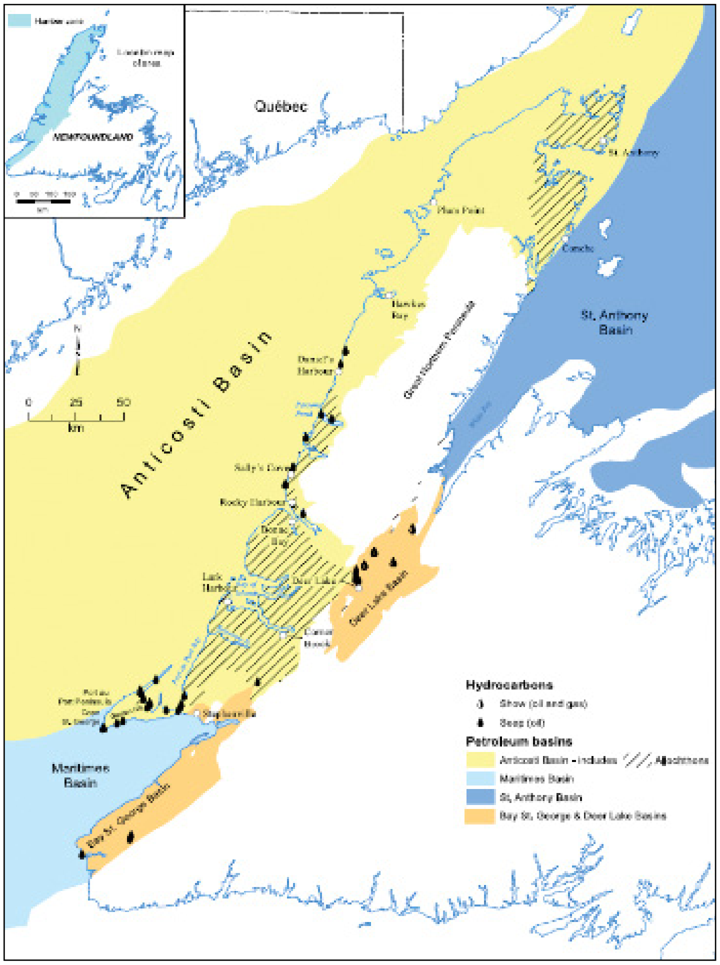

Figure 2.3. Potential hydrocarbon areas in Western Newfoundland (adapted from GNLDNR, 2014 b).

2.1 Parsons Pond (PP)

The PP area can be geologically included in the St. Paul's Inlet association. The soils in this area are mainly Podzolic soils, which have developed on gravelly coarse-textured dark greyish-brown morainal material derived from granitic gneiss, granite, and schist.

Orthic Ferro-Humic Podzols are the dominant soils of this association and are generally found at higher elevations on the upper slopes near the uplands of the Long Range Mountains. Gleyed Humo-Ferric Podzols, from a very shallow lithic phase, occur to a lesser extent and have developed on steep lower slopes on the western side of the Long Range Mountains. These soils are imperfectly drained because of lateral water movement between the soils and the lithic contact (Kirby et al., 1997).

2.2 Port au Port (PAP)

The PAP peninsula covers an area of about 149 square kilometres, where the soil parent material comes from sandstone, glacial and glaciofluvial deposits derived from sandstones, shales, limestone, dolomite, and igneous and metamorphic rocks. Figure 2.2 illustrates the soil texture in PAP. Generally, PAP soil textures range from loamy sand to silty clay. Well-drained soils cover around 28.5 percent of the area, while the poorly drained soils account for 13.9 percent. Fine-textured soils occupy about 28.7 percent of the peninsula; another 24.3 percent is medium-textured soils. The moderately coarse and coarse-textured soil make up to 5.8 percent and 0.5 percent of the total soils, respectively. Land types include peat, barrens, marsh, rockland, coastal beach, and quarries (Greenlee, 1984).

2.3 Bay St. George Basin (BSGB)

Both natural gas and oil have been documented in this area. The reported wells in BSGB include Gobineau-1 on the 03-106 permit, Hurricane-2 on the 96-107 permit, etc. The sedimentary rocks are deposited in two major tectono-stratigraphic units: a lower Carboniferous succession of clastics and volcanic rocks in fault-bounded sub-basins, and a middle to upper Carboniferous (post-rift) succession of carbonates, evaporites, and clastics. Coal beds are abundant in the upper Carboniferous. Basin structures are associated with rift faulting (and related inversion structures) and salt tectonics. The literature on soil texture in BSGB is limited. Based on information from the St. Fintan's area, the soils are generally formed on morainal tills, glaciofluvial outwash, and are fluvial and organic in origin with varying amounts of igneous rock. They are moderately fine to moderately coarse-textured, ranging from non-stony to exceedingly stony. The dominant soils are Humo-Ferric Podzols, Ferro-Humic Podzols, Dystric Brunisols, and Orthic Gleysols (Hender, 1987).

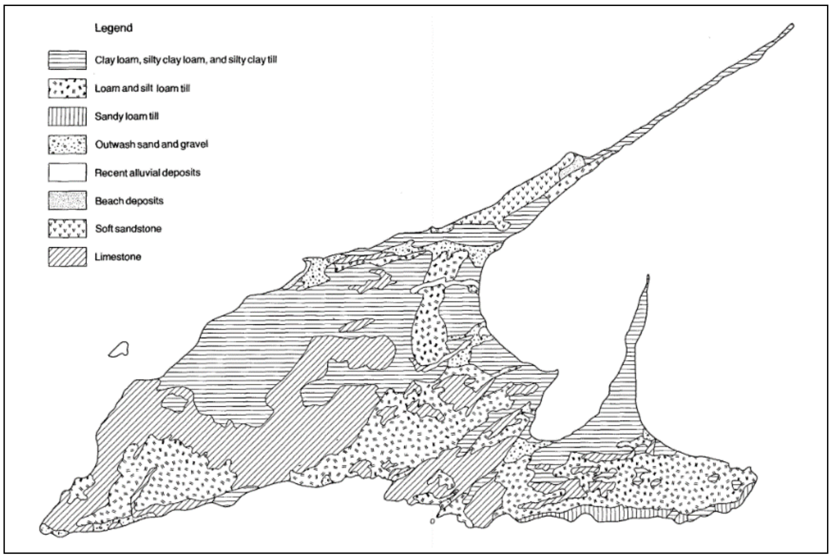

Figure 2.4. Soil texture in PAP.

2.4 Deer Lake Basin (DLB)

The DLB area lies in west-central Newfoundland. The bedrock of rolling lowland of the Deer Lake area consists of grey and greyish-green micaceous and arkosic sandstone and grey arkosic conglomerate with minor dark shale and argillite.

The main soils found in this area are Podzols, Gleysols, and Organics. Podzolic soils occur throughout the map area on well- to imperfectly drained sites. In the Deer Lake area, Gleyed Humo-Ferric Podzol dominates the soil group. The parental material is dark brown to dark yellowish-brown stony gravelly sandy loam till from granite. The surface texture of the soil is exceeding stony sandy loam to loamy sand. The soil is imperfectly drained. The average number of frost-free days in the DLB area is around 100 days every year. This indicates the average low temperature of soil in this area (Button, 1983).

When hydrocarbons are trapped in shale, they cannot flow naturally, so few shale wells can achieve commercial production without improved technology. Horizontal drilling and multi-stage HF have provided this improvement in flow and have created a new interest in the unconventional O&G resources in North America. This interest also includes the west coast of Newfoundland.

3.0 OVERVIEW OF HYDRAULIC FRACTURING OPERATIONS

HF is a process of transmitting pressure by fluid to cracks or open existing cracks in hydrocarbon-bearing rock. It involves pumping a mixture of water, sand, and chemicals into shale at a high pressure to create fissures or fractures in a tight rock formation. These fractures lead to an increase in the flow of natural gas and other hydrocarbons from the formation to the well (Precht and Dempster, 2015 c). The area where HF operations are performed creates a high conductivity path that extends from the wellbore through a targeted hydrocarbon-bearing formation for a significant distance so that the hydrocarbons and other fluids can flow more easily from the formation rock into the fracture, and ultimately to the wellbore (API, 2009).

The key technique for accessing O&G in shale is a combination of fracturing with horizontal drilling. After drilling between 6,000 and 10,000 feet deep the operator turns the drill sideways (Thomas and David, 2013). The purpose of horizontal drilling is to increase contact with the layer of shale containing the gas or oil (API, 2009).

HF requires very large volumes of water over the lifespan of the operation. The volume of water required for an operation varies widely, ranging from 3,500 to 70,000 cubic metres per well, depending on the geological characteristics of the reservoir. A typical multi-stage shale development uses 3,500 to 10,000 cubic metres of fracture fluid (CSUG, 2013).

HF is the technique driving the ongoing energy boom in the United States, where over a million wells have been hydraulically fractured since the 1940s (Brantley and Meyendorff, 2013). According to the Canadian Association of Petroleum Producers (CAPP), over 175,000 wells have been fracked in the provinces of Alberta and British Columbia (CAPP, 2012a).

Fracturing operations require multiple pieces of sophisticated, specifically designed equipment. In many cases, multiple pieces of the same kind of equipment, such as pumps, are necessary. The type, size, and number of pieces of equipment needed depend on the size of the fracture treatment, type of treatment, and the additives, proppants, and fluids that are used (PTAC, 2012). Table 3.1 lists the typical equipment used during a fracturing job and its purpose.

Table 3.1. Typical fracturing equipment (PTAC, 2012).

EQUIPMENT ITEM	PURPOSE	DESCRIPTION (SIZE, CAPACITY)	NUMBER ON-SITE
Fracturing Head	A wellhead connection that allows fracture equipment to attach to the well		1
Fracturing Pumps	Heavy duty pumps that take the fluid from the blender and pressurize it via a positive displacement pump	Number on-site depends on the pumping pressure and rates required for stimulation; for horizontal well shale gas fracturing there are usually multiple pumps on-site	2+
Blender Pumps	Takes fluid from the fracturing tanks and sand from the hopper and combines them with chemical additives before transferring the mixture to the fracturing pumps	A backup blender is sometimes on location	1+
Transfer Pumps	A trailer-mounted pump and manifold system that transfers fluid from one series of fracturing tanks to another or from ponds to the manifold	Typically used prior to the start of the fracturing job; once the job is started, the fracturing pumps perform water transfers	1+
Sand Storage Units	Large tanks that hold the proppant and feed it to the blender via a large conveyor belt	150 to 200 tonnes	3+
Fracturing Tanks – Supply	Water containment tanks that store the required volume of water to be used in fracture stimulations	~80 m^3/tank (Varies)	3+
Fracturing Tanks – Receiving	Water containment tanks that store produced water from hydraulic fracture stimulations	~80 m^3/tank (Varies)	3+
Gel Slurry Tanker Truck	Transports gel slurry to the job site; the equipment has two compartments to allow for the gel to be agitated between the compartments to prevent separation or breakdown	15 m^3	1
Chemical Storage Trucks	Flatbed trucks used to transport chemicals to the job site may contain a pump to transfer chemical additives from the on-board storage tanks to the required equipment (i.e., blender)		1+
Technical Monitoring Van	The work area for engineers, supervisors, pump operators, company representatives, and regulatory personnel		1
Acid Transport Trucks	Used to transport acids to job sites; a truck has separate compartments for the transport of multiple acids or additives	19 m^3/truck	1+
Manifold Trailer	Large manifold system that acts as a transfer station for all fluids; mixed fluids from blender pumps move through the manifold on the way to the pump trucks		1

3.1 Fracturing Fluid

The specific compounds used in a given fracturing operation depend on company preference, source water quality, and the site-specific characteristics of the target formation (PTAC, 2012; API, 2009). Generally, HF fluids are composed of water (typically 98-99%) and chemical additives (1-2%) and are mostly water-based (CCA, 2014). Most commonly fresh water is used; however, sea water may be used after the necessary treatments (CCA, 2014; Precht and Dempster, 2015 a, b). Chemical additives ensure that the fracturing operation is effective and efficient and serve many functions from limiting the growth of bacteria to preventing corrosion of the well casing.

3.2 Flowback Water and Produced Water

Once the injection process has been completed, internal reservoir pressures cause the fluid to return to the surface through the wellbore (Precht and Dempster, 2015 c). The fracturing fluid that returns to the surface along with the oil, natural gas, and produced water is called flowback water. The hydrocarbons are separated from the returned fluid at the surface, and the flowback and produced water are collected in tanks for treatment or injection (Precht and Dempster, 2015 c). The handling and disposal of returned fluids is a normal part of O&G drilling operations and is not limited to HF wells. Flowback water includes (Precht and Dempster, 2015 c):

- Injected water, sand (or other proppants), and injected chemicals,
- Natural gas or oil, and
- Some produced water, which is naturally occurring water from the reservoir, may contain salty brines, metals, nutrients, naturally occurring radioactive materials (NORMs), and other organic compounds which are brought to the surface with the flowback water.

Depending on formation properties, the fracturing program, design, and the type of fracturing fluid used, typically 25 to 75 percent of the injected fracturing fluid flows back to the surface when the well has been completed (Precht and Dempster, 2015 c). Flowback water will continue to return to the surface over the producing lifetime of the well but mainly occurs in the early stage of the production (Precht and Dempster, 2015 c).

On-site systems separate the hydrocarbons (oil and natural gas, including any liquefied petroleum gases in the natural gas [e.g., butanes and propane]) from the water and sand in the flowback water before directing the recovered hydrocarbons into the pipeline or storage tanks (Precht and Dempster, 2015 c).

Because shale contains more uranium than other types of rocks, NORMs may be found in the flowback water from wells drilled into shale reservoirs (API, 2009). Components such as wellheads, separation vessels, pumps, and other processing equipment can become contaminated with NORMs; this contamination can be found in drilling mud, sludge, and tank bottoms (API, 2009). This can create a potential radiation hazard to workers at the site, the general public, and the environment if necessary measures are not taken to monitor and manage NORMs. NORMs may also be present in waste fluids from the conventional O&G industry.

3.3 Environmental Risks

The development of hydrocarbon resources comes with consequences similar to those of other industrial activities, such as mining, forestry, and even agricultural industries. There will always be an environmental impact associated with developing the economic potential of natural resources. Understanding risks and managing them diligently allows the benefit to be derived with a minimum negative impact. Currently, the state of knowledge about the risks of unconventional hydrocarbon operations is mixed. On one hand, HF has been used in the US since the 1940s. Statistically, the number of proven environmental impacts caused by HF remains small in relation to the volume of HF activity (Healy, 2012). One estimate is that approximately one million O&G wells have been drilled and hydraulically fractured (King, 2012), including over 200,000 wells in Western Canada (CAPP, 2012a, b). On the other hand, in spite of this widespread use, very few peer-reviewed scientific studies have been published which examine the risks associated with HF. Because the risk is not well quantified, the best approach at this stage is to consider the full range of possible impacts, their magnitude, uncertainty, and potential environmental effects (Healy, 2012).

Figure 3.1 illustrates the typical HF activities and their potential risks. The subsequent sections of this report discuss some of these activities and corresponding risks to the environment.

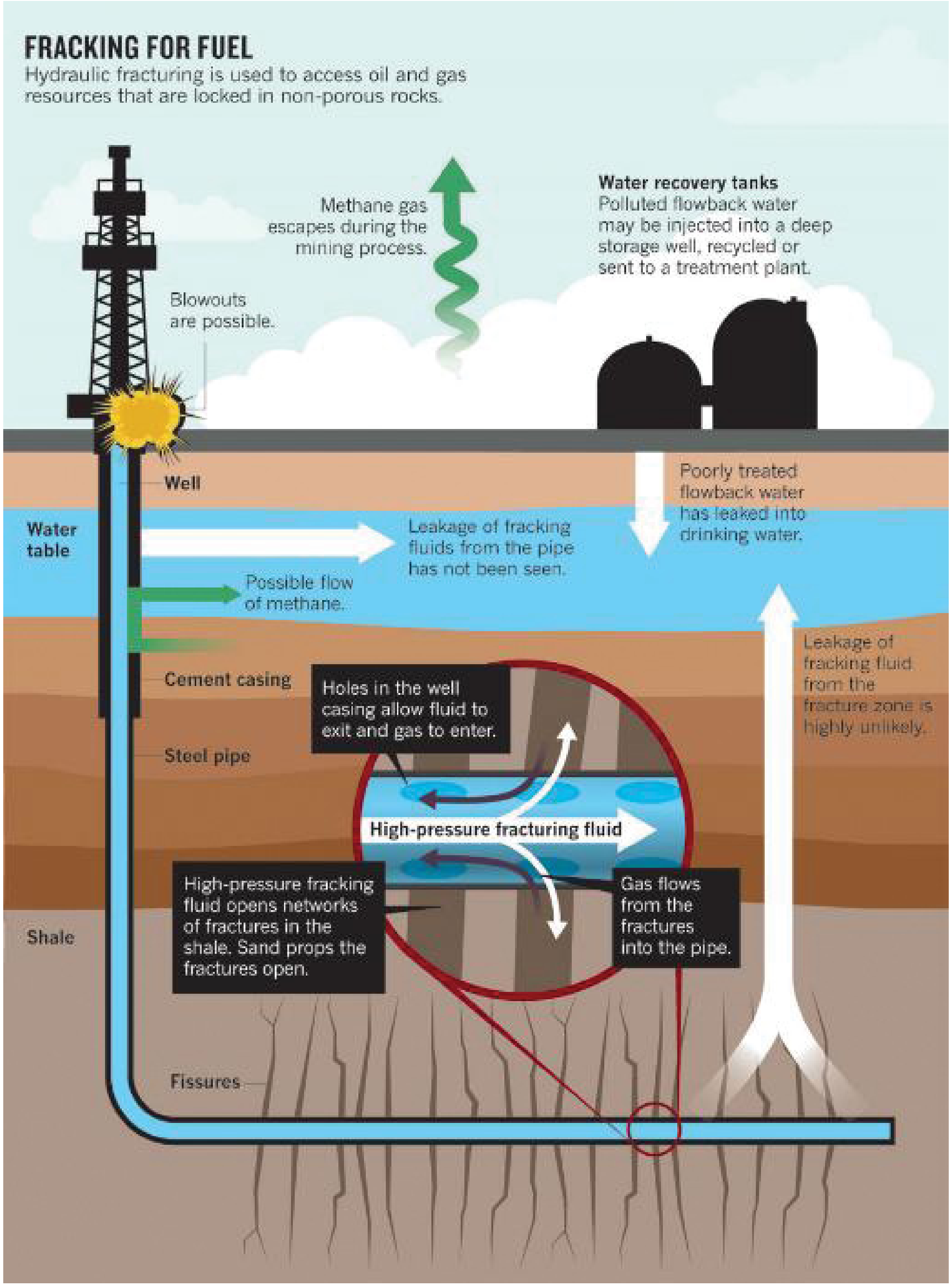

Figure 3.3.1. Typical environmental risks associated with fracturing operations (adapted from Howarth et al., 2011).

3.4 Regulatory Framework

Increasing concerns about HF's potential negative impact on human health and the environment have made it a controversial technique. The proper regulation of HF is critical to ensure that it does not lead to a significant negative impact on human health or the environment. Detailed regulations have been promulgated by both the federal and provincial authorities governing HF operations. Appendix A presents an overview of selected federal and provincial Canadian regulations, in addition to some international laws that apply to HF.

4.0 AIR QUALITY

4.1 Air Pollutants and Sources

Conventional O&G operations have been known to create harmful air emissions. These pollutants include diesel particle emissions, hydrocarbons, VOCs (e.g., benzene), PM, and greenhouse gas (GHG). The emission of air pollutants from fracturing operations is similar to that from conventional O&G operations, but it is of a higher magnitude around fracturing sites because of the greater effort required (Green, 2014). The United States Environmental Protection Agency (USEPA) is also concerned about air pollutants that result from HF; according to USEPA (2014), there have been well-documented air-quality impacts in areas with active natural gas developments, with increases in the emissions of methane (CH_4), VOCs, and hazardous air pollutants (HAPs). The main regional air emission issue is the generation of ozone (O_3), which in some circumstances could adversely affect air quality (CCA, 2014).

Studies recognize that fracturing activity may lead to an increase in the type of air pollutants generally found at conventional O&G operations, including those other pollutants specific to fracturing, such as silica sand, fracturing chemicals, and flowback wastewater (Srebotnjak and Rotkin-Ellman, 2014; Seth et al., 2014). In general, the air emissions involved in fracturing operations can be categorized as:

- On-site criteria pollutants and their precursors: carbon monoxide (CO), lead, nitrogen oxides (NO_x), O_3, PM, sulfur dioxide (SO_2) from process unit (EESI, 2011), and VOCs;
- Air toxics and other HAPs, including fugitive emissions from mixing chemicals, spills, and flowback fluids (which can also include VOCs); and
- GHG emissions such as carbon dioxide (CO_2) and CH_4.

The source of these emissions can include combustion engines; powering on-site equipment, and transportation equipment; drilling process wastewater, and condensate tanks; underground/downhole sources such as flowback fluids, fugitive emissions from sand, dust, mixing chemicals, spills, or other uncontrolled gas releases (Srebotnjak and Rotkin-Ellman, 2014; Tyner et al., 2014). Table 4.1 summarizes the potential activities/equipment and possible air pollutant emissions from a typical fracturing operation.

Table 4.1. Typical activities, sources, and air emissions from HF.

ACTIVITY AND ASSOCIATED EQUIPMENT	EMISSIONS & SOURCES	POTENTIAL AIR POLLUTANTS
Well site preparation and road construction	Trucks and heavy machinery	diesel PM, NO_x, CO_2, CO, BTEX, PAH, and dust
Well drilling, hydraulic fracturing, and well completion	Drilling	diesel PM, NO_x, CO_2, CO, BTEX, PAH, CH_4, volatile drilling mud fluids, and volatile hydrocarbons from drill cuttings
	Hydraulic fracturing	silica dust, volatile fracturing chemicals, BTEX, other volatile hydrocarbons, PM, NO_x, CO_2, and CO
	Flowback and produced water	volatile fracturing fluids, BTEX, other volatile hydrocarbons, and hydrogen sulfide (H_2S)
Production	Produced water	BTEX, other volatile hydrocarbons, and H_2S
	Gas flaring/venting	CH_4, NO_x, CO_2, CO, PM, H_2S, BTEX, and other volatile hydrocarbons
	Work-over and maintenance	diesel PM, NO_x, CO_2, CO, CH_4, BTEX, PAH, and other volatile hydrocarbons
Processing and storage	Gas venting	CH_4, H_2S, BTEX, and other volatile hydrocarbons
	Separators and condensate tanks	CH_4, BTEX, and other volatile hydrocarbons
	Compressors	diesel PM, NO_x, CO_2, CO, BTEX, PAH, and other volatile hydrocarbons
Transmission	Pipelines	CH_4, BTEX, and other volatile hydrocarbons
	Compressor stations	diesel PM, NO_x, CO_2, CO, BTEX, PAH, and other volatile hydrocarbons
	Gas venting	CH_4, H_2S, BTEX, and other volatile hydrocarbons
Well abandonment and site rehabilitation	Trucks and heavy machinery	diesel PM, NO_x, CO_2, CO, BTEX, and PAH
	Abandoned orphaned wells	CH_4

Compiled from Srebotnjak and Rotkin-Ellman, 2014; Tyner et al., 2014.

4.1.1 Criteria Pollutants

HF activities releases thousands of tons of air pollutants in the atmosphere, for example in 2012 alone fracturing activities in US emitted 13,000, 170,000, 250,000, 23,000 and 600 tons of PM, NO_x, CO, VOCs and SO_2 respectively (Ridlington and Rumpler, 2013). This potentially will pose significant impact on the local air quality. The following sections elaborates on various criteria pollutants and their impact on health.

Particulate Matter (PM)

Particulate emissions originate from the combustion engines of heavy trucks and machinery used during well-site preparation, drilling, and production. Particulate matter (PM) is a complex mixture of very small particles and liquid droplets found in the air, including dust, dirt, soot, smoke. The size of the particulate is directly linked to its potential for causing health problems. PM that is 10 micrometres (μm) in diameter or smaller (PM_{10}) poses a health concern because it can pass through the throat and nose and accumulate in the respiratory system. PM less than 2.5 μm in diameter ($PM_{2.5}$) is believed to pose the greatest health risk because it can get deep into a person's lungs and even into the bloodstream (USEPA, 2010). Total Particulate Matter (TPM) is the term applied to any particle suspended in the atmosphere, but typically it is limited to PM less than 44 micrometres in diameter. PM larger than 10 micrometres in diameter is typically associated with a nuisance rather than a health issue (DECNL, 2013). According to USEPA (2010), each well requires on average of between 2 and 5 million gallons of water per HF event. Water is generally transported by diesel trucks, each of which has an approximate capacity of 3,000 gallons (USEPA, 2011). It has been estimated that approximately 2,300 trips by heavy-duty trucks are required for each horizontal well during the early stages of shale gas development (USEPA, 2011). With thousands of such wells concentrated in high-development regions, the levels of truck traffic and diesel-associated air pollution will increase in these areas. In addition to diesel PM, other pollutants prevalent in diesel emissions, such as NO_x and VOCs, react in the presence of sunlight and produced ground-level O_3.

Diesel-engine exhaust contains many toxic chemicals, of which fine diesel soot particles are of the greatest concern as these can lodge deep within the lungs, increasing health risks such as asthma attacks, cardiopulmonary disease (including heart attack and stroke), respiratory disease, adverse birth outcomes, and premature death (John et al., 2014). Researchers are concerned about local residents' increased risk of exposure to diesel exhaust (John et al., 2014).

The pollutant of primary health concern emitted from the transportation component of shale gas development is fine diesel PM. Diesel PM is a well-understood health-damaging pollutant that contributes to cardiovascular illnesses and respiratory diseases such as lung cancer (Garshick et al., 2008; Pope et al., 2002). Particulates can also contain concentrated associated products of incomplete combustion, and, when a particle's diameter is less than 2.5 micrometres, it can act as a delivery system to the alveoli of the human lung (Smith et al., 2009). Numerous scientific studies have linked particle pollution exposure to a variety of problems, including (USEPA, 2010):

- Premature death in people with heart or lung disease,
- Nonfatal heart attacks,
- Irregular heartbeat,
- Aggravated asthma,
- Decreased lung function, and
- Increased respiratory symptoms, such as irritation of the airways, coughing, or difficulty in breathing.

Nitrogen Oxides (NO_x)

Nitric oxide (NO) and nitrogen dioxide (NO_2) are collectively referred to as NOx. These are produced due to combustion activities. In Canada, the main sources of NOx are from transportation (50%), petroleum industry (22%), electric power generation (10%), natural source (8%) and other industrial and non-industrial sources (10%). The adverse effect on human health due to NO2 exposure include inflammation of lung, severe respiratory diseases particularly to people with asthma. Some studies show a connection between breathing elevated short-term NO_2 concentration, and increased visits to emergency departments and hospital admissions. Small particles, which can penetrate deeply into sensitive parts of the lung are formed when NO_x reacts with ammonia and moisture. This results in other respiratory diseases such as emphysema and bronchitis.

Carbon Monoxide (CO)

Carbon monoxide (CO) is a colourless and odourless gas which reduces the delivery of oxygen (O_2) to the body's organs. Generally, incomplete oxidation of fuel results in the formation of CO. However, if sufficient O_2 is not present to complete the combustion of the hydrocarbon fuel, the oxidation to CO_2 and water (H_2O) is not completed, and hence CO is emitted.

Unlike other air pollutants, CO does not appear to affect the respiratory system (Boyd, 2006). However, exposure to elevated levels can adversely affect the functioning of the heart, which may cause myocardial ischemia (reduced O_2 to the heart), increased hospital admissions, and possibly increased cardiac mortality (USEPA, 2014; Fierro et al, 2001). According to Natural Resources Canada (NRC) (2012), shale gas has a low CO_2 content, similar to typical conventional gas production. Therefore, as more shale gas development occurs, the GHG emission per unit of shale gas produced and consumed should be similar to that from conventional natural gas production and use.

Volatile Organic Compounds (VOCs)

Fracturing fluids can contain VOCs such as benzene, which can be released into the atmosphere when the fluid evaporates (Colborn et al., 2011). The wellheads themselves vent VOCs such as benzene and toluene that can combine with combustion by-products to create smog (Conrad et al., 2010). However, according to Bunch et al. (2014), shale gas production activities did not result in community-wide exposure to concentrations of VOCs at levels that would pose a health concern.

Ozone (O_3)

Ozone (O_3) is a secondary pollutant that is formed in polluted areas by atmospheric reactions involving two main types of precursor pollutants: VOCs and NO_x. CO from the incomplete combustion of fuels is also an important precursor for O_3 formation. The formation of O_3 and other oxidation products (e.g., peroxyacyl nitrates and hydrogen peroxide), including oxidation products of the precursor chemicals, is an extremely complex reaction that depends on the intensity and wavelength of sunlight, atmospheric mixing and interactions with cloud and other aerosol particulates, the concentration of VOCs and NOx in the air, and the rates of all chemical reactions. The majority of ground-level O3 is formed when the O3 precursors NOx, CO, and VOCs react in the atmosphere in the presence of sunlight (Conrad et al., 2010). VOC sources can come from ponds, condensers, and other gas-processing equipment and compressor-transmission operation (Conrad et al., 2010).

4.1.3 Greenhouse Gas (GHG) Emissions

HF operations require a significant amount of energy and, as HF locations are generally remote, that energy has to be generated on-site (Green, 2014). In most cases, conventional power generators fueled by diesel fuel, natural gas, or other fossil fuels are used. The combustion of such fuel leads to the emission of GHGs (Green, 2014). In addition, improperly drilled wells may leak CH_4 and other GHGs to the atmosphere during and after the production period of the well. The literature claims that HF would increase natural gas emissions to the atmosphere due to leakage during the HF process and at the beginning of gas recovery (Green, 2014). CH4 is considered to be one of the most potent GHGs. It is estimated that 100 million tons of CO_2 equivalent is released since 2005 due to HF activities in US, thus contributing to global warming (Ridlington and Rumpler, 2013).

More recently, reduced emissions completions (RECs), or “green completions,” which capture and separate natural gas during well completion and workover activities, have become a key technology to limit the amounts of CH_4, VOCs, and HAPs that can be vented during the flowback period without the disadvantage of flaring. RECs use portable equipment that allows operators to capture natural gas from the flowback water. After the mixture passes through a sand trap, a three-phase separator removes natural gas liquids and water from the gas, which is then sent to sales pipelines for distribution. REC operations have been found to be very cost-effective even with low natural gas prices (Green, 2014).

According to Natural Resources Canada (NRC) (2012), “most prospective shale gas developments have low carbon dioxide content, similar to typical conventional gas production. Therefore, as more shale gas development occurs, the greenhouse gas emissions per unit of shale gas produced and consumed should be similar to that from conventional natural gas production and use.”

Numerous other cost-effective technologies have been developed to reduce natural gas leakage, such as plunger lift systems, dry seal systems, and no-bleed pneumatic controllers (PTAC, 2012). Through the use of these technologies and practices, nearly 90 percent of the natural gas leakages could be addressed (PTAC, 2012). To further reduce the emissions impacts at well sites in densely populated areas, electric motors could be used instead of internal combustion engines (Clark et al., 2013).

4.2 Potential Health Risks

The specific health effects due to air contaminants and their extent are dependent on a variety of factors such as the type and length of exposure to a contaminant as well as the health status and lifestyle of the exposed individual (CDPHE, 2010; McKenzie et al., 2012).

Along with the concern of increased GHG emissions, the impact of air emissions from HF has become a debated issue in the environmental movement. Due to a low emission rate, some emissions have been acknowledged to be relatively harmless to human health. NORMs, one identified source of emissions, are brought to the surface during shale gas production but remain in such places as rock pieces with the produced water (USDOE, 2009). As the radiation from these NORMs is weak, it cannot penetrate dense materials or cause extreme risks from exposure. However, radiation hazards must be evaluated so that it does not exceed regulatory standards concentrations (USDOE, 2009).

Other chemicals have been detected in drilling locations that are highly detrimental, particularly to air quality. For example, with benzene, a carcinogen that typically causes leukemia, health concerns arise when its level reaches 1.4 parts per billion. In 2009, air samples from a Targa Resources compressor station outside Decatur, Texas, revealed that the level of benzene reached 1,100 parts per billion; a sample from a nearby Devon Energy well revealed 15,000 parts per billion (Hawes, 2009). Of the 300 air samples taken from 30 facilities in north central Texas, 50 exceeded the Texas Commission of Environmental Quality's standard for long-term health risk (WISE, 2010).

Air emissions can also be attributed to the equipment used to extract natural gas by HF. Millions of gallons of water are commonly transported by tanker trucks; for instance, over 1,000 truck trips were required for one fracture (WISE, 2010). Each truck trip could stir up dust and release PM, NO_x, and CO2 into the air. Diesel engines needed to run the drilling equipment use large amounts of fuel that also produce a significant amount of emissions (WISE, 2010).
A health impact assessment conducted by Witter et al. (2008) for O&G development concluded that air quality is most likely affected during well-pad construction and well completion and through truck traffic. Fugitive emissions from production equipment are another possible long-term source of air contamination that needs to be controlled. Table 4.2 lists the potential health effects from air pollutants released from O&G development which will be associated with HF operations.

Table 4.2. Air contaminants associated with HF and their effects.

SUBSTANCE	POTENTIAL HEALTH EFFECTS	ENVIRONMENTAL AND CLIMATE EFFECTS
Particulate Matter (PM)	• Non-fatal heart attacks • Irregular heartbeat • Aggravated asthma • Reduced lung function • Increased respiratory symptoms (e.g., coughing, difficulty breathing) • Premature death in people with heart or lung disease	Impairs visibility, adversely affects ecosystem processes, and damages and/or soils structures and property. Variable climate impacts depending on particle type. Most particles are reflective and lead to net cooling, while some (especially black carbon) absorb energy and lead to warming. Other impacts include changing the timing and location of traditional rainfall patterns.
Oxides of Sulfur (SO_x) from process unit (EESI, 2011)	Aggravate asthma, leading to wheezing, chest tightness and shortness of breath, increased medication use, hospital admissions, and ER visits; very high levels can cause respiratory symptoms in people without lung disease.	Contributes to the acidification of soil and surface water and mercury methylation in wetland areas. Causes injury to vegetation and local species losses in aquatic and terrestrial systems. Contributes to particle formation with associated environmental effects. Sulfate particles contribute to the cooling of the atmosphere.
Nitrogen Oxides (NO_x)	• Irritated respiratory system aggravated asthma, bronchitis, or existing heart disease • Combines with VOCs to form O_3	Contributes to the acidification and nutrient enrichment (eutrophication, nitrogen saturation) of soil and surface water. Leads to biodiversity losses. Impacts levels of O_3, particles, and CH_4 with associated environmental and climate effects.
Carbon Monoxide (CO)	• Exacerbation of cardiovascular disease behavioural impairment • Reduced birth weight increased daily mortality rate	Contributes to the formation of CO_2 and O_3, GHGs gases that warm the atmosphere.
Volatile Organic Compounds (VOCs)	• Carcinogen (some VOCs) • Leukemia and other blood disorders (benzene) • Birth defects (some VOCs) • Eye, nose, and throat irritation (some VOCs) • Adverse nervous systems effects	Contributes to O_3 formation with associated environmental and climate effects. Contributes to the formation of CO_2 and O_3, GHGs that warm the atmosphere.
Ground Level Ozone (O_3) (Smog)	• Reduced lung function • Aggravated asthma or bronchitis • Permanent lung damage	Damages vegetation by visibly injuring leaves, reducing photosynthesis, impairing reproduction and growth, and decreasing crop yields. O_3 damage to plants may alter ecosystem structure, reduce biodiversity, and decrease plant uptake of CO_2. O_3 is also a GHG that contributes to the warming of the atmosphere.
Methane (CH_4)	Asphyxiation in confined spaces. May cause rapid breathing, rapid heart rate, clumsiness, emotional upset, and fatigue. At greater exposure, may cause vomiting, collapse, convulsions, coma, and death.	
Benzene	Known carcinogen. May cause anemia; can lessen white blood cell count, weakening the immune system. Prolonged exposure may result in blood disorders like leukemia, reproductive and developmental disorders, and other cancers.	
Toluene	Long-term exposure may affect the nervous system, cause irritation of the skin, eyes, and respiratory tract, and birth defects.	
Ethylbenzene	Long-term exposure may result in blood disorders.	
Xylene	Short-term exposure to high levels may cause irritation of the nose and throat, nausea, vomiting, gastric irritation, and neurological effects. Long-term exposure at high levels may damage the nervous system.	

Data source: Fierro et al., 2001; USEPA, 2013a, 2013b, 2013d; McKenzie et al., 2012.

A human health risk assessment of air emissions carried out in a region of Colorado with a shale gas development near a rural population detected several different air emissions in close proximity to the development. The study found that the highest air pollution concentrations occurred during well development and completion (McKenzie et al., 2012). Overall, two-thirds more hydrocarbons were detected during well completion than during the production phase. The range of concentrations detected for several VOCs and BTEX during completion was large. For instance, the minimum detected concentration of m-xylene/p-xylene was 2.0 micrograms per cubic metre of air, whereas the maximum was 880 micrograms per cubic metre of air (McKenzie et al., 2012). Health Canada's tolerable concentrations over a lifetime for xylene isomers (m-xylene/p-xylene) are 180 and 348 micrograms per cubic metre, respectively (Ruth, 1986; Health Canada, 1996).

4.3 Meteorology and Dispersion Modelling

Air dispersion modeling is the mathematical simulation of how air pollutants disperse in the ambient atmosphere. Air dispersion models use mathematical and numerical techniques to simulate those physical and chemical processes that affect air pollutants as they disperse and react in the atmosphere. Based on meteorological data and source information such as emission rates and stack height, these models are used to characterize air pollutant dispersion patterns in the atmosphere. As discussed in the previous sections, several pollutants could potentially be released in the atmosphere as a result of HF activities. Employing the air quality models, the dispersion of these pollutants could be studied. The following sections summarize general meteorology of Western Newfoundland, quantify air pollutants due to HF activities and simulate a hypothetical dispersion scenario and analyze the results of the simulation.

4.3.1 Meteorology of Western Newfoundland

General Climate

The western Newfoundland area is located between the latitudes 46°36′ and 51°38′. Due to the influence of ocean, the area experiences slightly warmer winter and cooler summer than the inland areas. The average temperature in summer remains in the 20-25° range, while winter temperatures are below zero. Geographically, the whole area is located in westerlies winds (30-60° of latitude), the dominating wind direction prevail from west. However, with the influence of ocean currents the wind direction of the area varies.

Temperature and Precipitation

Deer Lake city that represents in-land station and Stephenville Airport that represents coastal station were selected for the statistical analysis of temperature and precipitation. Figures 4.1 and 4.2 illustrates 30 years daily maximum, minimum and average temperature and precipitation. The average temperature in summer was around 23°, and while the average in winter were below 0°. The average lowest temperature occurs in both stations in February. The year round precipitation of Stephenville is relatively higher than it of Deer Lake. Both stations show the same trend in the amount of precipitation. The most precipitation occurred in January which was about 110mm of Deer Lake, while 125mm of Stephenville.

Winds

The winds were analyzed based on five-year meteorological data (2010-2014) obtained from National Centers for Environmental Information (NCEI)[1] for various weather stations in western Newfoundland (Table 4.3). Three stations i.e., Stephenville, Deer Lake and St. Anthony were selected to analyze the wind patter. Due to the influence of ocean currents, wind direction varies in different seasons of western Newfoundland.

1 www.ncdc.noaa.gov/

Seasonal and annual round average wind rose diagrams are shown in Figures 4.3-4.14. The dominant winds tend to prevail from W sectors for six stations with the exception of Wreck House, which the dominate winds tend to prevail from N and S. Five-year wind rose plots indicated that the wind speed of areas on the coast is generally will be higher than it of inland areas. The dominate wind speed of Deer Lake is 3.00-5.70 m/s in summer and 5.70-8.80 m/s in winter, while it is 5.70-8.80 m/s in summer at St. Anthony and Stephenville, and over 8.80 m/s in winter at these two stations. Wind speed in summer could be 1-2 classes lower than it in winter. The dominate wind direction of all three stations are prevail from W in winter and SW in summer. In recent years, the trend of wind direction of St. Anthony is tending to SW in winter and SE in summer and varies in spring and fall. At Deer Lake station, the dominate wind direction prevail to WSW and NE all year round. In spring, NE is the dominate wind direction, while WSW in summer and winter. The trend of the wind direction of Deer Lake is moving to SW and SSW in summer. At Stephenville station, the dominate wind direction prevail from W and E. WSW is the dominate wind direction in summer, while E in spring. W and WNW are the dominate wind direction in winter. Recent years trend indicates that in summer the dominate wind direction prevail to WSW, while W in winter and ENE in spring.

Table 4.3. Air contaminants associated with HF and their effects.

STATION	STATION ID	PERIOD OF RECORD	LATITUDE (N)	LONGITUDE (W)	ELEVATION (M)
St. Anthony	718190	2010-2014	51.400	56.067	32.9
Corner Brook	717386	2011-2015	48.933	57.917	152.0
Rocky Harbour	715880	2010-2014	49.567	57.867	68.0
Deer Lake	718090	2010-2014	49.217	57.400	21.9
Stephenville Airport	718150	2010-2014*	48.533	58.550	25.0
Wreck house	711800	2010-2014	47.700	59.300	32.0
Port Aux Basques	711970	2011-2014	47.567	59.150	40.0

**Data for year 2011 and 2012 are unavailable.*

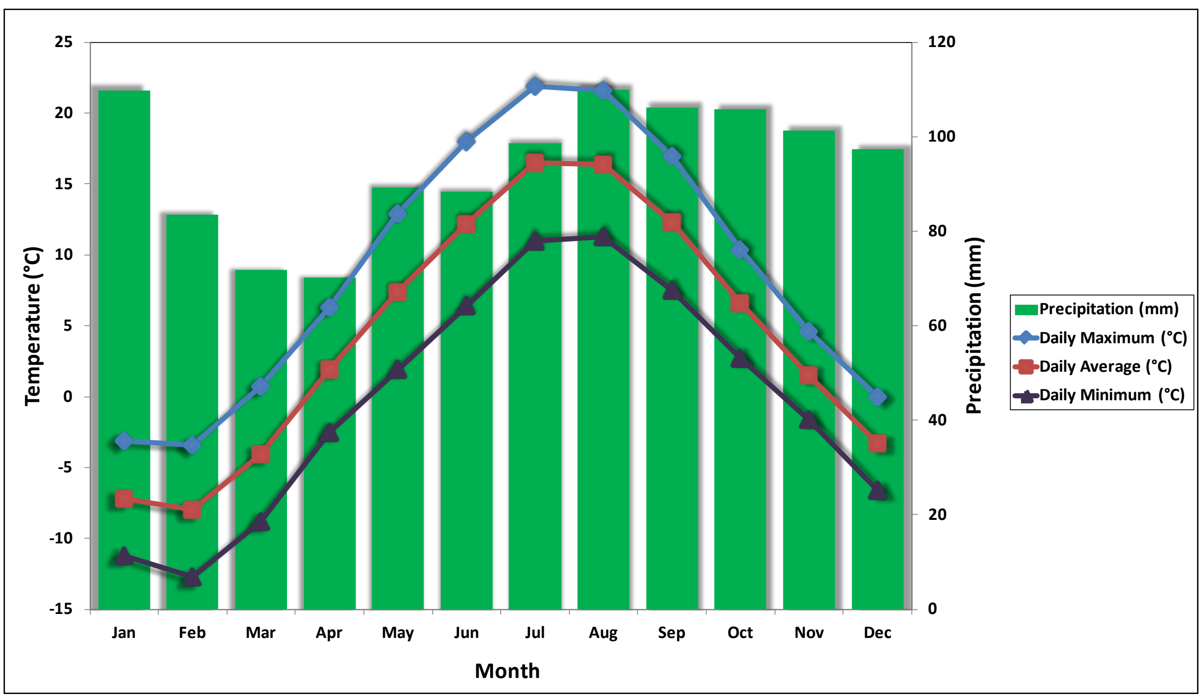

Figure 4.1. Temperature and Precipitation Chart for 1981 to 2010 at Deer Lake station (Weather Canada).

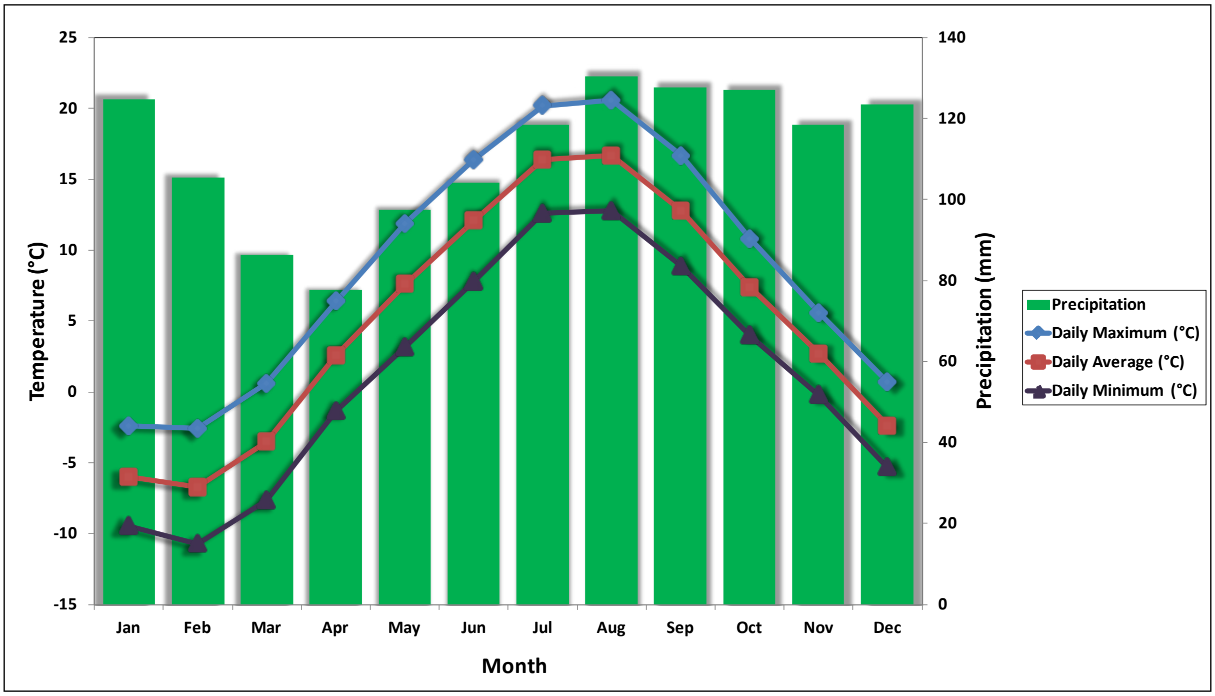

Figure 4.2. Temperature and Precipitation Chart for 1981 to 2010 at Stephenville airport (Weather Canada).

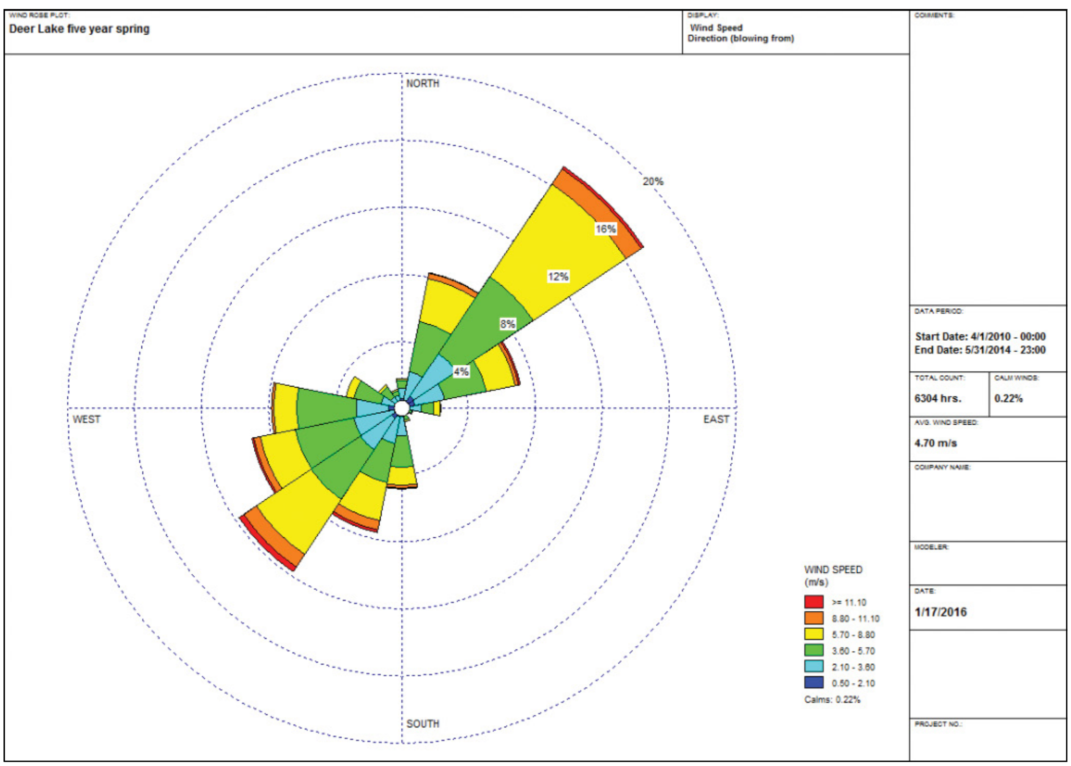

Figure 4.3. Five-year wind rose at Deer Lake meteorological station in spring.

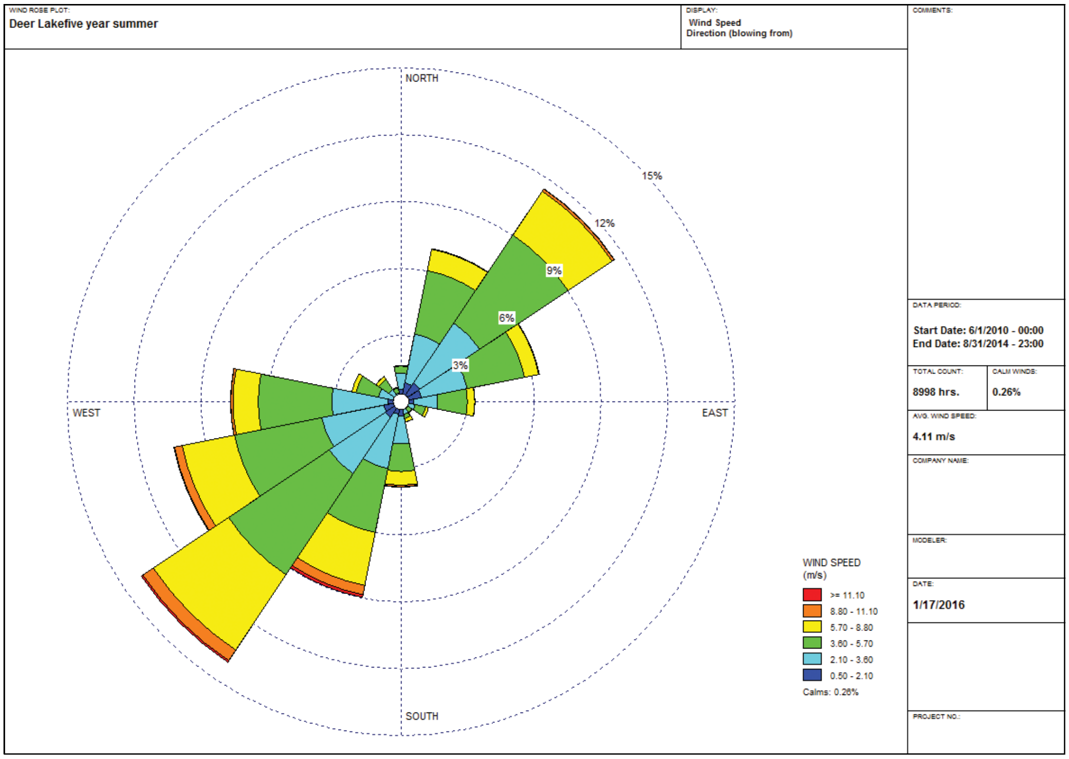

Figure 4.4. Five-year wind rose at Deer Lake meteorological station in summer.

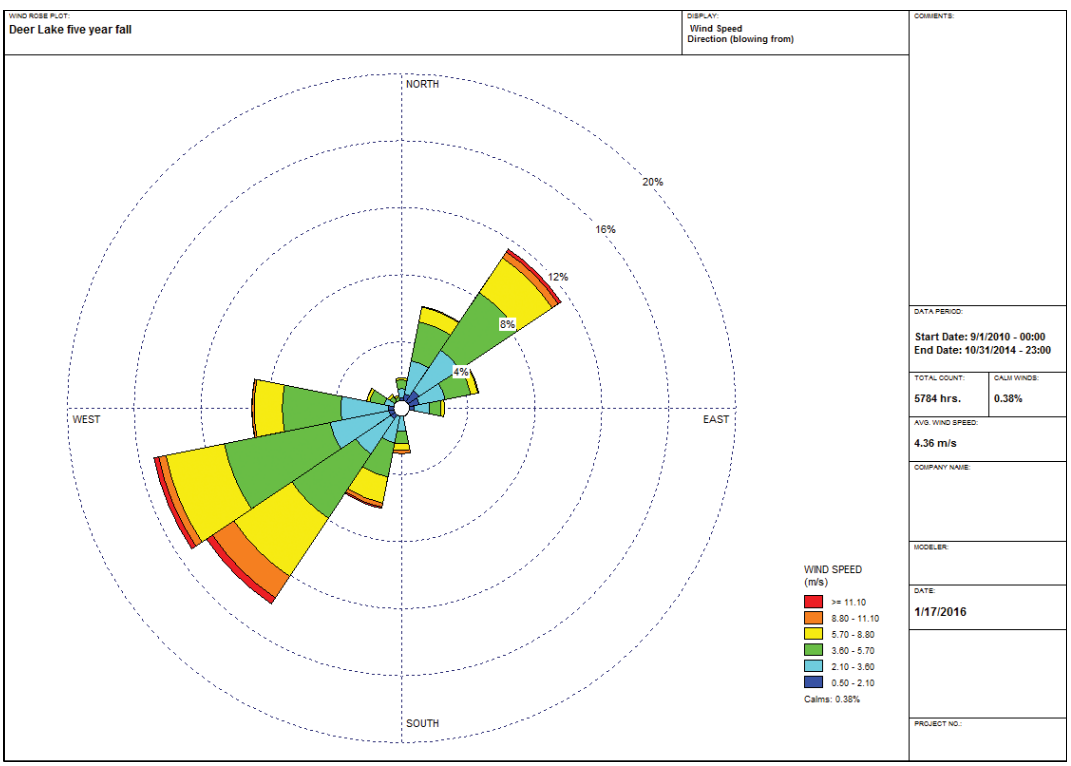

Figure 4.5. Five-year wind rose at Deer Lake meteorological station in fall.

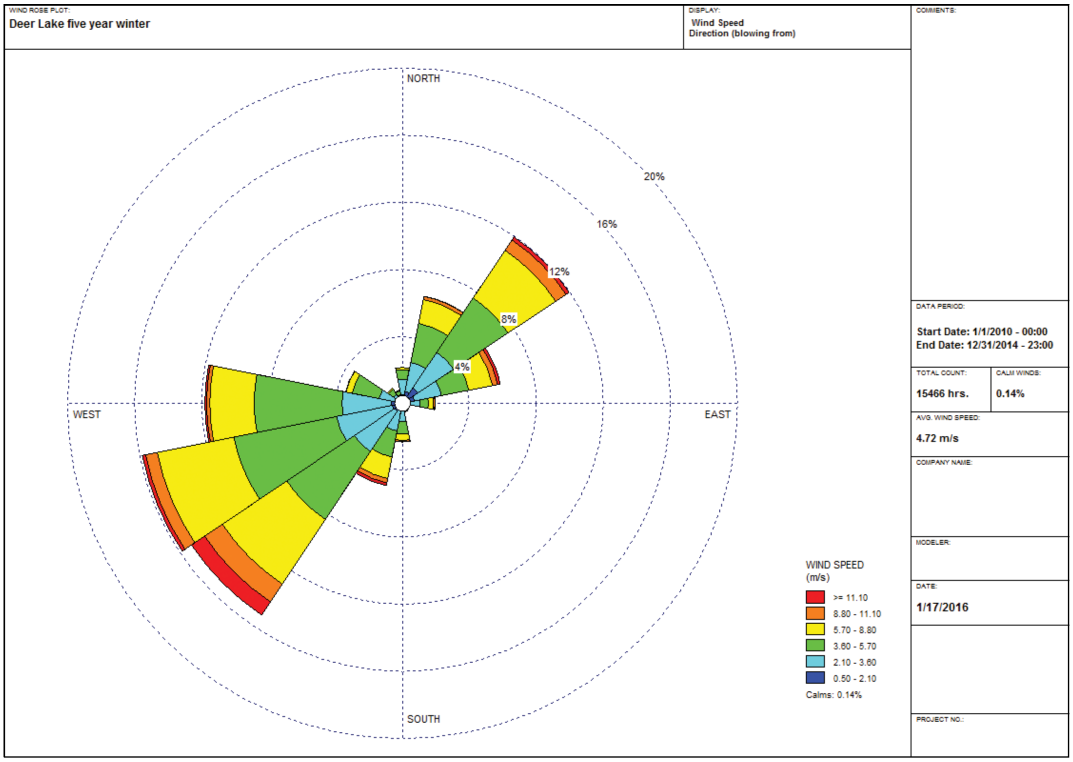

Figure 4.6. Five-year wind rose at Deer Lake meteorological station in winter.

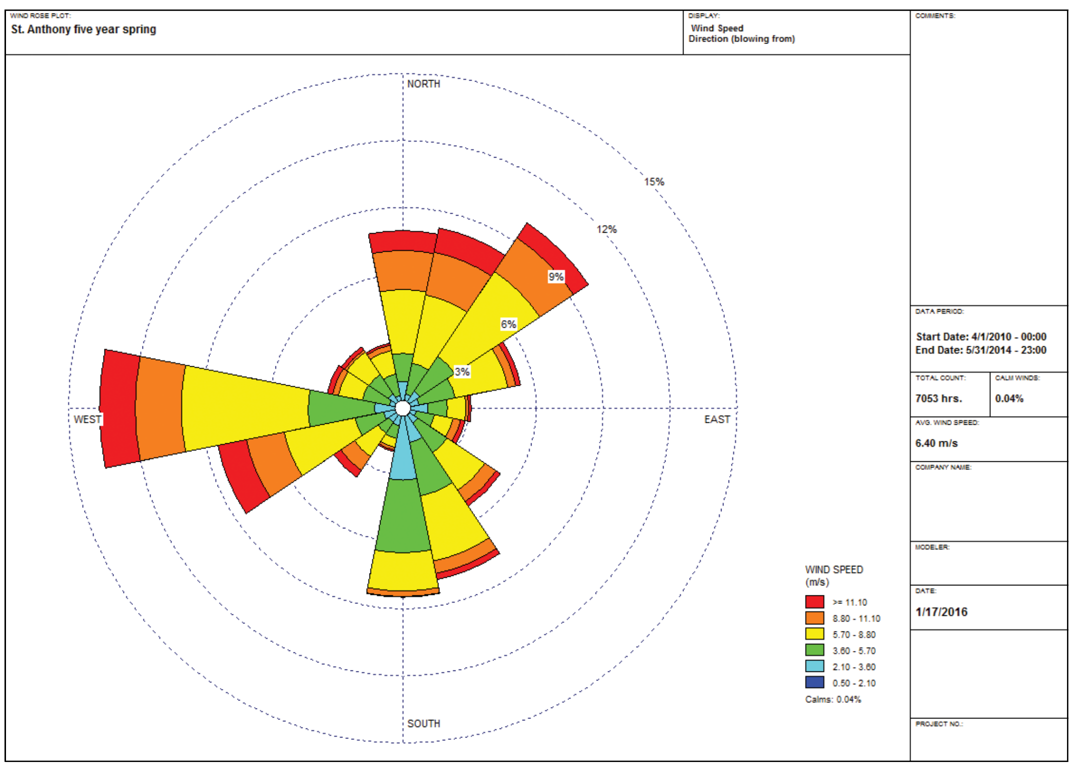

Figure 4.7. five-year wind rose of St. Anthony meteorological station in spring.

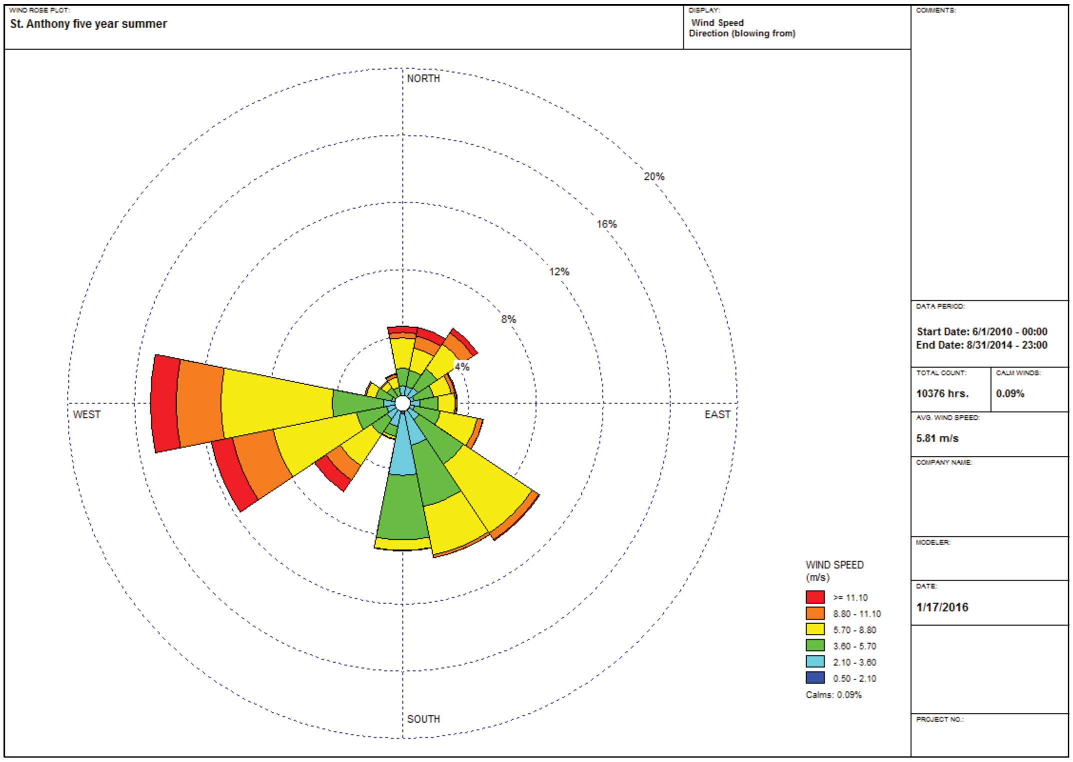

Figure 4.8. Five-year wind rose of St. Anthony meteorological station in summer.

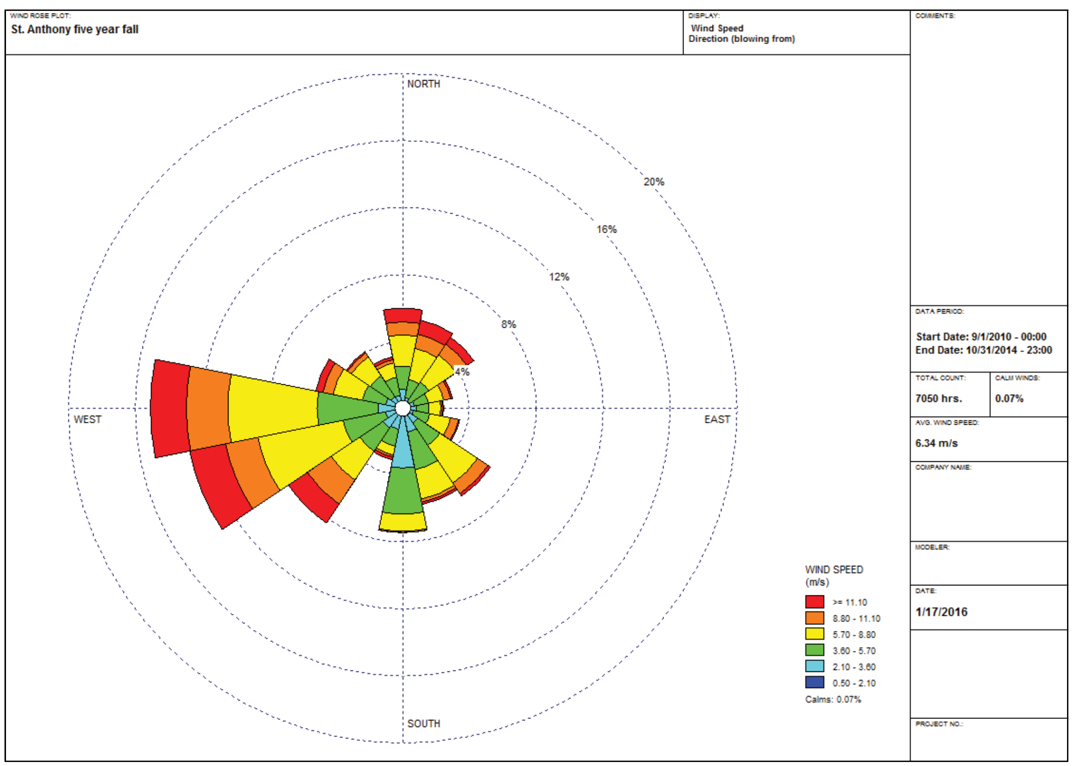

Figure 4.9. Five-year wind rose of St. Anthony meteorological station in fall.

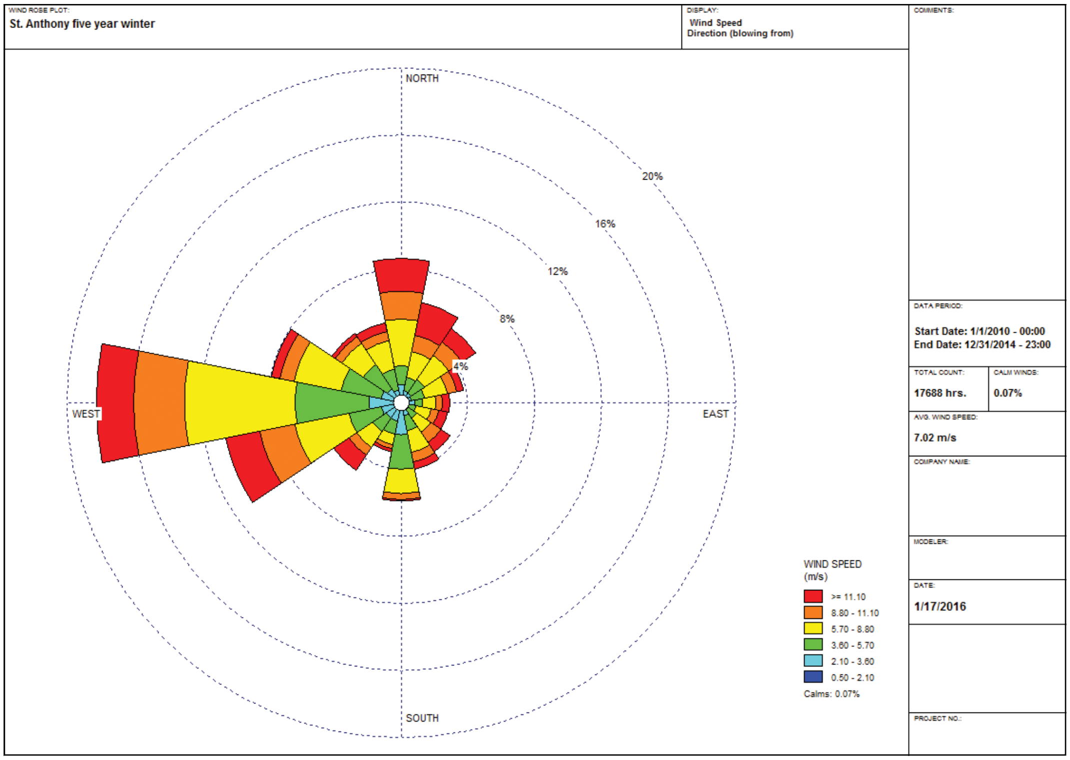

Figure 4.10. Five-year wind rose of St. Anthony meteorological station in winter.

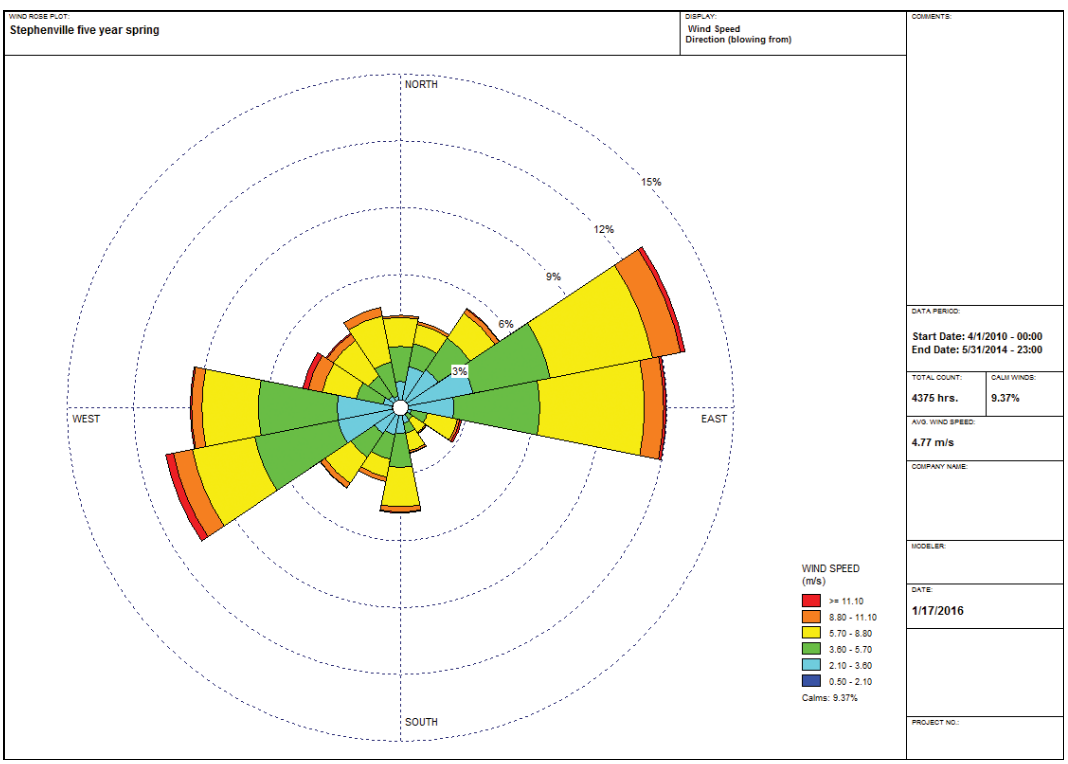

Figure 4.11. Five-year wind rose of Stephenville meteorological station in spring.

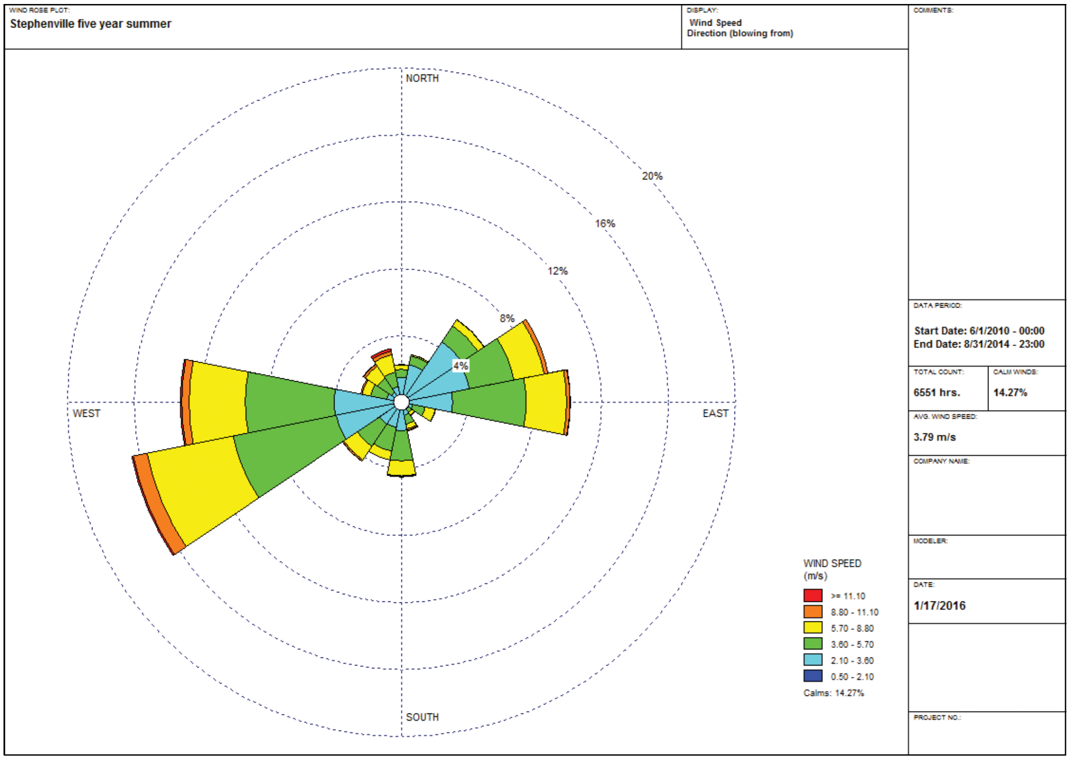

Figure 4.12. Five-year wind rose at Stephenville meteorological station summer.

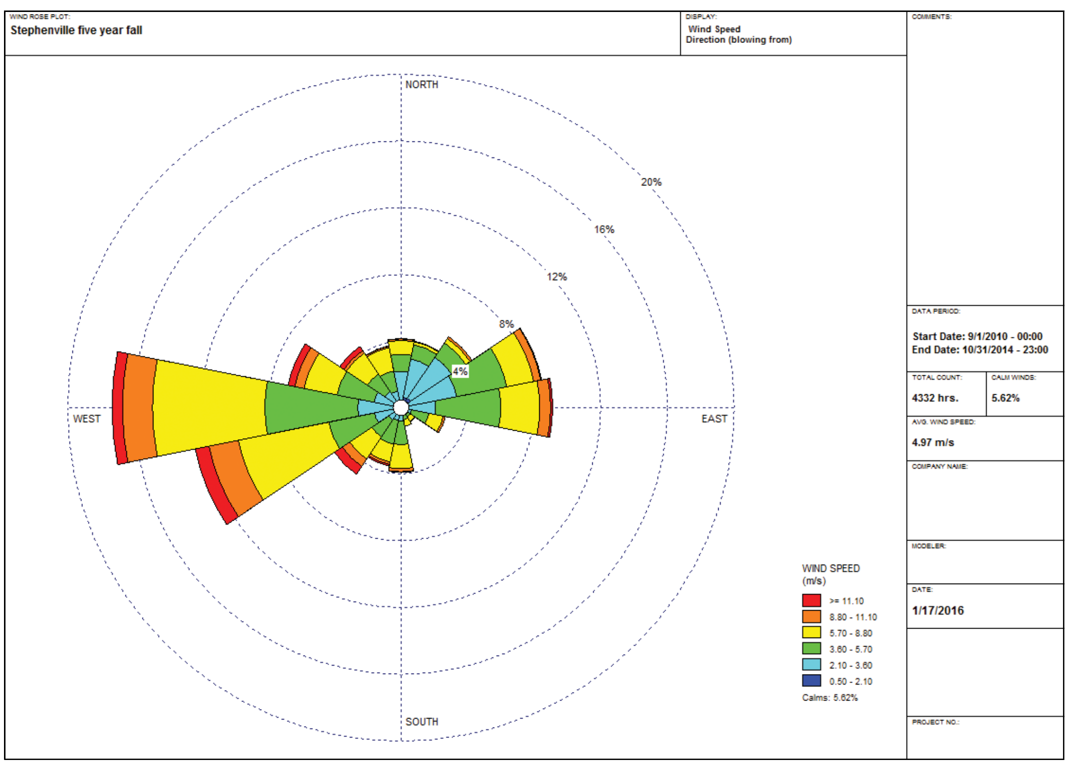

Figure 4.13. Five-year wind rose at Stephenville meteorological station fall.

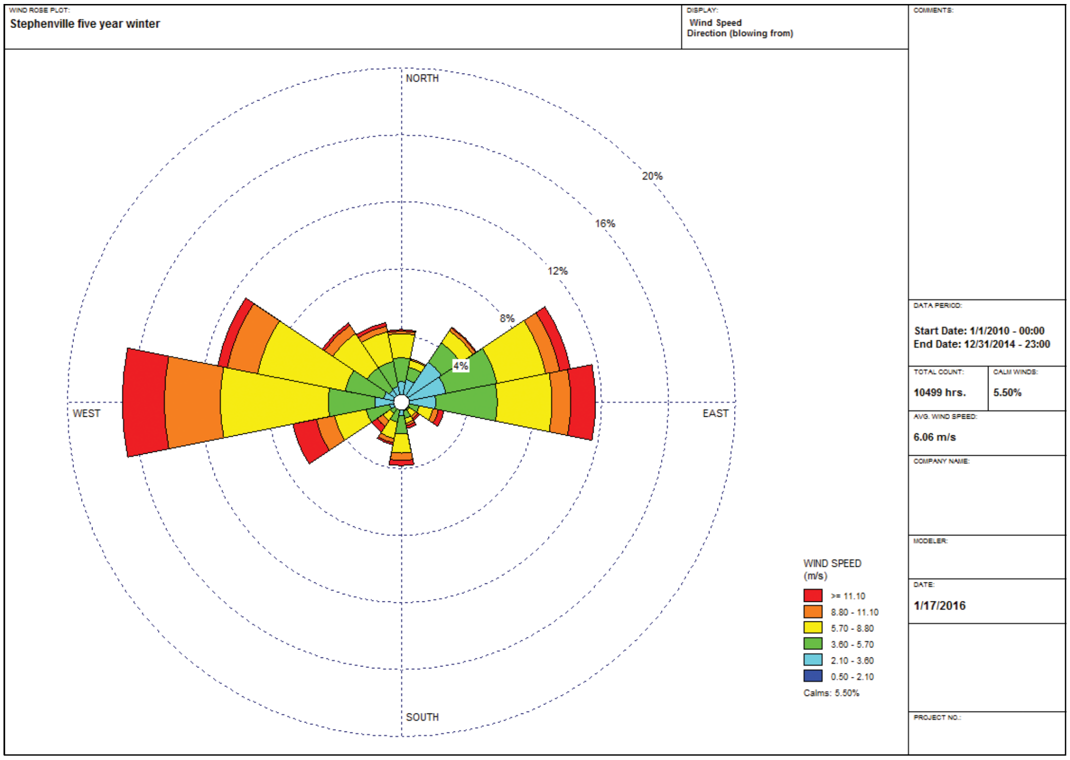

Figure 4.14. Five-year wind rose at Stephenville meteorological station in winter.

4.3.2 Dispersion Modelling

Dispersion Models

Several air dispersion models have been developed so far, however three main models are widely used, namely AERMOD (AERMOD, 2004), CALPUFF (Scire et al., 2000 a) and CMAQ (CMAS, 2015). AERMOD is a steady-state plume dispersion model designed to predict near field concentration of pollutants, while CALPUFF is a lagrangian Gaussian puff dispersion model for both near and far field applications. CMAQ is a 3D grid-based photochemical air quality model and it specialized in simulating O3 and photochemical oxidants. These models have been developed by US EPA and used as regulatory model for several purposes. CALPUFF is selected for modelling a hypothetical scenario in Western Newfoundland, as it is recommended model for all regulatory applications in NL (NL Guideline for Plume Dispersion Modelling, 2012).

Modelling Scenario

In order to study the extent of impact of air emissions, two hypothetical release scenarios are developed and modelled. Table 4.4 shows the drill rig emissions per well for criteria pollutants, HAPs, and GHG. The estimates are based on the following assumptions:

- It requires approximately 600 hours of operation (approximately 25 days at 24 hour/day).
- Drill rig horse power is 1, 500 hp
- Diesel fuel sulfur content 0.0005 % (EPA standard)
- AP-42 emission factors are used.

Table 4.4. Drill Rig Emissions Per Well of Criteria Pollutants and VOC (adopted from Drill Rig Emissions, 2012).

SPECIES	DRILLING RIG		
Criteria Pollutants & VOC	**Emission Factor**	**Per Well (lb/hr)**	**Per well (g/s)**
NO_x[a]	0.0152	9.12	1.1490
CO[a]	5.73E-03	3.44	0.4330
PM_{10}[a]	4.00E-04	0.24	0.0302
$PM_{2.5}$[b]	4.00E-04	0.24	0.0302
SO_2[b]	4.05E-06	2.43E-03	0.0003
VOC[a]	2.20E-03	1.32	0.396
HAPs			
Benzene[d]	5.82E-06	3.49E-03	1.05E-03
Toluene[d]	2.11E-06	1.26E-03	3.79E-04
Xylenes[d]	1.45E-06	8.69E-04	2.61E-04
Formaldehyde[d]	5.92E-07	3.55E-04	1.07E-04
Acetaldehyde[d]	1.89E-07	1.13E-04	3.40E-05
Acrolein[d]	5.91E-08	3.55E-05	1.06E-05
Naphthalene[e]	9.75E-07	5.85E-04	1.76E-04
Total PAH[e,f]	1.59E-06	9.54E-04	2.86E-04
Greenhouse Gases			
CO_2[b]	1.16	696	207
CH_4[b,c]	7.05E-04	0.423	0.127

[a] *Emission factors for Tier II non-road diesel engine emission standards from dieselnet.com (NOX, CO, VOC and PM) – Tier II emission standards are not set for VOC (listed as Hydrocarbons), so the Tier I Standard is used – Tier II or Tier I emission standards are not set for $PM_{2.5}$, so the PM_{10} emission factor is used*

[b] *AP-42 Volume I, Large Stationary Diesel Engines Tables 3.4.1 and 3.4.2 Diesel Fuel, 10/96. VOC emission factor represents total Hydrocarbon Emissions*

[c] *CH4 Emission Factor listed in notes of AP-42 Table 3.4.1 as 9% of Total Organic Compounds*

[d] *AP-42 Volume I, Large Stationary Diesel Engines Table 3.4.3*

[e] *AP-42 Volume I, Large Stationary Diesel Engines Table 3.4.4*

[f] *PAH (Polycyclic Aromatic Hydrocarbons) includes naphthalene and are a HAP because they are polycyclic organic matter (POM)*

The emissions from a single well activity is very low, however HF drilling are performed in large numbers for sustainable production. In US, over 13,000 wells are drilled per year.

Two modelling scenarios were undertaken in this report, one assuming 500 wells will be drilled per year in the Western Newfoundland (hereafter referred to as South-West NL run), and the second scenario assumed 80 wells per year in a small domain near Port au Port bay (hereafter referred to as Port au Port run). Table 4.5 illustrates the calculation of number of wells that needs to be drilled simultaneously. It is assumed that the drilling operations are executed only during summer months due to adverse weather conditions in other months.

Table 4.5. Calculation of number of wells to be drilled simultaneously.

ITEM	500 WELLS/YEAR	80 WELLS/YEAR
Number of wells to be drilled per year	500	80 wells
Number of days required per well	25	25 days
Total drilling days	500 x 25 = 12,500	80 x 25 = 2, 000
Available days for drilling (May, June, July, August, September)	150 days	150 days
Simultaneous drilling	12,500/150 ~ 83 wells	2,00/150 ~ 13 wells

Study Area and Modelling Domain

HF activities potentially could occur in entire Western Newfoundland, hence study must cover the geography of Western Newfoundland. Ideally the area should be divided into at least 3 domains, size of each should be suitable to study the impacts on nearby cities and towns as shown in Figure 4.15. Further, small areas of interest may be selected and fine resolution modelling could be done to study the local impacts of the air pollutants.

Due to limitation of resources and time, southern most domain (Domain 3) and the smaller domain (Domain 4) are selected for performing this modeling study and the pollutants modelled were PM_{10}, $PM_{2.5}$, NO_x CO and SO_2. However similar study must be done for other domains and pollutants.

The meteorological South-West domain was 130 km x 130 km with a resolution of 4 km as shown in Figure 4.16. This domain was scaled down to 17.5 km x 17.5 near Port au port with a resolution of 500 m to study the local impacts in the area as shown in Figure 4.17.

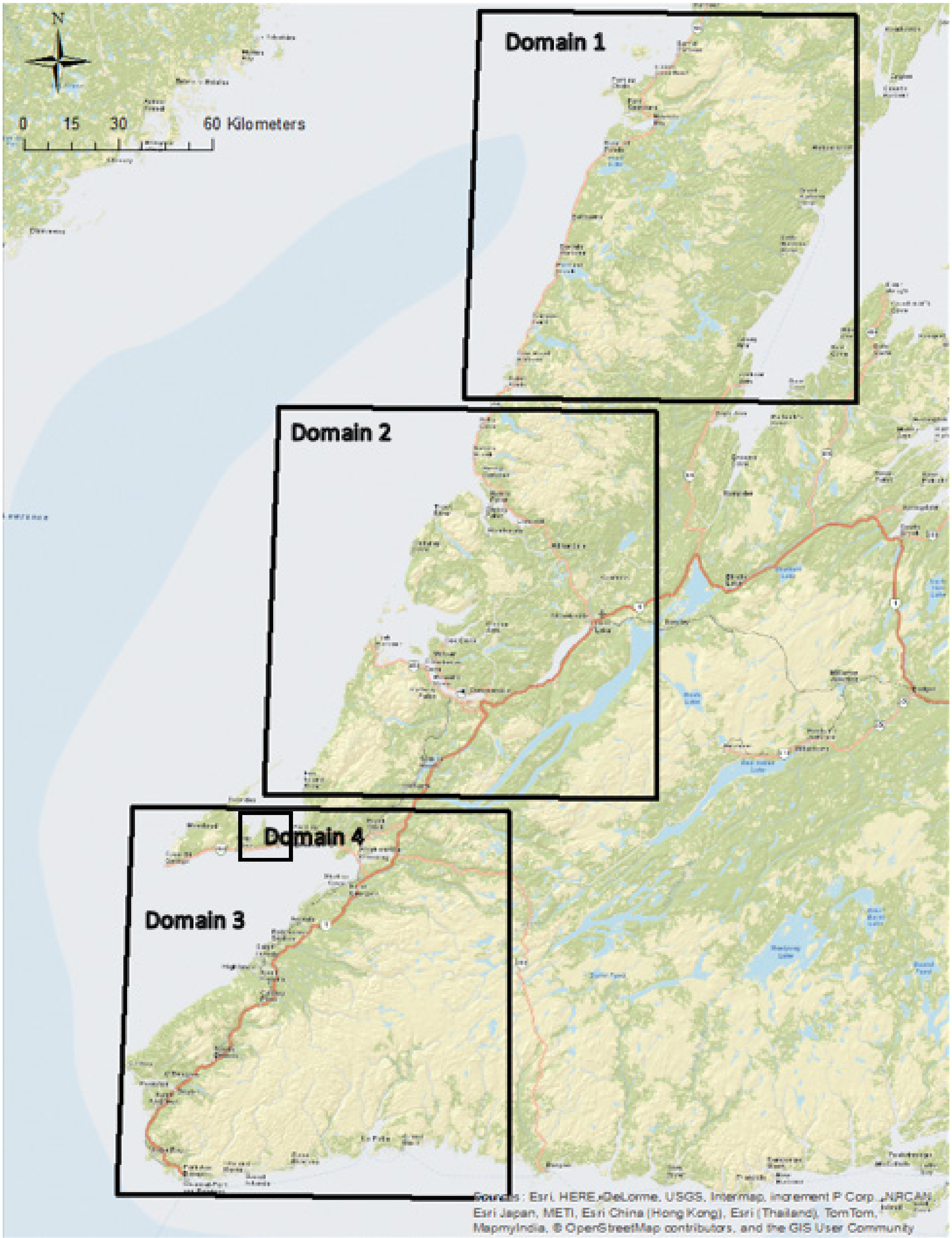

Figure 4.15. Domains for air quality modelling in Western Newfoundland.

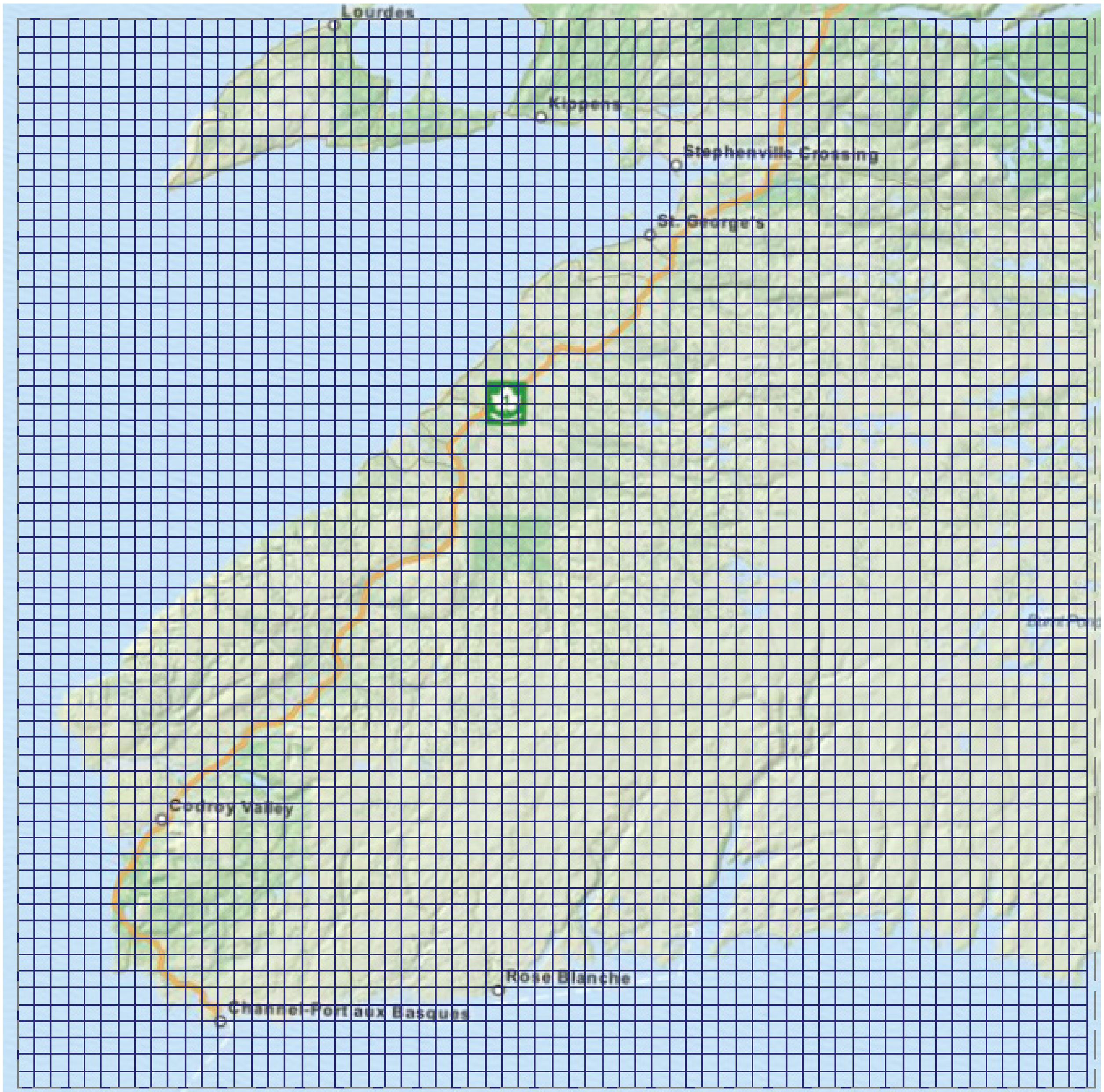

Figure 4.16. Meteorological grid in the South-West NL domain for dispersion modelling.

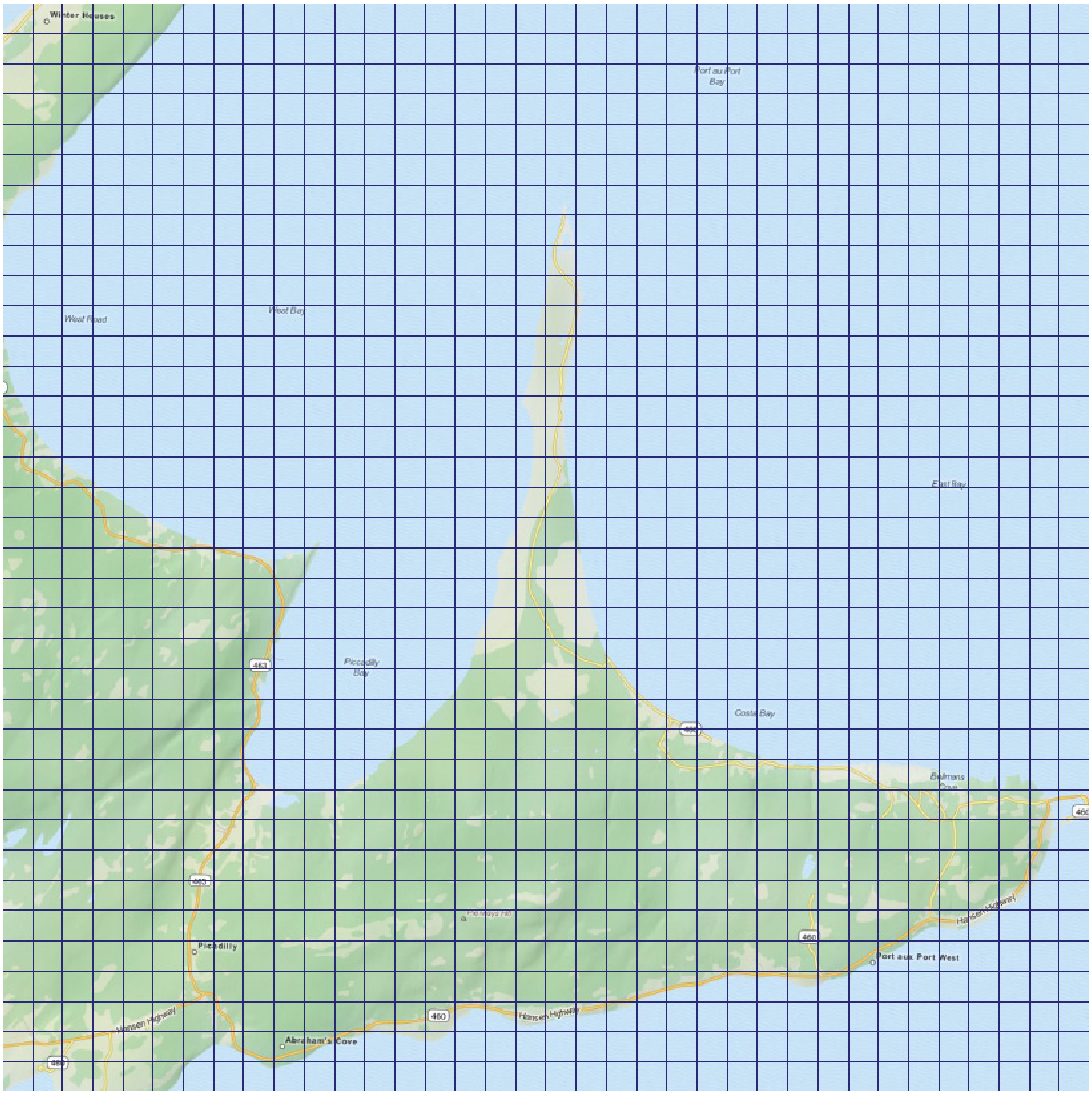

Figure 4.17. Meteorological grid in the Port au Port domain for dispersion modelling.

Meteorological Modelling

The CALPUFF simulation model requires meteorological data to represent the transport and dispersion of pollutants in the domain. The meteorological characteristics over the domain vary both spatially and temporally. The CALMET diagnostic model was used to provide CALPUFF model the spatial and temporal meteorological parameters. The WRF prognostic meteorological model was used to generate input for CALMET as described briefly in the following sections.

CALMET Ready WRF Data

WRF version 3.4.1 (next-generation mesoscale model) is a prognostic meteorology model developed in partnership by the National Center for Atmospheric Research, the National Oceanic and Atmospheric Administration, the Air Force Weather Agency, the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration. The model is a hydrostatic, terrain-following, eta-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation. WRF was primarily developed using FORTRAN coding, is used as a community model in over 150 countries and is updated on an annual basis. For the current simulation, CALMET ready files were obtained from Lakes Environmental[2] based on the WRF model for 2014 with horizontal resolution of 4 km.

CALMET

CALMET is a diagnostic meteorological model that produces 3-D wind fields based on parameterized treatments of terrain effects such as slope flows, terrain blocking effects, and kinematic effects. Using available sources of meteorological and geophysical information it produces a spatially varying wind field that is consistent with the local terrain and land use features, as well as atmospheric stability conditions and mixing height values necessary for the dispersion modeling.

The domain size configured in CALMET for South-West run was 128 km x 128 km, slightly less than WRF domain. The horizontal domain was downscaled to 2 km to study the dispersion of pollutants in detail. It consisted of 64 x 64 grid cells with a Universal Transverse Mercator (UTM) map projection of 21N and datum of WGS-84. Similarly for Port au port run, the domain was 17.5 km x 17.5 km with a resolution of 500m and 36 x 36 grid cells.

In order to properly simulate pollutant transport and dispersion, it is important to define the vertical profile of meteorological parameters such as wind speed, temperature, turbulence intensity and wind direction with the atmospheric boundary layer. Eleven vertical levels are centred at 10, 30, 60, 120, 240, 480, 820, 1250, 1850, 2600, and 3500 meters above the ground. The cell face heights corresponding to these grid points are 0, 20, 40, 80, 160, 320, 640, 1000, 1500, 2200, 3000 and 4000 meters.

The resolution of terrain and land use data used in the modelling were 23 meters and 25 meters respectively. The source of terrain data was from Canada Digital Elevation Data (CDED, 1999) and the source of land use was Earth Observation for Sustainable development (EOSD, 2003). Figures 4.18 to Figure 4.21 illustrates the variation of terrain and land use in both domains.

CALMET derived wind rose diagram during summer 2014 at the center of domain at an elevation of 10 m is shown in Figure 4.22 and Figure 4.23 for South-West and Port au Port domain respectively.

As observed from the Figure 4.22, winds in South-West were either blowing from south-east or north-west, however were predominant from south-east. The wind speed was most of the time in the range of 5-8 m/s with about 1% calm conditions. This shows that the pollutants are expected to disperse in all direction with a higher tendency to move towards north-west.

2 www.weblakes.com/

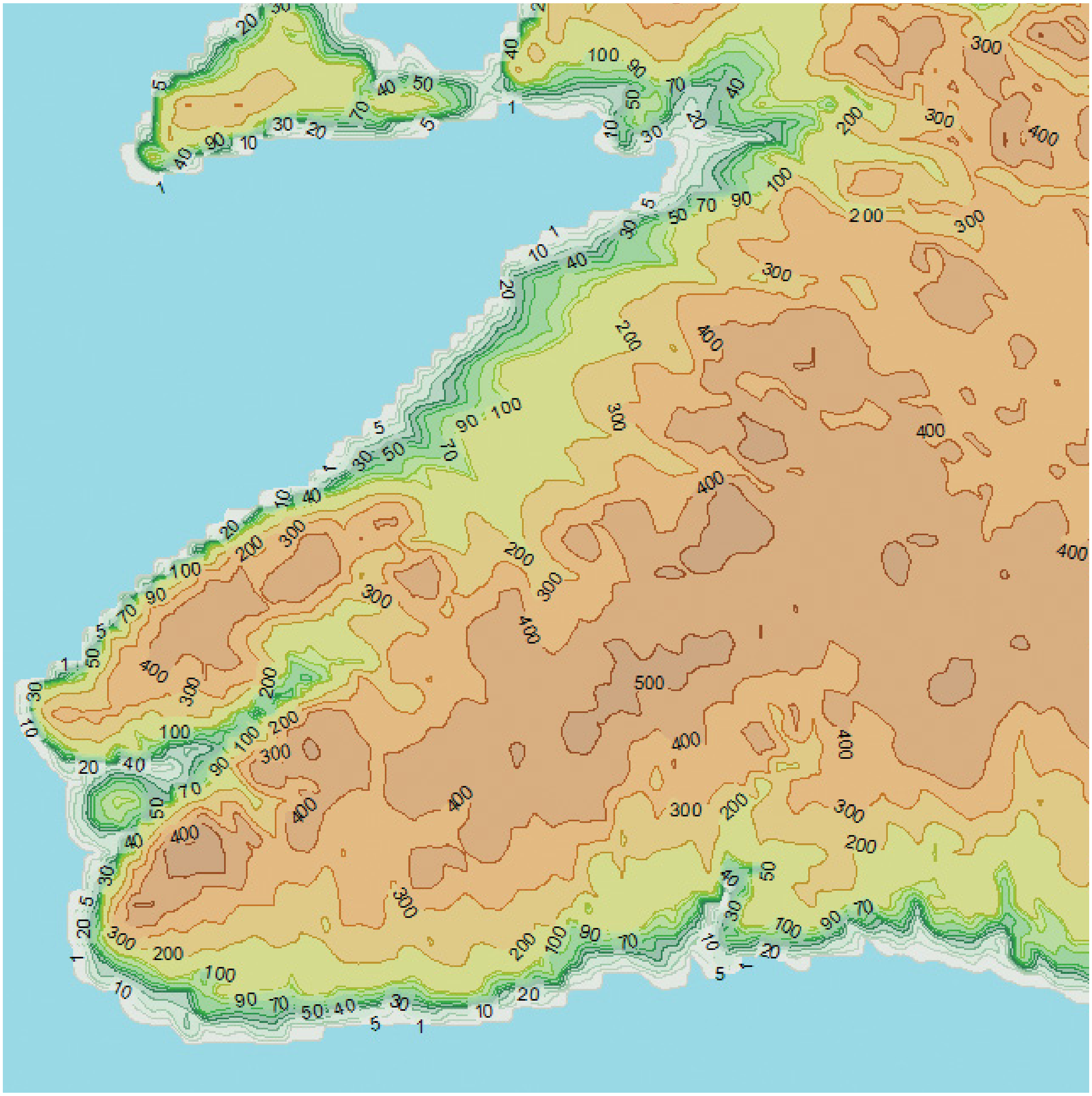

Figure 4.18. Terrain elevations in South-West domain.

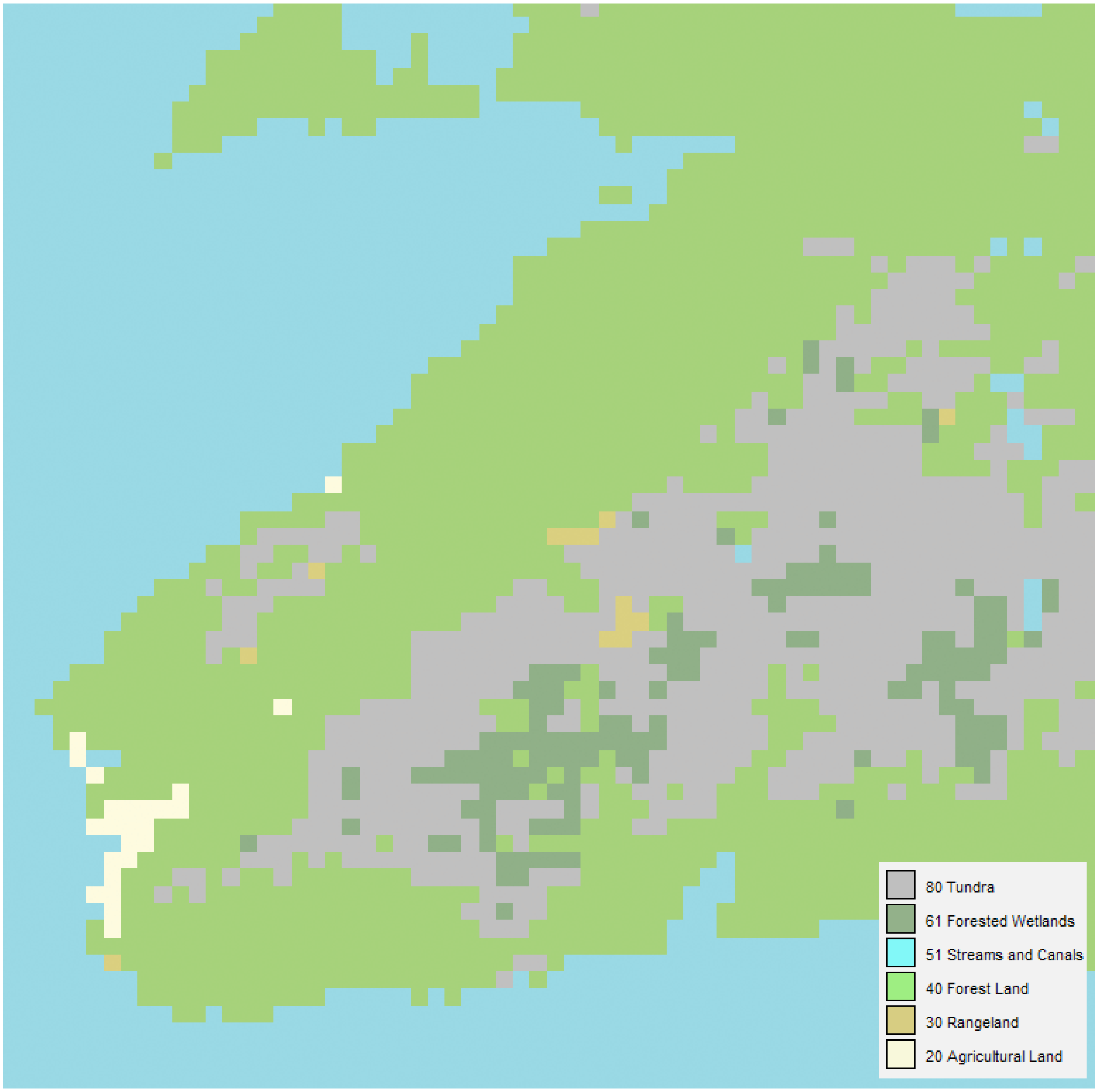

Figure 4.19. Land use map of the South-West domain.

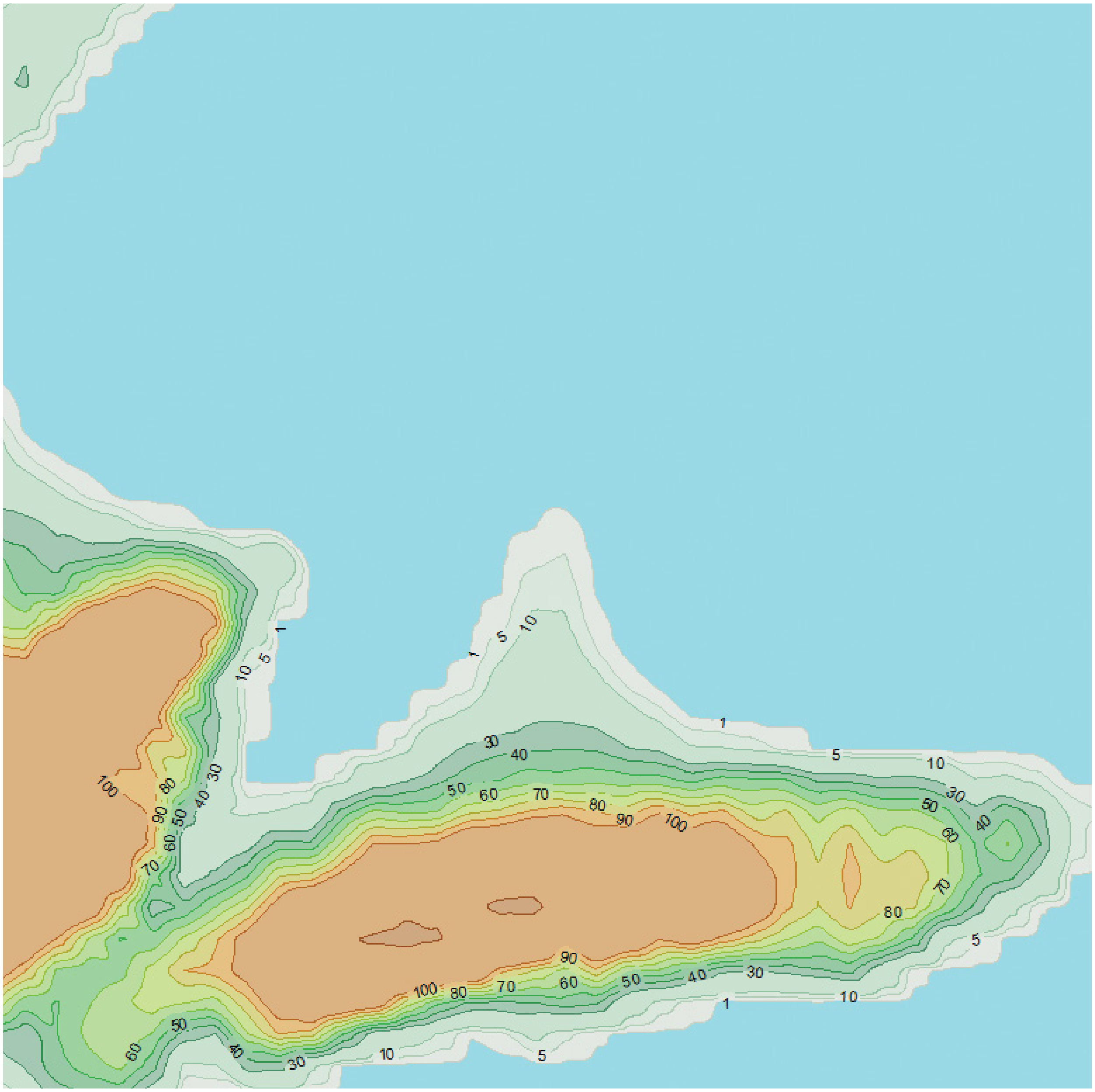

Figure 4.20. Terrain elevations in the Port au Port domain.

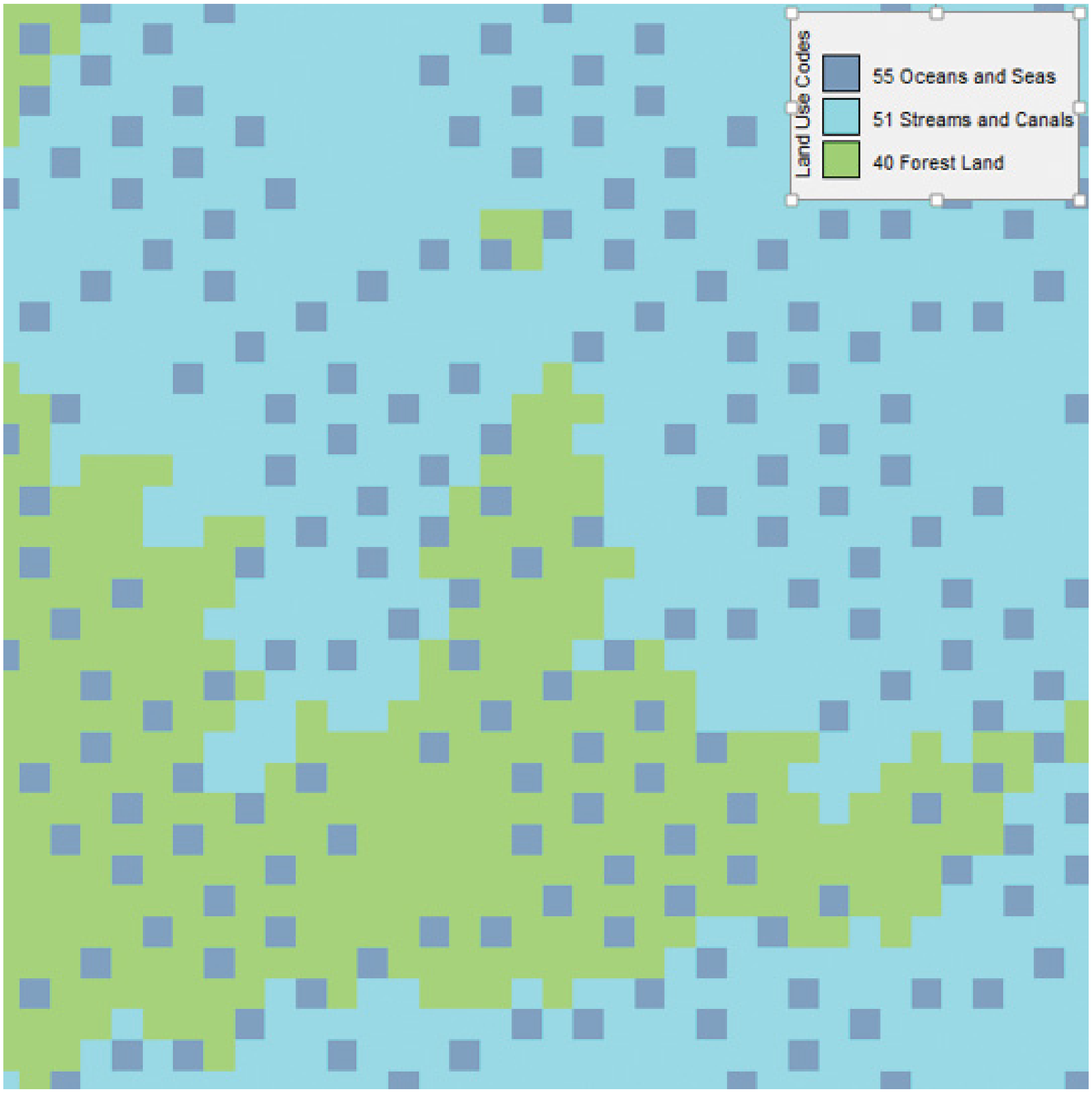

Figure 4.21. Land use map of the Port au Port domain.

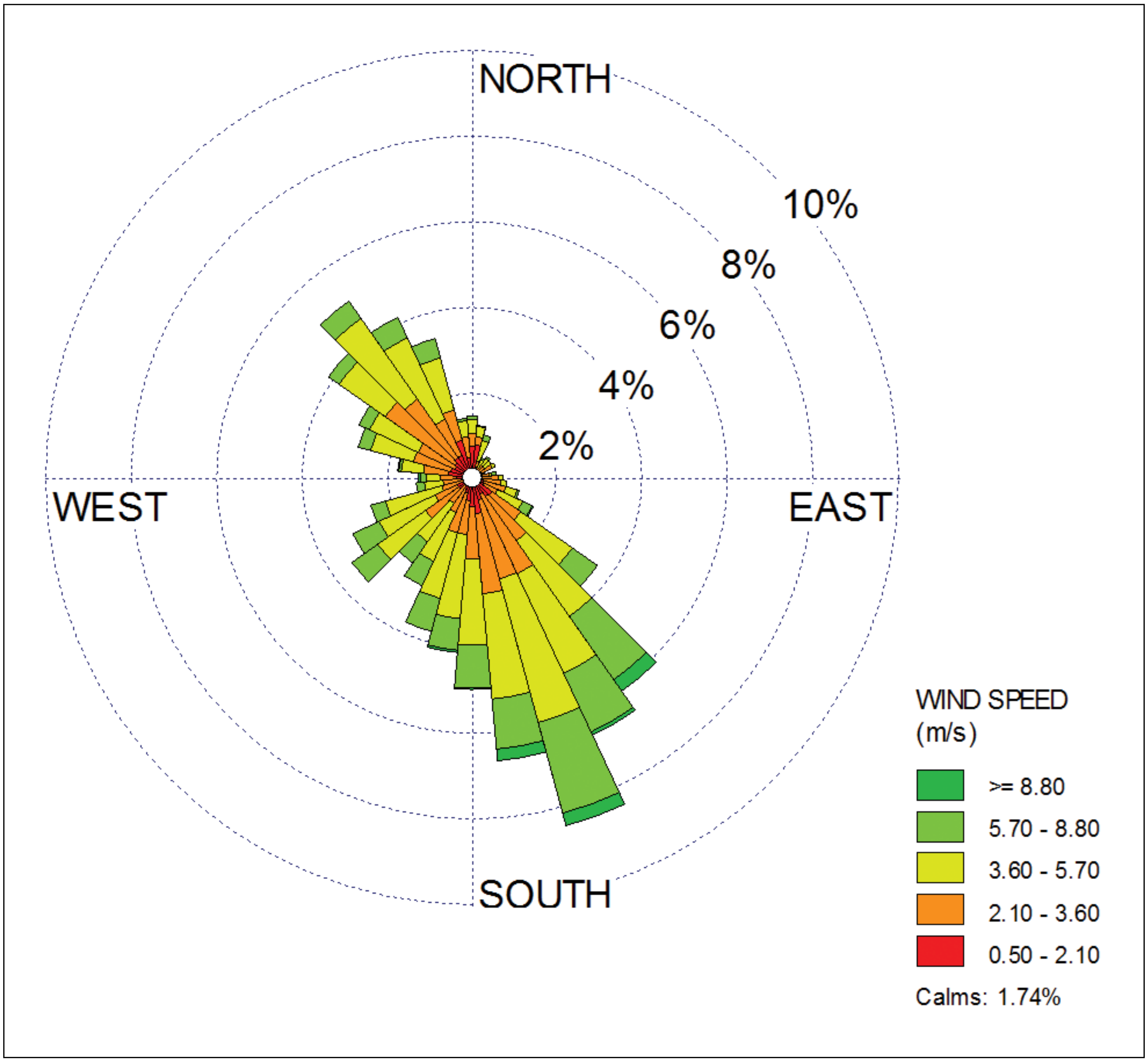

Figure 4.22. CALMET derived wind rose at 10 m elevation at the center of the South-West domain in summer 2014 (winds directions are blowing from).

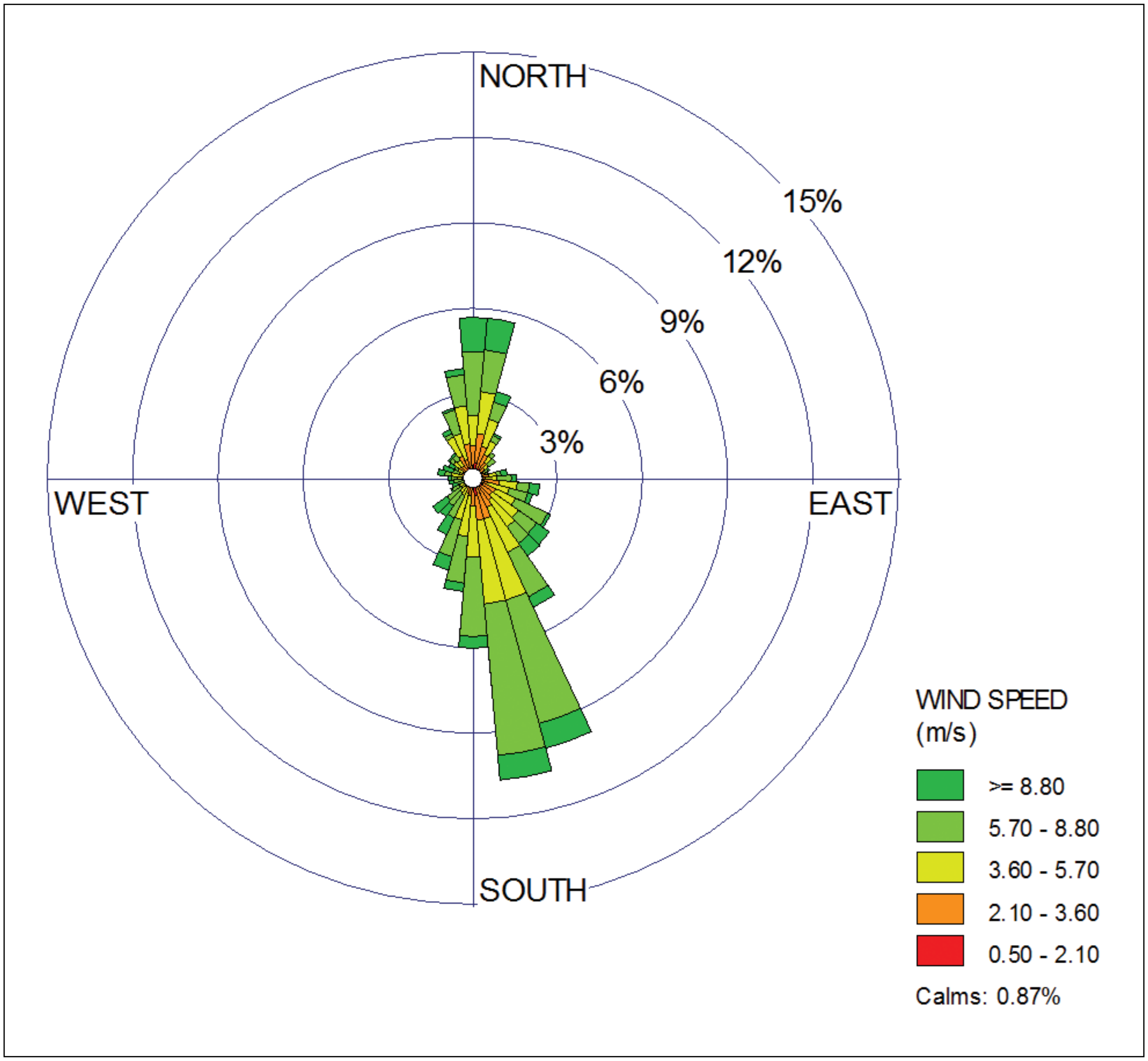

Figure 4.23. CALMET derived wind rose at 10 m elevation at the center of the Port au Port domain in summer 2014 (winds directions are blowing from).

CALPUFF Modelling

In this modelling study, the CALPUFF simulations were conducted using the following model options:

- Gaussian near-field distribution;
- Transitional plume rise;
- Stack tip downwash;
- Turbulence based dispersion coefficients;
- Transition of σy to time-dependent (Heffter) growth rate;
- Partial plume path adjustment for terrain;
- Modeling of dry deposition;
- Consideration of chemical transformations and;
- No consideration of wet deposition.

CALPUFF View™, the Lakes Environmental graphical user interface was used to process the input and output. CALPUFF Version 7 was applied on five months (May-Sep) CALMET data. Continuous release of five criteria pollutants from 81 wells for five months was assumed. For the South-West run, the wells were assumed to be in the middle of the domain as shown in Figure 4.24, while wells are scattered over the coastline for Port au Port run as shown in Figure 4.25. The CALPUFF computational grid was same as CALMET, species modelled for both runs were NO_x, CO, PM_{10}, $PM_{2.5}$, and SO_2.

The input emissions are provided to CALPUFF by variable point emission sources files, these are prepared by specialized processors in the format PTMAERB. The format is defined in the CALPUFF user guide (Scire et al., 2000 a).

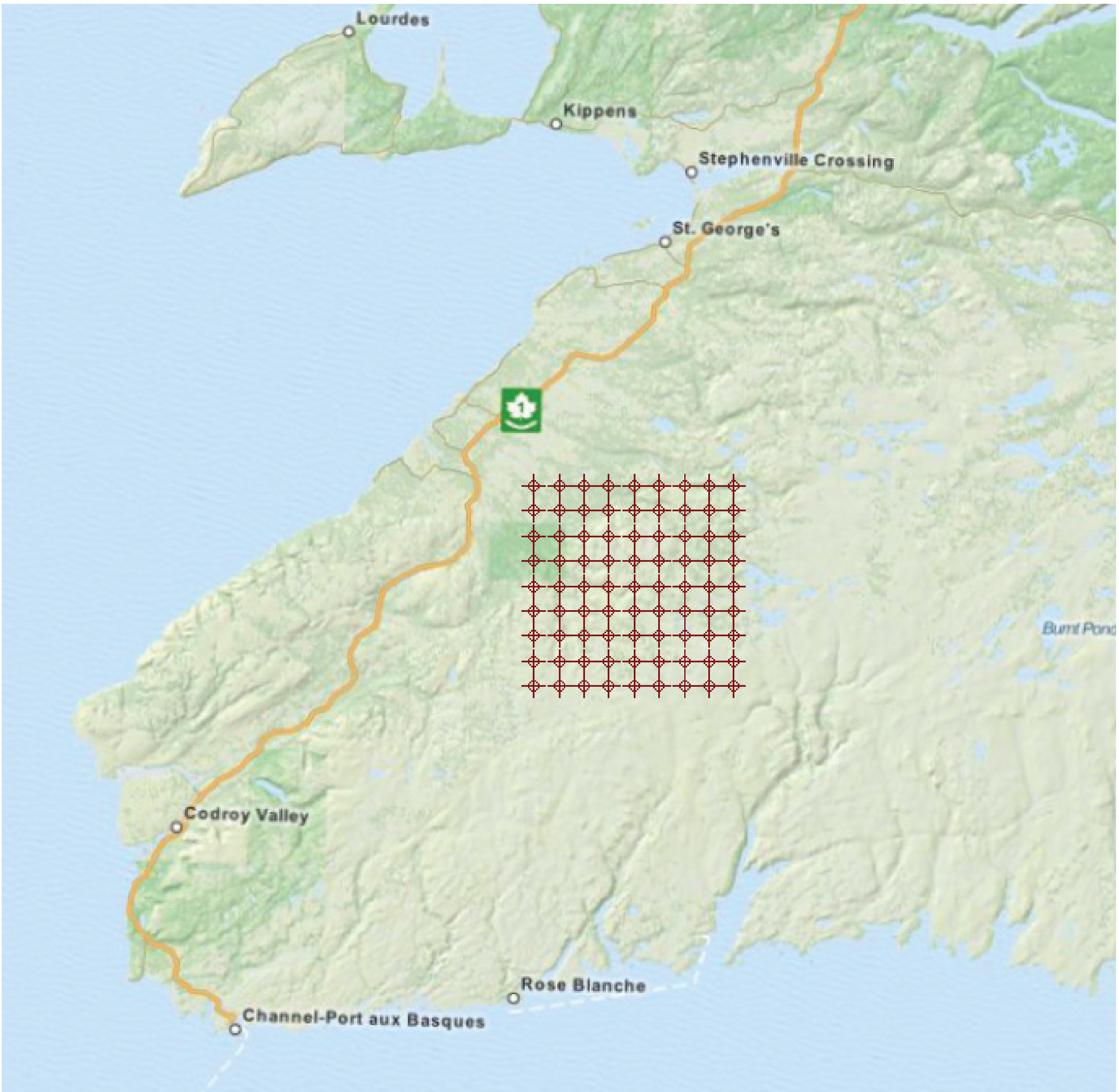

Figure 4.24. HF drilling locations placed in center of domain for South-West run.

Figure 4.25. HF drilling locations in Port au Port run.

Dispersion Results

The results of South-West and Port au Port runs are summarized in Table 4.6. The peak concentrations in the domain are compared with NL ambient air quality standards. The peak concentrations of all the pollutants are within the standards, however NO_2 shows significant high values. The peak concentrations of NO_2 were 168.71 µg/m^3 and 115.15 µg/m^3 for the South-West and Port au Port runs respectively. Due to highly varying winds the pollutants dispersed in all directions. The location of peak for the Port au Port run was towards south near the peninsula, while the peak for South-West run were in the vicinity of the assumed drilling location in the center of the domain. The spatial variation of the pollutants are presented as contour plots. Figures 4.26 to 4.39 shows contours plots for modelled pollutants for different averaging times.

Table 4.6. Modelled peak concentrations of criteria pollutants.

	NL Air Quality Standard (µg/m³)	Peak Concentration (µg/m³)	
		South-West Run[1]	Port au Port Run[2]
NO_2			
1-hour	400	168.71	115.15
24-hour	200	13.76	12.81
Annual	100	2.59*	1.92*
PM_{10}			
24-Hour	50	0.37	0.36
Annual		0.07*	0.05*
$PM_{2.5}$			
24-hour	25	0.37	0.36
Annual	-	0.07*	0.05*
CO			
1-hour	35,000	64.51	42.04
8-hour	15,000	14.56	8.63
SO_2			
1-hour	900	0.04	0.02
24-hour	300	0.004	0.003
Annual	60	0.0006*	0.0005*

[1] *Based on drilling 500 wells/year (81 simultaneous) spread over western NL domain (300 km x 300 km)*

[2] *Based on drilling 80 wells/year (15 simultaneous) spread in Port au Port bay domain (17.5 km 17.5 km)*

* *Values are run length average (5 months)*

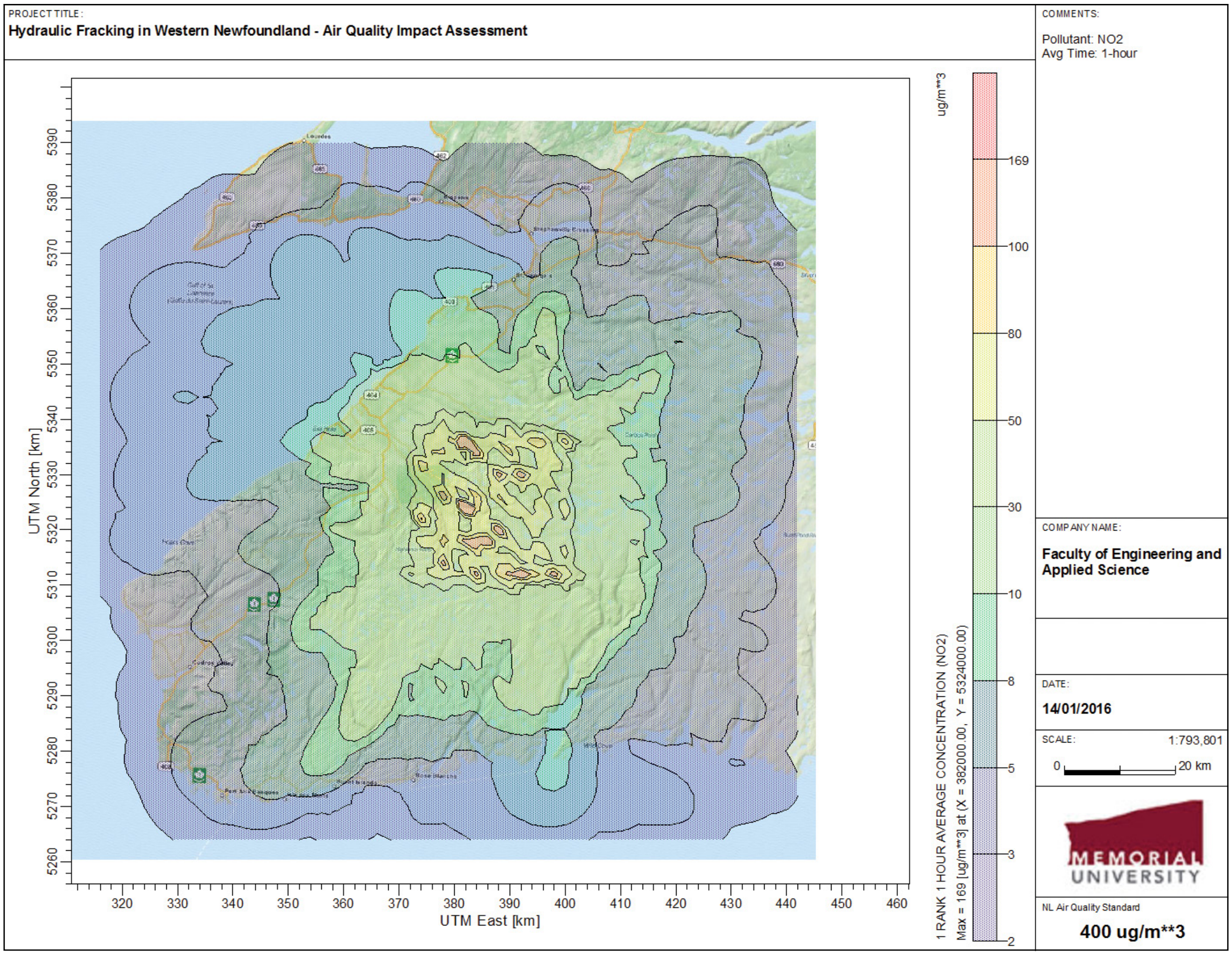

Figure 4.26. South-West Run: Peak 1-hour average NO_2 concentrations.

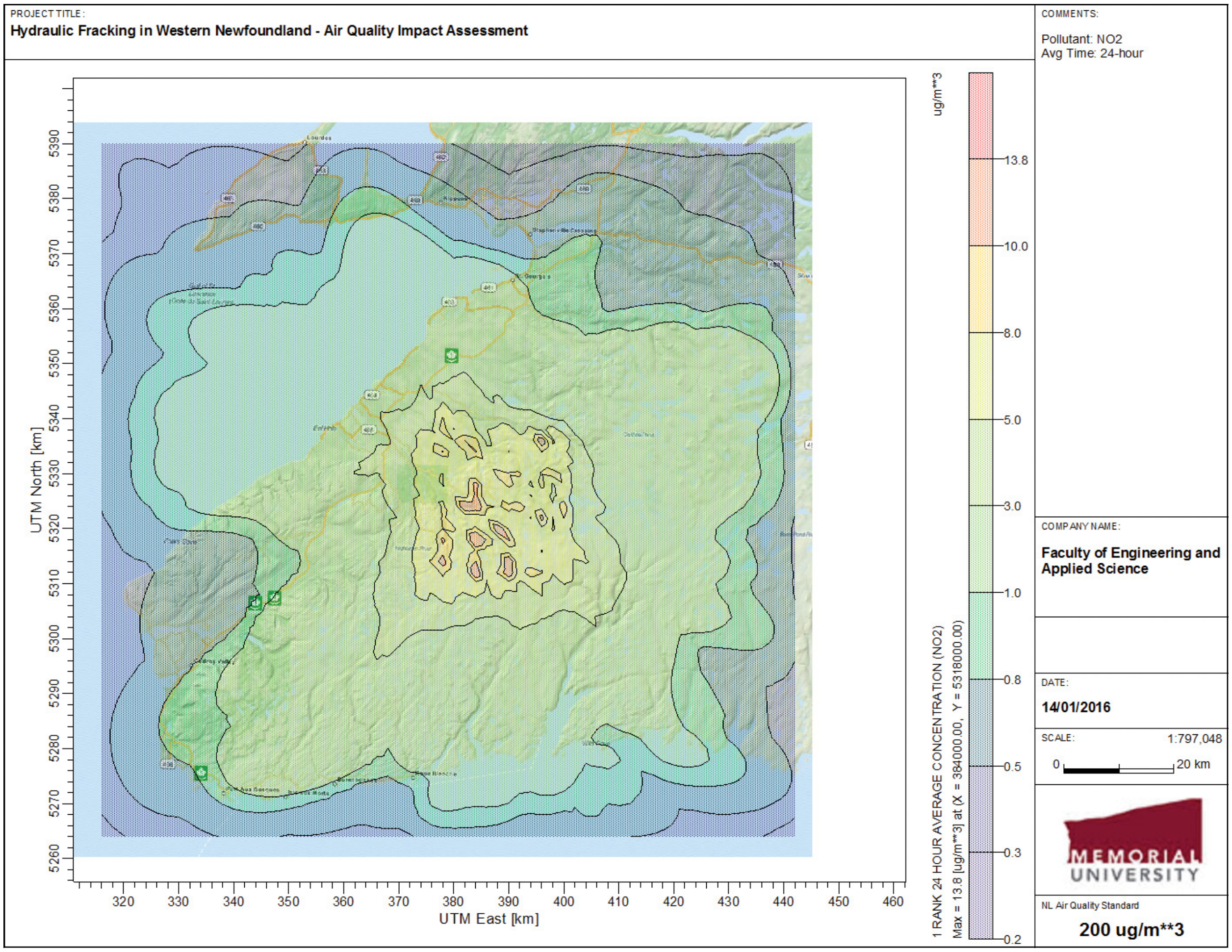

Figure 4.27. South-West Run: Peak 24-hour average NO_2 concentrations.

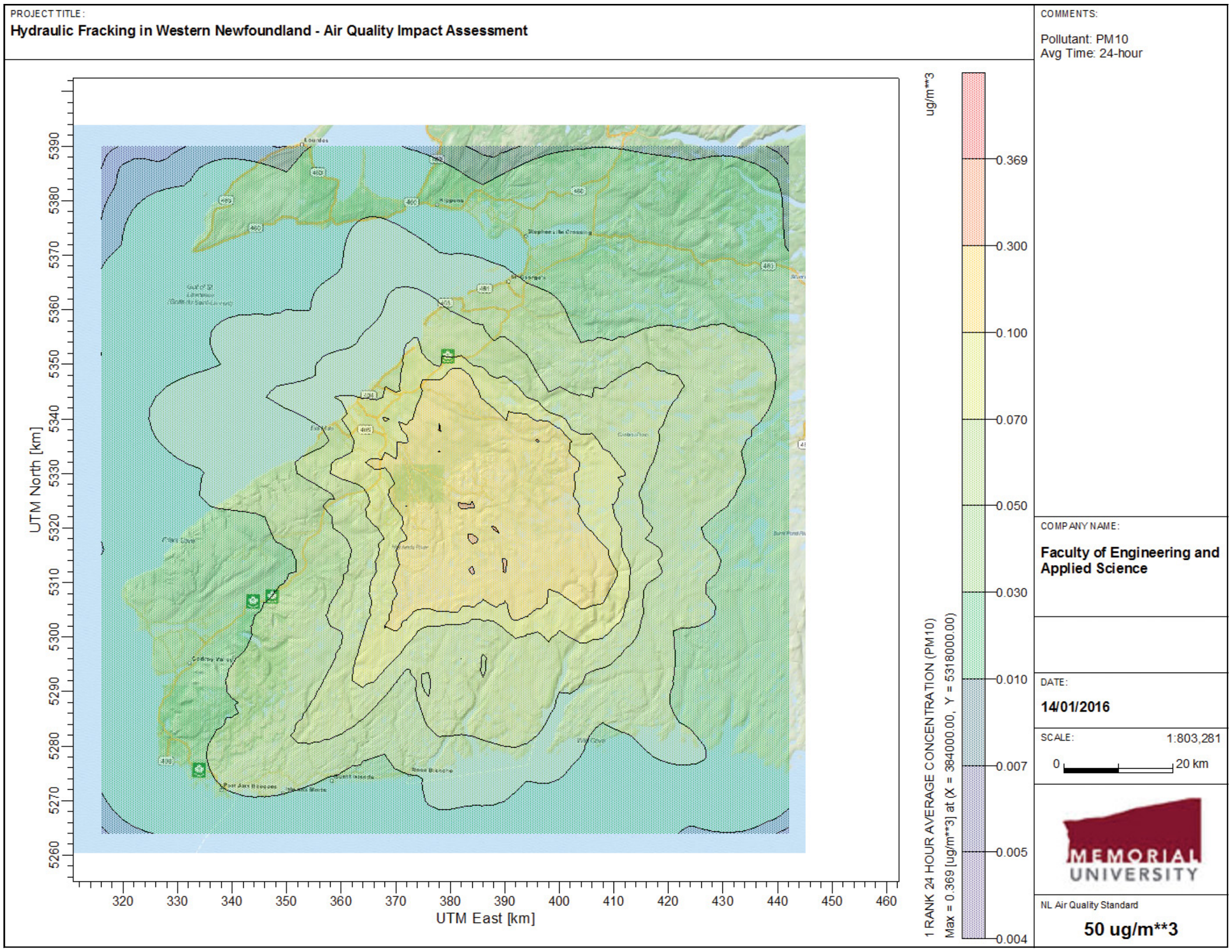

Figure 4.28. South-West Run: Peak 24-hour average PM_{10} concentrations.

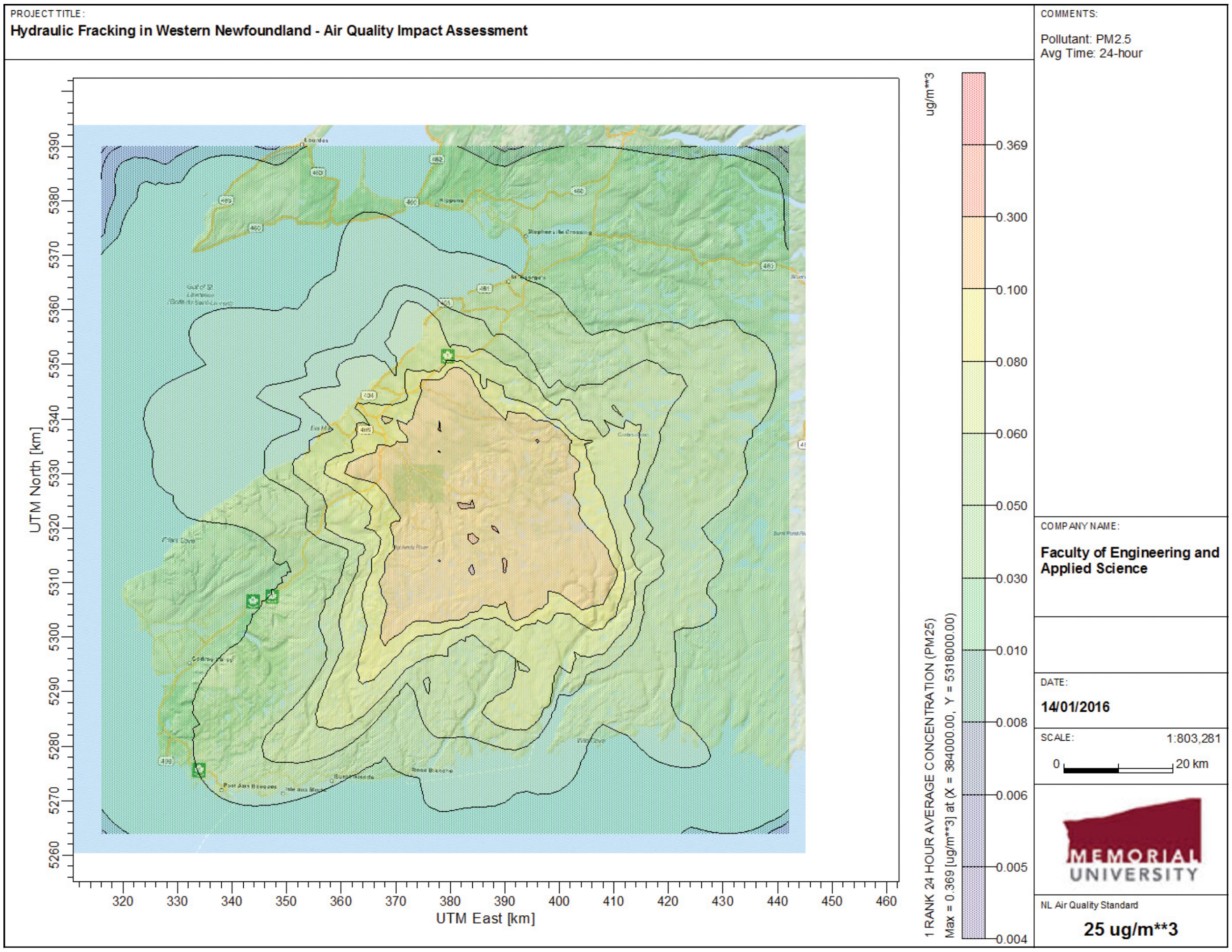

Figure 4.29. South-West Run: Peak 24-hour average $PM_{2.5}$ concentrations.

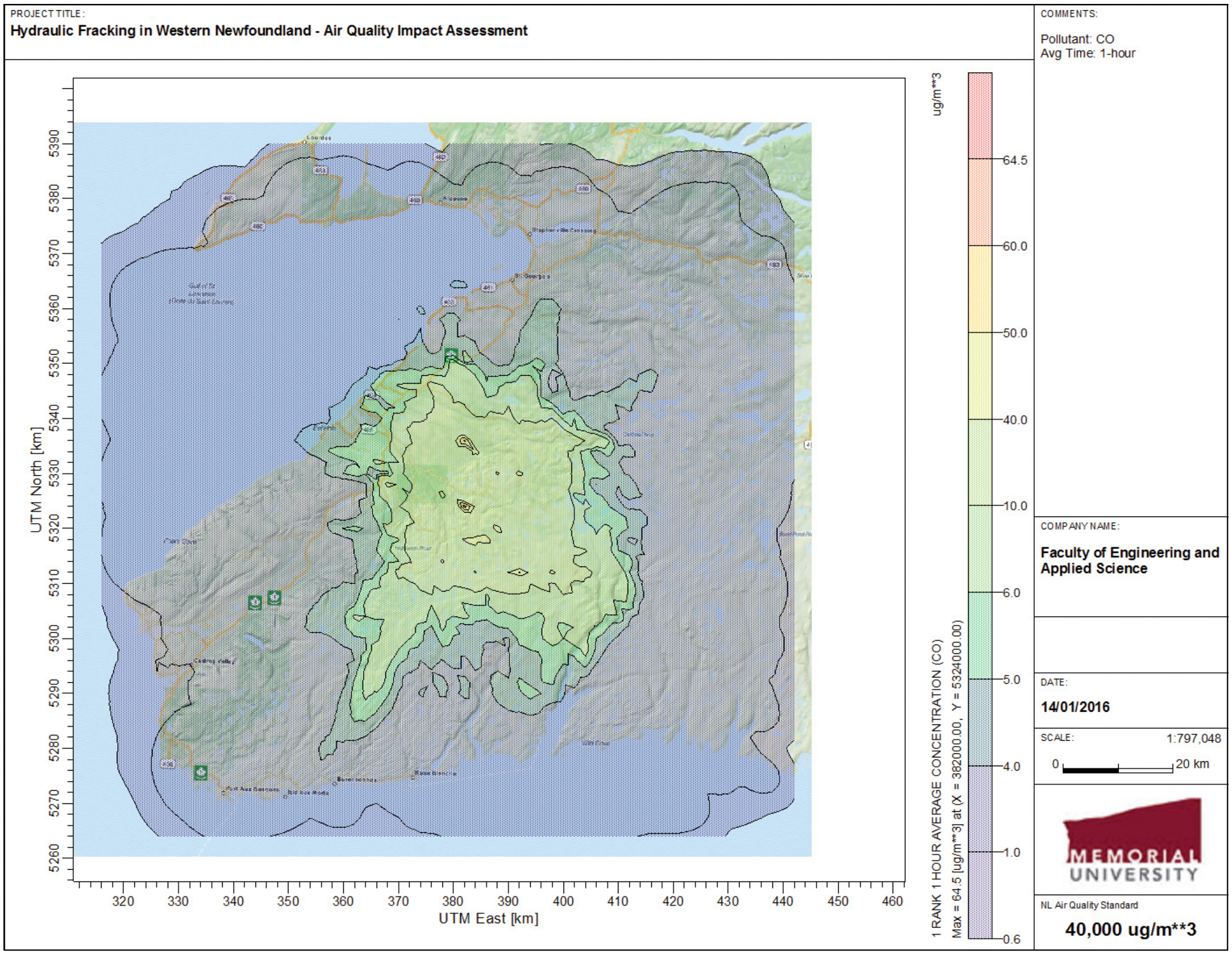

Figure 4.30. South-West Run: Peak 1-hour average CO concentrations.

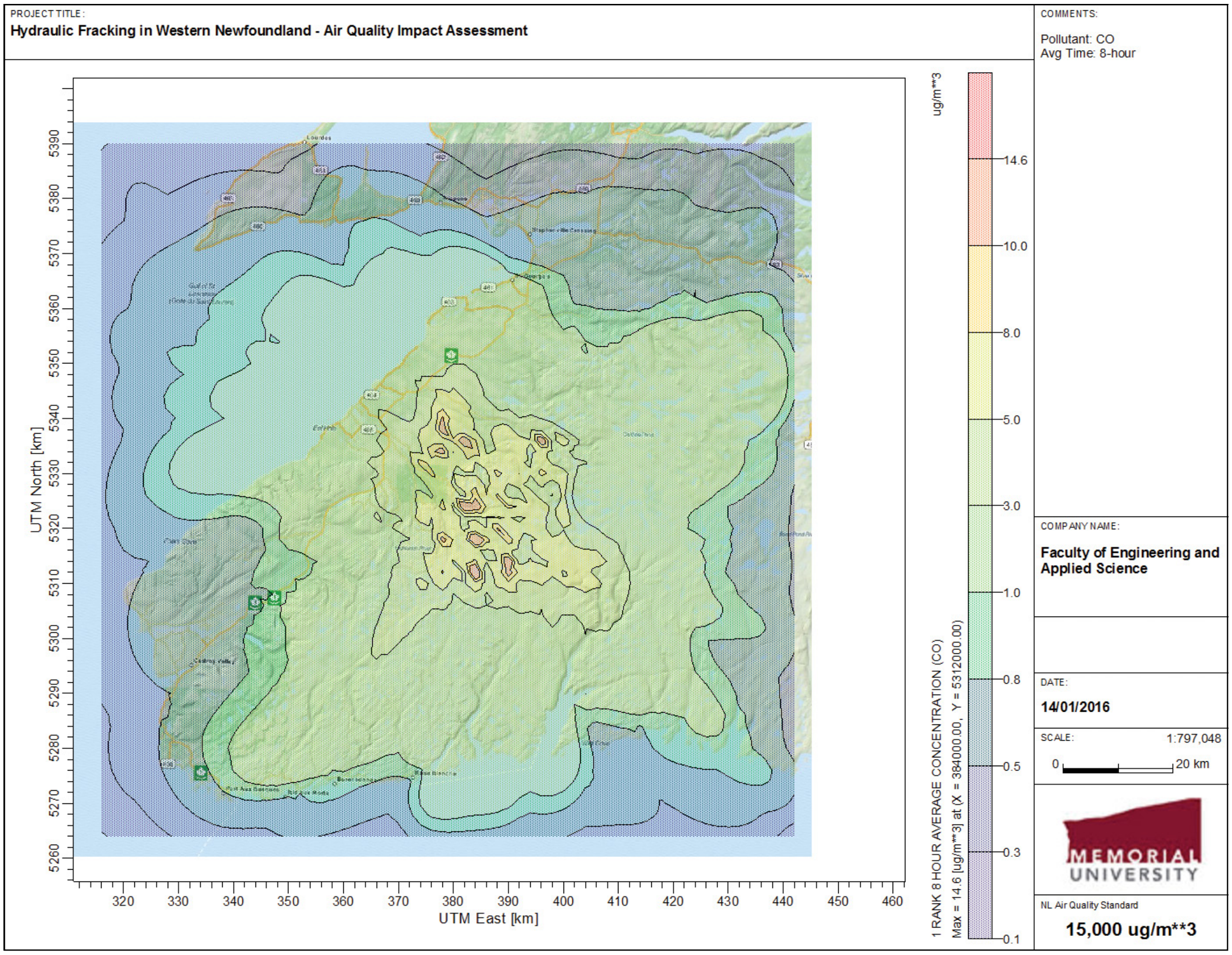

Figure 4.31. South-West Run: Peak 8-hour average CO concentrations.

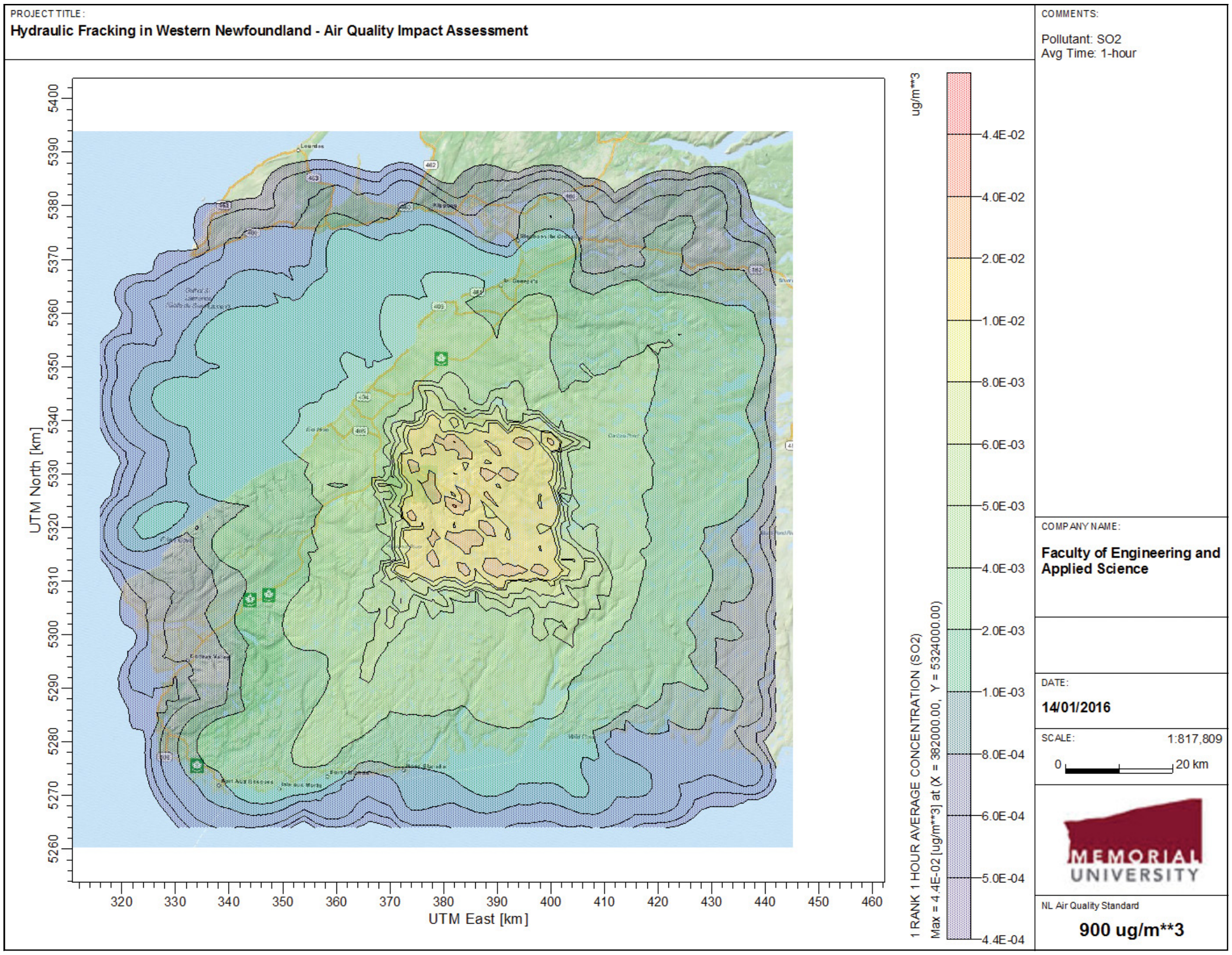

Figure 4.32. South-West Run: Peak 1-hour average SO_2 concentrations.

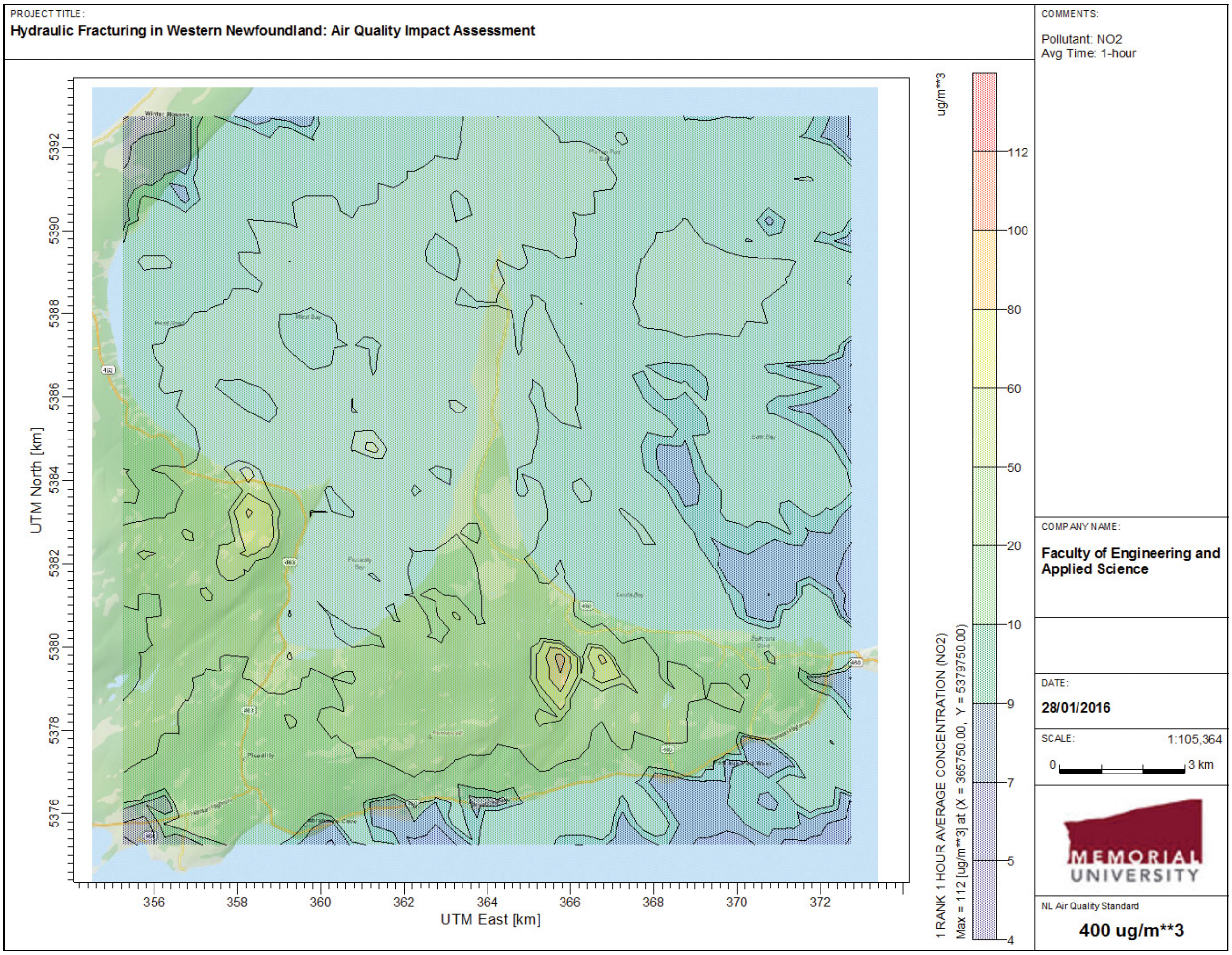

Figure 4.33. Port au Port Run: Peak 1-hour average NO_2 concentrations.

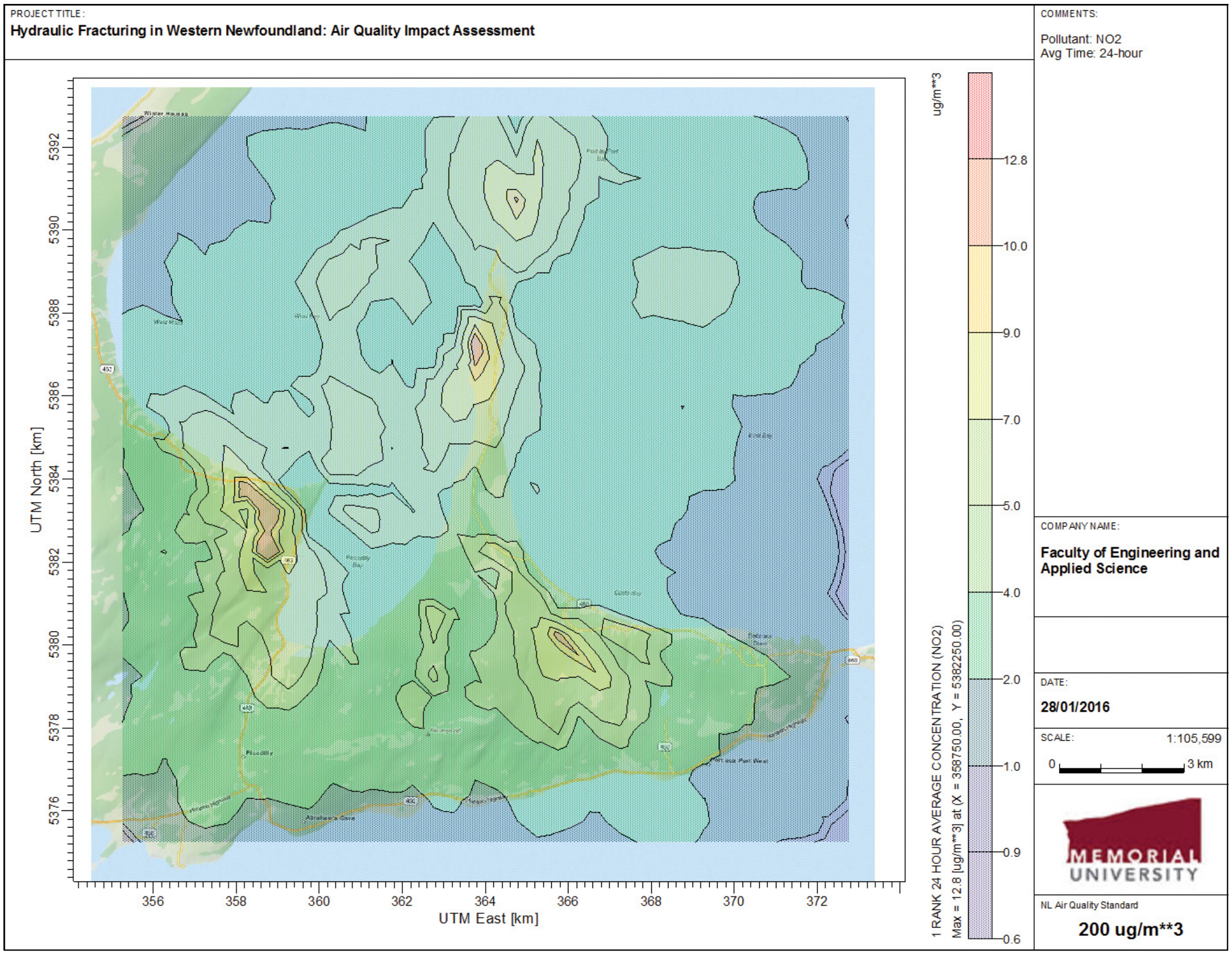

Figure 4.34. Port au Port Run: Peak 24-hour average NO_2 concentrations.

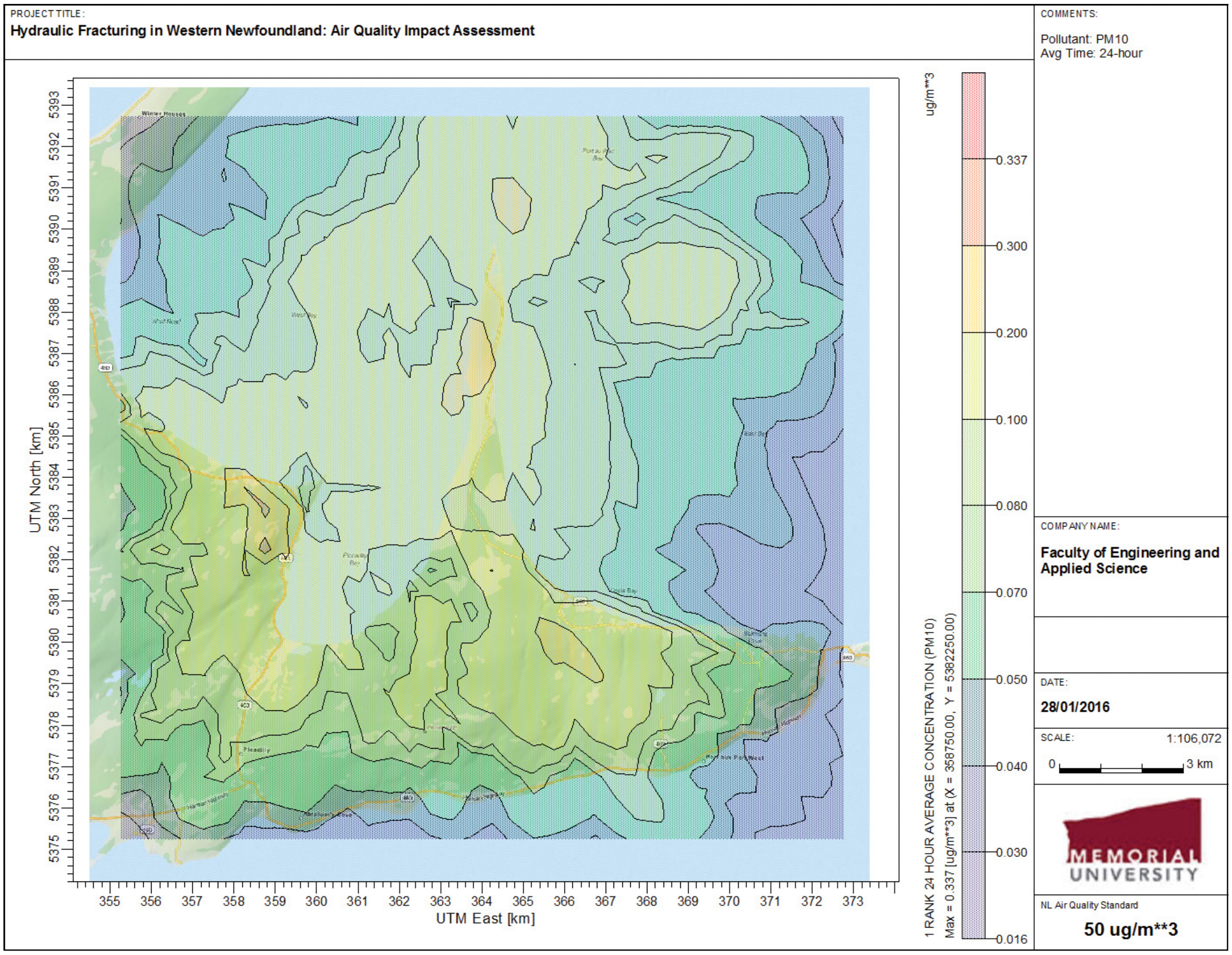

Figure 4.35. Port au Port Run: Peak 24-hour average PM_{10} concentrations.

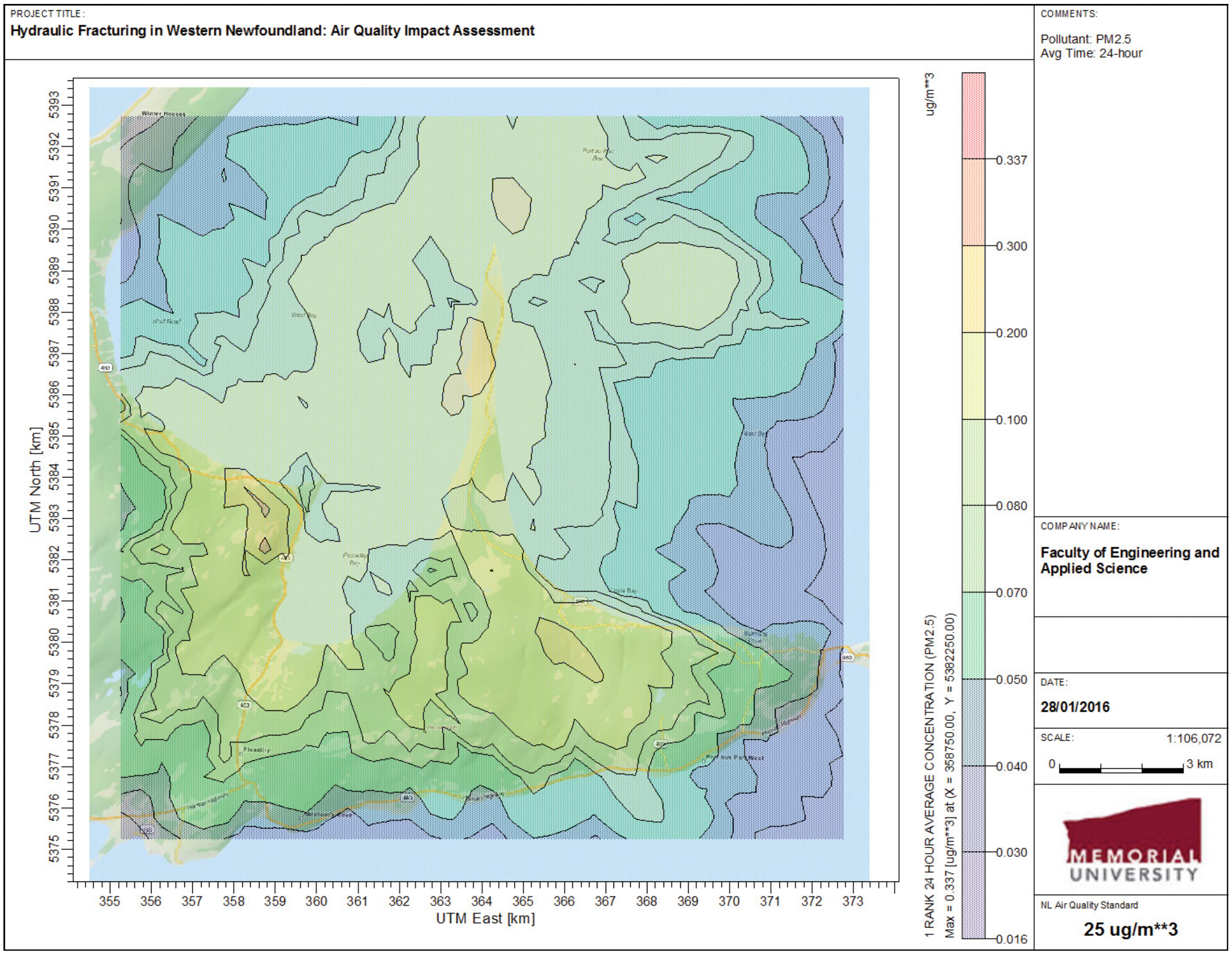

Figure 4.36. Port au Port Run: Peak 24-hour average $PM_{2.5}$ concentrations.

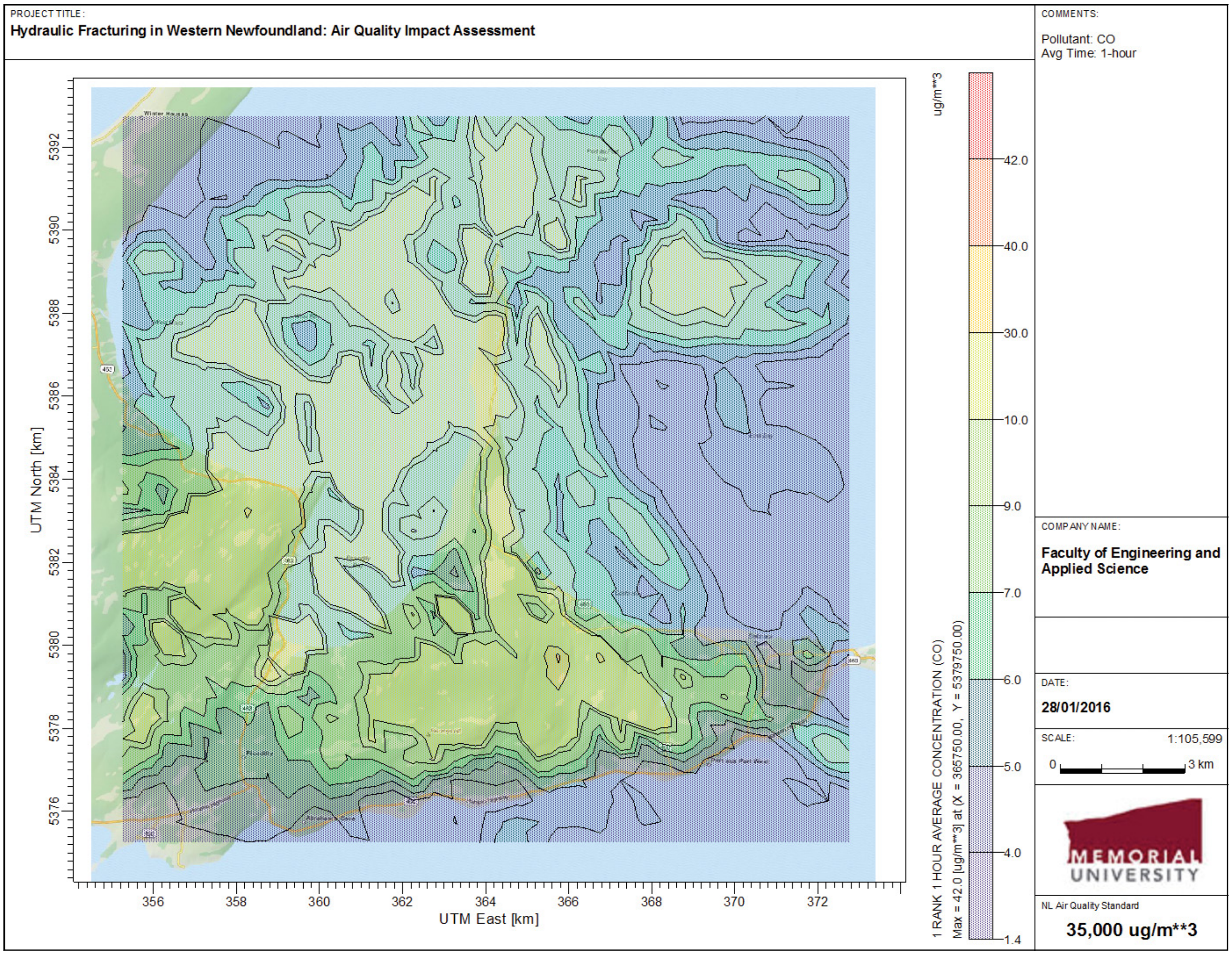

Figure 4.37. Port au Port Run: Peak 1-hour average CO concentrations.

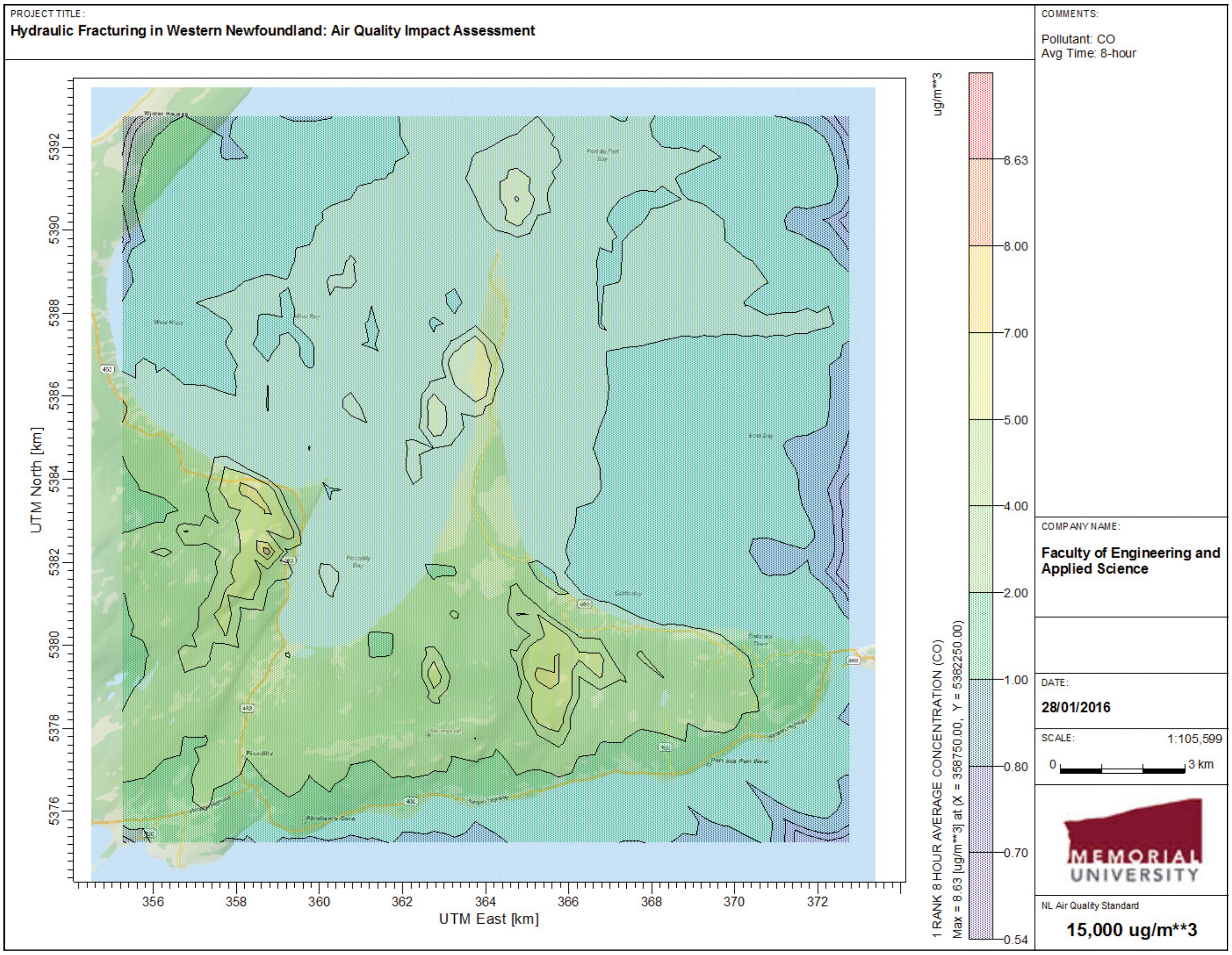

Figure 4.38. Port au Port Run: Peak 8-hour average CO concentrations.

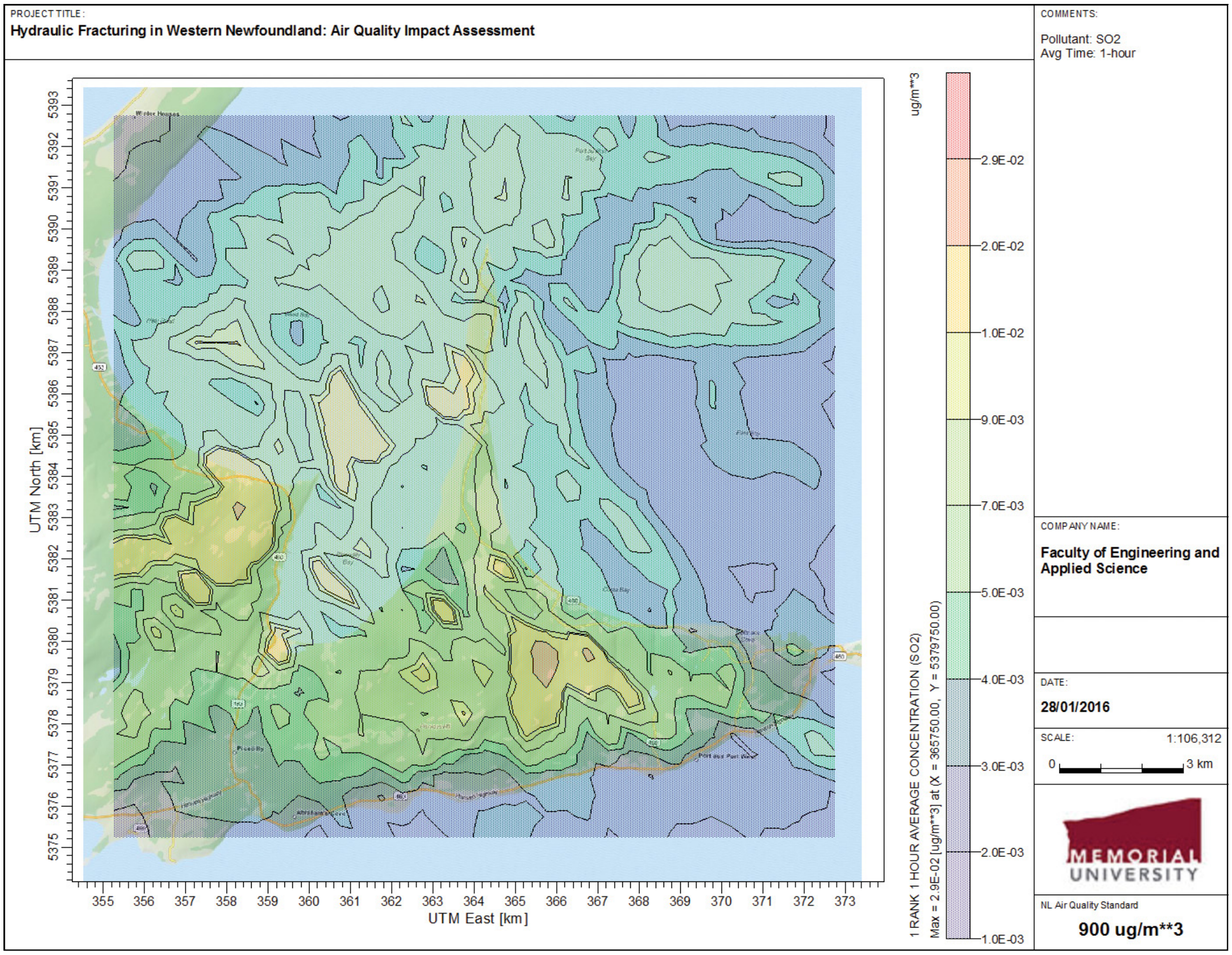

Figure 4.39. Port au Port Run: Peak 1-hour average SO_2 concentrations.

4.4 Review of Best Practices and Mitigation Measures

Detailed BMPs have been established by the Petroleum Technology Alliance of Canada (PTAC) and CAPP. Implementing these BMPs in HF operations not only mitigates the impacts on the overall environment but also on the air quality. Recently, CAPP has developed comprehensive guiding principles and operating procedures to support an emergency air-quality-monitoring procedure that can be utilized as a responsible approach for HF operations. Although the comprehensive guidelines are presented in Appendix A, the following sections outline those guiding principles and recommended mitigation measures that are related to air quality.

4.4.1 Air-Quality Monitoring

Parameters and Equipment

According to CAPP (2014), the air-quality parameters that should be measured and documented include the following:

Concentration Data
The target concentrations monitored depend on the nature of the chemical or condition being evaluated, the focus of concern (i.e., safety, health, and the environment), and the sensitivity of the monitor. A device that is capable of measuring specific chemicals or chemical mixtures at peak concentrations or concentrations over a range of averaging periods (e.g., 15 minutes) for concentration levels has been referred to in published standards (i.e., regulatory requirements). Concentration levels reported by specific devices reflect the sensitivity of the device.

Location
The location of the measurement and an understanding of the surrounding topography enable the data to be interpreted in the appropriate context. Location data may be obtained and documented using Global Positioning Satellite (GPS) systems or through written descriptions relative to local features or coordinate information.

Meteorological Conditions
Wind direction, wind speed, temperature, and atmospheric stability determine the transport and the dilution of the released substance. These conditions can be estimated by observation or determined by measurements.

Air Monitoring and Related Equipment
A broad range of monitoring equipment is used to detect the presence of gases, vapours, and particulates and to describe the location and movement of these substances in the atmosphere. Air monitoring and related equipment must be:

- Fit for purpose: The technology, accuracy, precision, sensitivity and responsiveness, ruggedness and reliability, ease of use, and options selected must match the hazards present on-site and in the environment where the device will be used.
- Calibrated on a regular schedule: Calibration should be according to the manufacturer's specifications and appropriate documentation must be available to verify the testing and calibration requirements.
- Familiar to the user: Before using any air-monitoring equipment, the user should be familiar with its specific purpose, limitations, and operating practices.

Specialized service firms should be engaged for air-quality-monitoring services as their personnel will be familiar with more complex air-quality-measurement equipment and the related technologies.

Ambient-Air-Quality Monitoring
Generally, an ambient-air-quality monitoring station is not required at each individual well-pad location. Instead, they should be located where clusters of O&G activities occur. The scope of an ambient-air-quality monitoring program

depends on potential cumulative air-quality impacts, including the intensities and types of existing and proposed activities in a given area (e.g., trucking, the presence of other oil or natural gas operators, and the presence of other industrial activities near residential areas). However, if the predicted emission concentrations in a sensitive location (such as residential areas) or the maximum ground-level concentrations exceed Newfoundland's Ambient Air Quality Standards mentioned in Newfoundland and Labrador Regulation 39/04, an ambient-air-quality monitoring station may be required in order to determine the actual emission concentrations and to aid in the preparation of an emission reduction plan. Ambient-air-quality monitoring may also be required to determine the cumulative effects of air emissions or as directed by the director in consultation with the Department of Environment and Conservation. The monitoring program may need to include any of the following components:

- Baseline air-quality studies,
- Compiling emissions showing the total pollutants in an area,
- Ground-level impact modeling to show the potential impact on ambient air quality, including the potential levels of smog-forming chemicals such as O3,
- Installing real-time multi-parameter ambient monitoring stations,
- Collecting grab samples,
- Odour monitoring, and
- Occurrence monitoring when odours or other unusual events occur.

Baseline Air-Quality Data
It is recommended that all operators conduct a baseline air-quality study in conjunction with periodic, site-specific air-quality monitoring at their facilities as determined by the director in consultation with the Department of Environment and Conservation. The decision to require this will be based on the director's review of the air emissions' inventory and emission dispersion modeling results. Complaints related to air quality may also lead to a requirement for site-specific monitoring.

4.4.2 Minimization of GHG

HF fluid and related wastewater can emit natural gas and other contaminants to the atmosphere, including chemical additives from the fracturing fluid and vapour from the shale formation. Once a well has been completed, fluids that return to the surface include HF flowback fluids and gas from the producing formation, along with a small amount of granular proppant (CCA, 2014). Until recently, the standard practice in the US was to direct the flowback water into storage and vent or flare the natural gas, as the equipment used was not designed to handle the abrasive mixture of flowback water, sand, and gas (CCA, 2014). CH_4 gas may be emitted by the HF process, but an ongoing debate exists about whether the amount is more or less than that from conventional gas operations (Cathles et al., 2012; O'Sullivan and Paltsev, 2012). If CH_4 leakage is high, then shale gas operations have the potential for a larger GHG footprint than coal (Healy, 2012). Because of the risk to air quality and the atmosphere, industry best practices aim to limit air pollution and minimize GHG emissions during the completion and testing of HF wells. Conserving petroleum is another part of a sound air-quality strategy. Operators who follow best practices know all the potential emission sources in their operations. They predict and then monitor emissions so that they operate within the set limits. Even before the well begins operation, they keep emissions at a minimum by using "green completion" techniques to trap emissions that would otherwise have escaped or been flared off.

To limit emissions, minimize GHG emissions, and conserve petroleum during the completion and testing of HF wells, the operator is required to:

- Set emission limits,
- Create inventories of emission sources,
- Model and monitor emissions, and
- Reduce emissions using "green" completion techniques.

AER Draft Directive 60: Upstream Petroleum Industry Flaring, Incinerating, and Venting (AER Directive 60, 2013) provides the requirements for the flaring, incinerating, and venting activities conducted in Alberta at all upstream petroleum industry wells and facilities. These requirements were developed to eliminate or reduce the potential impacts associated with these activities and to ensure that public safety concerns and environmental impacts were addressed prior to commencing flaring, incinerating, and venting activities. Directive 60 requires operators to address and evaluate the following three questions, in this sequence:

- Can flaring, incinerating, and venting be eliminated?
- If it cannot be eliminated, can flaring, incinerating, and venting be reduced?
- If it cannot be reduced, will flaring, incinerating, and venting meet performance standards?

The director of the HF operations will require operators planning to conduct HF operations in Newfoundland and Labrador to address these questions and adopt acceptable goals and standards respecting flaring, incinerating, and venting arising from HF operations in the province. If the flaring and venting arises from HF for crude oil production, Newfoundland and Labrador is signature to the World Bank Standard for Global Gas Flaring and Venting Reduction. This is a voluntary standard that provides guidance on reducing the flaring and venting of gas associated with crude oil production and, ultimately, in minimizing the continuous and non-continuous production of flaring and venting of associated gas.

4.4.3 Emission Inventory

Operators planning to conduct HF in Newfoundland are required to submit an emissions inventory that describes predicted emission rates for all emission sources, including flares and incinerators, vents, storage tanks, and transportation (trucking, etc.). Emission categories such as those used by USEPA may be used for this purpose. The emissions of principal interest are:

- Criteria air contaminants,
- Toxic air pollutants,
- GHGs, and
- H_2S.

The inventory should also describe the general locations of stationary emission sources (e.g., stack locations and heights).

4.4.4 Fugitive Emissions

Operators planning to conduct HF in Newfoundland must prepare, adopt, and follow a fugitive emissions management and GHG emission reduction plan for the construction, completion, and operation of well drilling, well completion, and the production and initial processing of O&G.

The director will require that each operator develop and implement a program to detect and repair leaks that meets or exceeds the Canadian Association of Petroleum Producers' Best Management Practice for Fugitive Emissions Management.

4.4.5 Venting Prohibition

Operators must prepare, adopt, and follow a venting management plan approved by the director. Vented volumes include tank venting and surface casing vents and venting from pneumatic instruments.

4.4.6 Detailed Air Quality and Climate Change Modelling

This report presented air quality dispersion modelling of one scenario for selected criteria pollutants. The study was limited to a small geographical location. However, a detailed study is strongly recommended to study the dispersion of pollutants and its impacts on the cities and towns in Western Newfoundland. It was shown that NO_x is released in relative high quantity. As NOX participates in photochemical activities, it is also recommended to study regional ozone formation using photochemical model such as CMAQ. As evidenced, HF activities increases GHG emissions, a climate change modelling should be undertaken to study the long term impacts of HF.

5.0 LAND IMPACTS

The pedosphere, the outermost layer of the Earth that is composed of soil, tolerates the brunt of all human activities. Annually, tons of dumped industrial, domestic, and agricultural wastes pollute the soil. Since soils are the centre of the terrestrial ecosystem, any soil contamination cascades to the whole ecosystem.

As with any other operation, HF poses a significant risk to the environment, including the land. Several activities during HF operations were identified which necessitate land clearance, gravel quarrying, and the construction of roads and bridges. The impacts associated with these are primarily those on the land, flora, and fauna, and the contamination of soil from fluid spillage. The impacts of these activities and corresponding regulations are discussed in the following sections.

5.1 Activities Associated with HF That Can Impact Soil and Land

5.1.1 Access Roads

The drilling locations of HF wells are generally in remote areas, most likely in an area of little or no existing infrastructure, including access roads. Good access roads are required for HF activities in order to transport large pieces of equipment such as high pressure pumps, slurry blenders, and fracturing pumps. A well-connected road network exists in Western Newfoundland (Figure 5.1); however, there are still areas not connected with the existing road network, particularly the Great Northern Peninsula and in the area around Burgeo Bank in the south. Drilling in these and other such areas requires the construction of additional access roads, which can impact the soil and land.

5.1.2 Well Pads

Well pads are a necessary part of construction for the drilling of hydraulic wells. The well pad required for HF is approximately twice the size of that required for traditional drilling. It could be up to 3 hectares (Broomfield, 2012), about the size of four standard football fields. This large size must accommodate heavy equipment and trucks required for drilling. Figure 5.2 illustrates a typical drilling pad with the necessary equipment. Additionally, since multiple wells are drilled from a single pad, larger well pads are needed. It has been estimated that for the Utica Shale development in Quebec City the full-scale shale gas development required over 5,000 hectares of land (BAPE, 2011). A general estimate of 1 to 2 percent of land is reclaimed during drilling operations and less than 0.5 percent during production (Council of Canadian Academies, 2014).

5.1.3 Work Camps

In addition to the required equipment, manpower plays a significant role in HF operations. Generally, people work round the clock at the site; this requires the building of accommodations and necessary amenities. Land must be reclaimed for this purpose.

5.1.4 Storage and Handling of Additives

Storage facilities for additives are generally part of the well pad, but sometimes an additional place is required adjacent to it. This necessitates reclaiming additional surrounding land for this purpose, and the handling of these additives could pose a soil pollution hazard due to spillage.

5.1.5 Waste processing facilities

It is estimated that approximately 3,500 to 10,000 cubic metres of fracture fluid is required to frack a well (CSUG, 2013). Roughly 10 percent of this fluid is pumped back to the surface; this is called the flowback fluid. This fluid typically contains heavy metals and radioactive materials. To treat this fluid, it is generally stored in a pond or tank near the well pad (Figure 6.3). The requirement of land for such ponds sometimes is more than that for the well pads.

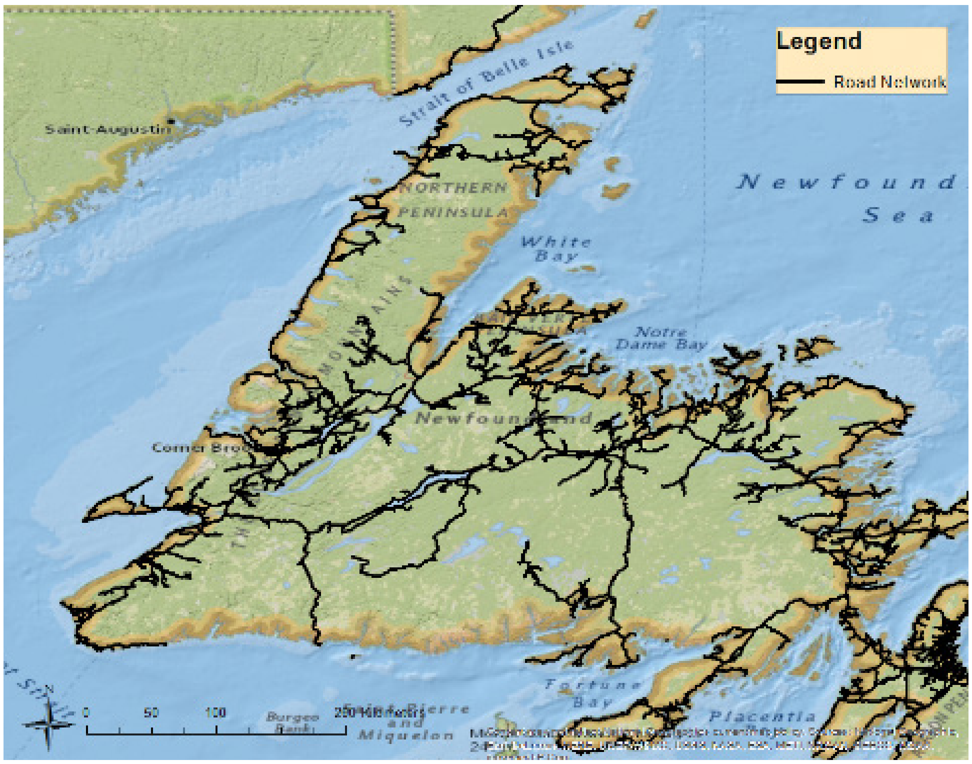

Figure 5.5.1. Existing road network in Western Newfoundland (data source: NRC, 2010).

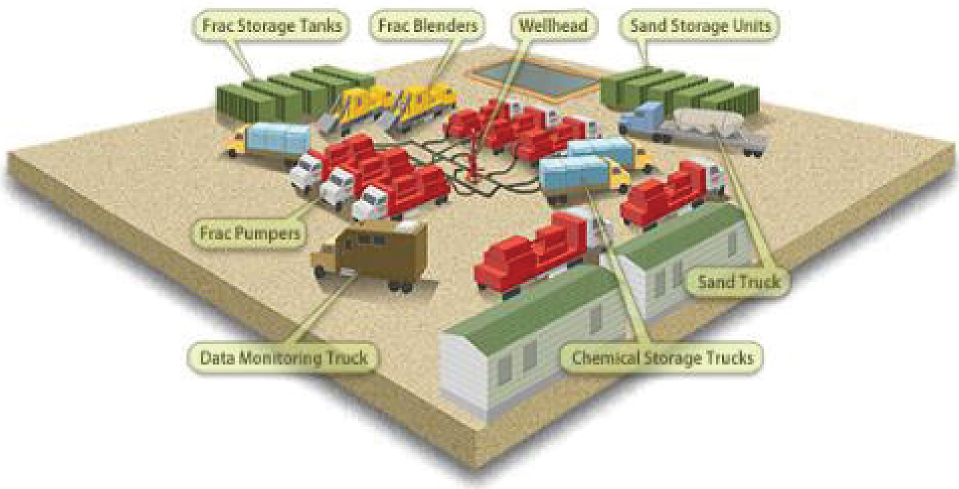

Figure 5.5.2. Schematic view of a HF well pad[3].

Figure 5.5.3. Flowback pond near drilling site[4].

3 www.fracfocus.ca/hydraulic-fracturing-process
4 cen.acs.org/articles/92/web/2014/03/Analytical-Test-Underestimate-Radioactivity-Fracking.html

5.1.6 Supporting Utilities

Utilities such as pumping stations, gathering lines, and electrical and telecommunication lines are required for drilling activities. Developing this infrastructure requires a considerable area of land. The proppant material used for fracturing treatment may require additional infrastructure.

King (2012) estimates that 1.5 million kilograms of proppants are required for every 20,000 cubic metres of fracturing fluid. Developing this material on-site or close to the site might be another stressor on land acquisition.

5.1.7 Other activities

Activities such as handling and managing the produced water, drilling mud, sludges, slimes, and mineral scales from pipes could impact the land, especially contaminating the soil.

5.2 Potential Risks to Soil and Land

5.2.1 Flora

As a result of land-clearing activities, it is inevitable that an area's vegetation is destroyed, usually permanently. The impact on flora is potentially due to an increase in soil erosion, sedimentation, and habitat fragmentation. These could occur because of the activities associated with HF operations. The level of impact on the flora depends on the characteristics of the site. In order to understand the potential impact on flora in Western Newfoundland, the type of land in the area was studied. Figure 5.4, which presents the land cover map of Newfoundland, indicates that most of Western Newfoundland is dominated by mixed forest in the south and coniferous forest in the north. These forests are home to a variety of plants, some of which are classified as rare.

For example, the plants Burnt Cape Cinquefoil and Braya Fernaldii are threatened species, as shown in Figures 5.5 and 5.6 respectively. These plants are abundant in the Burnt Cape Ecological Reserve located near the tip of the Great Northern Peninsula due to its cold climate, unique landscape, and calcium-rich soil.

Other specific plant species are pitcher plants, rare orchids, and other types of plants that grow in marshlands. Ecological reserves and parks that host these species are shown in Figures 5.7 and 5.8; they also show the location of the Burnt Cape Ecological Reserve. Other noteworthy reserves are Little Grand Lake Provisional Ecological Reserve, Glover Island Public Reserve in the south and Main River Waterway Provincial Park, Watts Point Ecological Reserve, Hare Bay Islands Ecological Reserve, and Pistolet Bay Provincial Park on the Great Northern Peninsula. As Gros Morne National Park, which is host to these ecological reserves, is a UNESCO world heritage site, any HF activities near this should be undertaken with the utmost case.

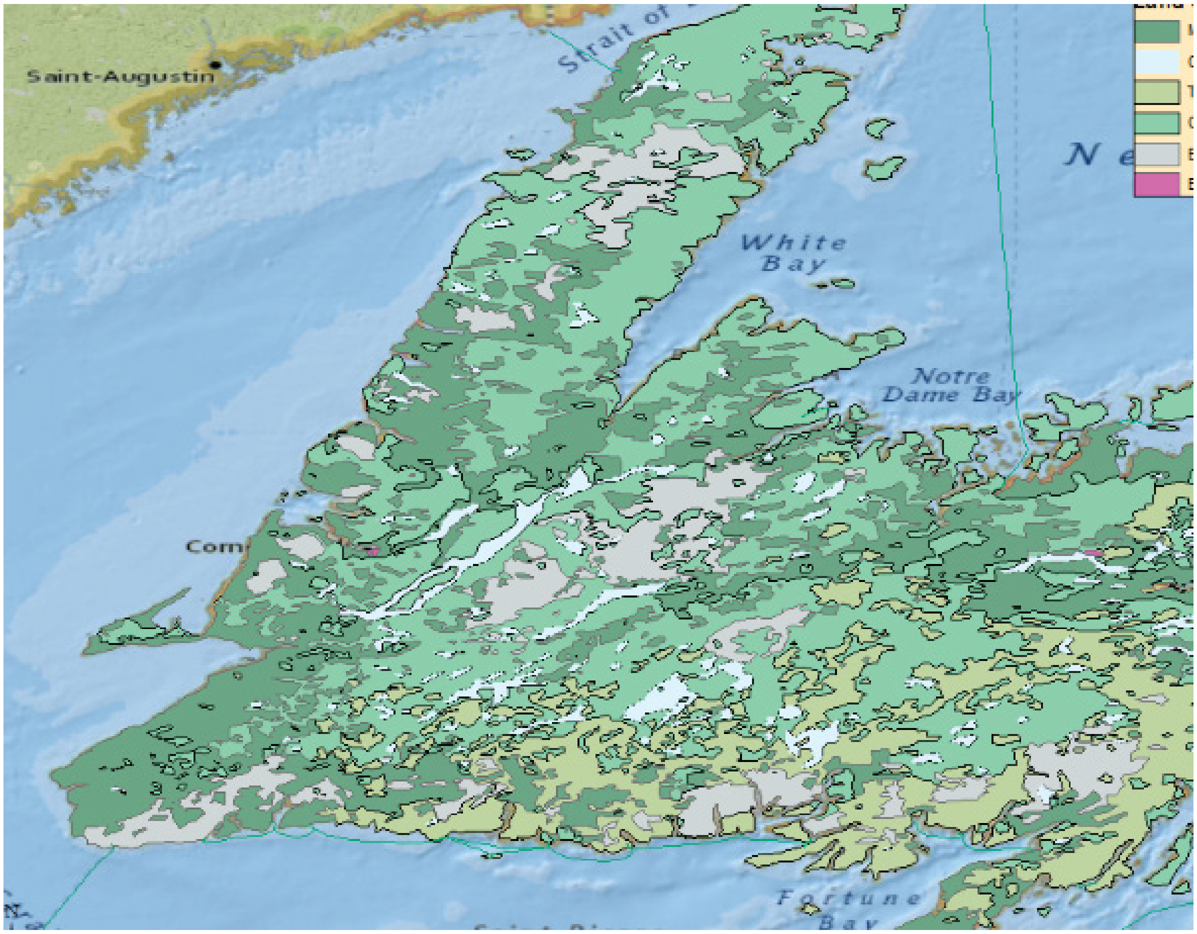

Figure 5.5.4. Land cover map of Western Newfoundland (data source: NRC, 2010).

Figure 5.5.5. Burnt Cape Cinquefoil[5].

5 www.digitalnaturalhistory.com/genus_potentilla_index.htm

Figure 5.5.6. Braya Fernaldii[6].

6 limestonebarrens.ca/Endemics.htm

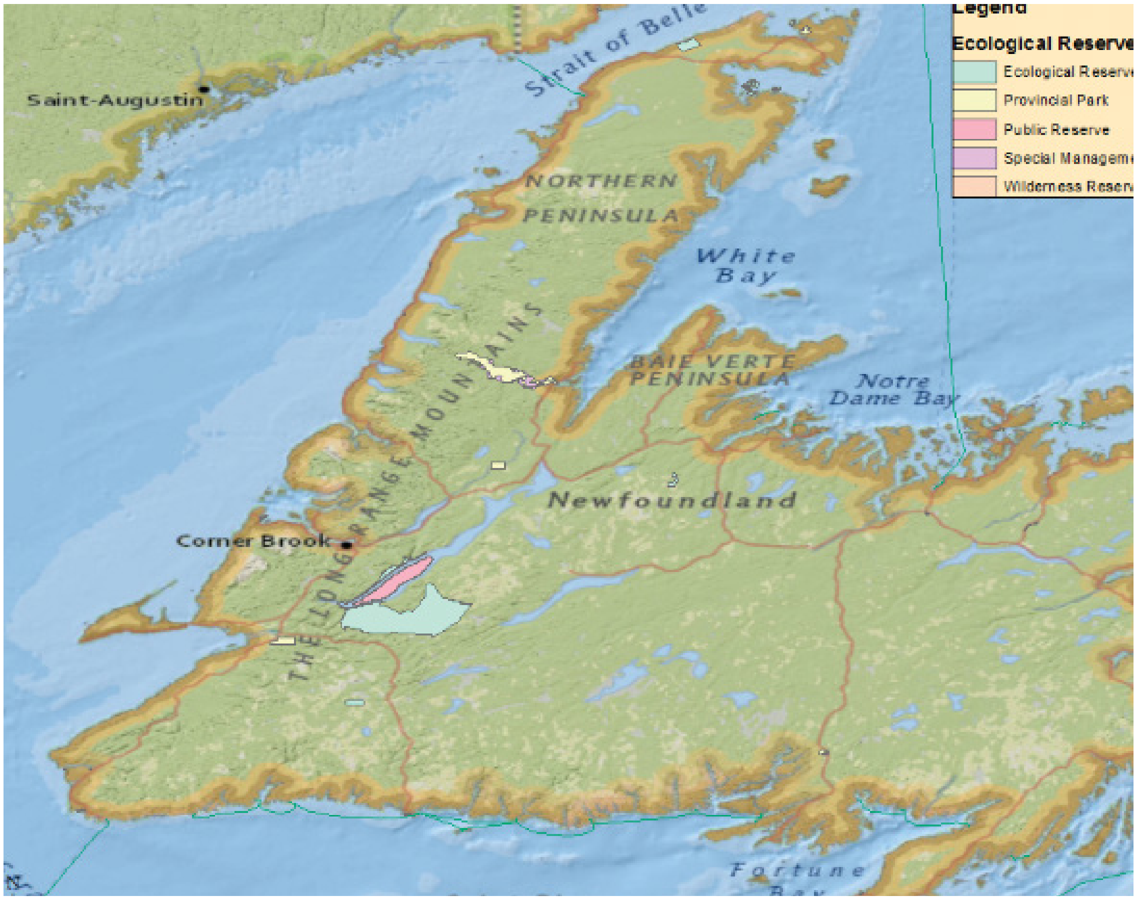

Figure 5.5.7. Ecological reserves in Western Newfoundland (data source: NRC, 2010).

Figure 5.5.8. Burnt Cape Ecological Reserve, which hosts a variety of threatened plant species.

5.2.2 Fauna

Reclamation of land, the destruction of vegetation which serves as food for several animals, and the light and noise due to the transport and operations of heavy equipment disturb regional fauna. The noise is primarily due to compressors, pumping stations, and the movement of traffic. Light and noise greatly impact wildlife, migratory birds, and amphibians in the area. Studies near O&G wells have found that wildlife and ecology are significantly impacted during the drilling and production phases (Burton et al., 2014). Most of the time the fauna migrates to another area and sometimes may perish because of these activities.

The native animals of Newfoundland are black bear, woodland caribou, otter, muskrat, fox, lynx, and the Newfoundland pine marten, in addition to moose, which is fairly numerous. Little Grand Lake Provisional Ecological Wildlife reserve in the south is the main reserve where these animals live (Figure 5.8). Among them, the Newfoundland pine marten (Figure 5.9) is a threatened species found only in Newfoundland. Its population was estimated at 630 to 875 in the early 1980s; however, recently their numbers have declined significantly due to large-scale timber harvesting (Wikipedia[7]). If HF activities are undertaken in the areas of its habitat, the Newfoundland pine marten will be at a greater risk of further population decline.

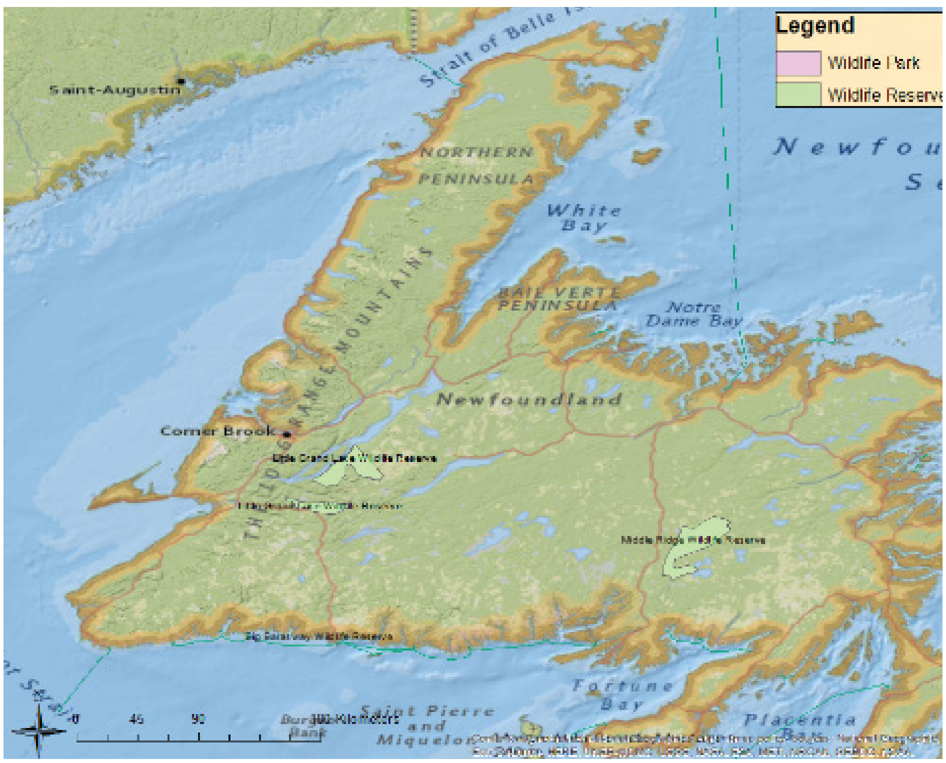

Figure 5.5.9. Wildlife reserves in Western Newfoundland (data source: NRC, 2010).

[7] en.wikipedia.org/wiki/Newfoundland_pine_marten

Figure 5.5.10. Newfoundland pine marten (source: Wikipedia).

5.2.3 Soil contamination

Essentially, fracturing operations require the use of a special fracking fluid. It may consist of water, sand, and chemical additives. The chemical additives enhance the fracking procedure, especially to smooth the fluid flow and kill bacteria that hamper the operation. Different types of additives have been used in fracking fluids (presented in Section 7 of this report); however, those that are harmful to the environment, including to soils, are BTEX and a few aromatic compounds. A view of soil contamination due to a fracking fluid spill is shown in Figure 5.11.

Fracking involves injecting these fracking fluids at high pressures. Leakage of fracking fluid from the injecting pipeline could be one source of soil contamination. Pipeline joints, values, and hoses could also be a source of leakage. A significant quantity of the fracking fluid pumped back (flowback fluid) is a known leading cause of soil contamination (Herridge et al., 2012); it often contains radioactive materials such as strontium, uranium, and radon, which have a deleterious effect on soil. Other common soil pollutants are heavy metals such as lead, mercury, chromium, barium, and arsenic, all of which are contained in flowback fluid. Produced water too contains harmful chemicals which cause soil contamination. Surface spills of fracking fluid or produced water could also occur due to the improper storage and handling of hydraulic fluids containing harmful additives.

Produced water and flowback fluid are generally stored in evaporation pits and ponds or tanks near the well pad for treatment. In addition to damaging the pond's surface, these fluids tend to seep into the surrounding areas, contaminating the soil. Generally as part of BMPs, appropriate natural or artificial liners are constructed to prevent the percolation of this fluid into the groundwater. The liner is made of clay or some synthetic materials (such as polyethylene). An example of an evaporation pond and its liner material are shown in Figures 5.12 and 5.13 respectively.

Figure 5.5.11. Soil contamination due to a fracking fluid spill[8].

Figure 5.5.12. Evaporation ponds storing flowback and produced water.

8 www.ohiocitizen.org/fracking-fluid-blows-out-nearby-well

Figure 5.5.13. Liner in an evaporation pond.

5.3 Regulations and Best Practices

Several regulations are in place both federally and provincially to minimize the impact of O&G activities due to HF on the land. Appendix A presents various aspects of these regulations, including the impact on land, flora, and fauna and the contamination of soils. In the province of Newfoundland and Labrador, the Department of Natural Resources provides guidelines for conducting petroleum exploration surveys (NL Guidelines, 2013); even though it does not mention HF, these guidelines are applicable to HF operations. The guidelines specific to land are summarized below.

Restricted Areas
The NL guidelines restrict exploration activities in the following categories of areas:

- Forestry reserves;
- Restricted areas;
- Commercial outfitting camps;
- Designated watersheds;
- Wildlife areas;
- Agriculture development areas;
- Blueberry management units;
- Regional pastures;
- Wilderness, ecological, and provisional reserves; and
- Provincial parks.

As illustrated in Figure 6.4, the Western Newfoundland area is mostly covered by forests, and includes several ecological reserves and parks (Figure 6.7). Drilling in these areas is absolutely prohibited; however, operations are allowed while honoring certain proximity distances:

- At least 1 kilometre from a known archaeological site;
- Two kilometres from a provincial park; or
- Two kilometres from wilderness or ecological reserves, a provisional reserve, or an international biological program site.

Other areas of restriction include:
- Vicinity of fur farms during whelping season,
- Near poultry barns,
- Near staging and breeding areas of migratory birds, and
- Land with sensitive habitats as designated by relevant authorities.

Vegetation
- Salvage may be necessary if a significant amount of timber is cut during the operations;
- If surface vegetation is removed, actions such as re-vegetation are needed to prevent soil erosion;
- Special efforts must be made to avoid disturbing surface vegetation; and
- Areas of threatened species must be avoided.

Wildlife
- Land designated as wildlife areas must be avoided;
- Operations must be away from areas with known sensitive wildlife or containing populations which may be adversely affected by these operations; and
- Cut lines may have the potential to create or increase snowmobile and ATV access into sensitive wildlife areas, and proper signage must be installed to avoid unnecessary access to these areas, which would result in disturbance/damage to wildlife.

HF operations include the movement of equipment, goods, and people. These are a few pathways that potentially bring with them invasive species of flora and fauna (Environment Canada, 2014). Utmost care must be taken to prevent such an invasion. Threatened species of flora and fauna exist in potential HF exploration zones; these areas must be avoided. Regulations on the prevention of soil contamination are mostly related to the handling and storage of additives, which is discussed in Section 6. Post-spill soil-remediation techniques are presented in Section 7.

6.0 WASTE MANAGEMENT

Fracturing fluids are extensively used in modern HF operations. They are injected under an extremely high pressure to create and maintain fractures inside the shale formations so that O&G can be recovered more easily during production.

It is also critical, however, to note that potential environmental impacts and health risks may originate from the waste of HF activities – flowback water. Flowback water contains detrimental chemical additives, a mixture of hydrocarbons and solid wastes, as well as by-products of subsurface reactions. Therefore, it is important to achieve a better understanding of the composition of fracturing fluids, to identify the environmental risks associated with fracturing waste, and to derive optimal waste management practices.

6.1 Fracturing Fluids and Additives

6.1.1 Types of Fluids

The main body, or the pad, of fracturing fluids, which can make up to 99 percent of the total volume, is the key component for creating fractures in the formation. These fluids may be primarily based on water, oil, or alcohols under different operational conditions (Spellman, 2012).

Water-Based Fluids

Water-based fluids are dominant in prevailing practical operations. Their typical compositions and corresponding proportions are illustrated in Figure 6.1. Compared with other options for the pad, water is more economical, more versatile, and safer to handle. Due to the existence of water-sensitive clays within sedimentary rocks, fresh water usually cannot be applied directly to the targeted site before adding potassium-, calcium-, ammonium-, or sodium chloride, which can prevent hydrogen bonding with water. Hence, the produced formation brine is the most favourable option (Donaldson et al., 2014).

Large volumes of water are required for HF operations; this water can be supplied from nearby surface waters, groundwater sources, or municipal plants. It is considered a significant impediment for operational regions where water resources are scare or deep-well injection disposals are limited (Gregory et al., 2011). To overcome this challenge, the on-site reuse of flowback water is a particularly attractive option. Recycling flowback water can reduce the need for an external water supply and makeup demand, as well as the environmental risks associated with wastewater treatment and disposal (Denney, 2009). However, the amount of flowback water depends on multiple factors, including geologic conditions, which may vary from case to case. Studies have shown that the percentage of fluid recovery generally falls between 25 and 61 percent, and the recovery rate of polymers was also limited (Forman and Lupberger, 2012).

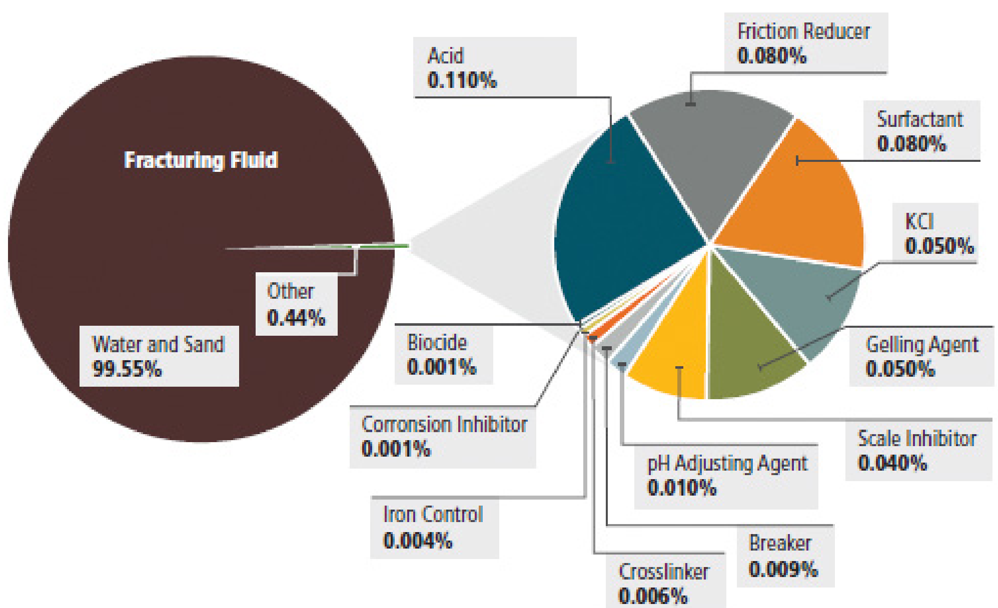

Figure 6.6.1. Typical fracturing fluid composition (adapted from CCA, 2014).

Hydrocarbon-Based Fluids

These types of fluids are actually initiated at the beginning stage of HF operations, which directly pump the produced fluids back into the well at a high pressure to facilitate the fracturing of the subsurface formations. The fluids are usually light crude oil, gasoline, kerosene, and diesel oil.

Hydrocarbon-based fluids are still popular in cold regions where water-based fluids tend to freeze. Efforts have also been taken to prevent the loss of fracturing fluids by adding chemicals that raise their viscosity. Hydrocarbon-based fluids also apply to highly water-sensitive formations, where the blocking of reservoir fluids frequently occurs as a consequence of the reactions between clay and fresh water. Liquefied natural gas provides a solution for practical operations in which water sensitivity matters (Barati and Liang, 2014). However, with gas reservoirs, the introduced hydrocarbon-based fluids may also occupy pore spaces when the shale is under-saturated with oil, and lead to a drop in the permeability of the matrix. Alcohol is normally injected to overcome this obstacle, but only marginal effects can be expected with such expensive and complicated procedures (Donaldson et al., 2014).

Energized Fluids

Energized fluids contain large fractions of gas and small fractions of water. Their multiphase nature is presented as foam; therefore, energized fluids are also called foam-based fluids. Nitrogen and CO_2 are two more common gas phase components that generate foam, and CO2-based energized fluids have resulted in higher recovery rates (Burke et al., 2011).

The main advantages of applying energized fluids include limiting the physical damage caused by the invading fluids and capillary pressure, improving the recovery of hydraulic conductivity, minimizing the contact between water-sensitive clays and water, and reducing fluid losses. However, limited access to the gases, the potential safety concerns of pumping gases at high pressure, and the corresponding higher costs impede the general application of energized fluids (Gupta, 2011).

Alcohol-Based Fluids

Alcohol-based fluids are usually applied in dry gas reservoirs with low permeability. The alcohols (methyl and isopropyl) work particularly well in removing “water-blocks” caused by a high saturation of water or oil in the vicinity of the wellbore. However, substantial operational cost and health risks significantly restrict their application (Donaldson et al., 2014).

6.1.2 Types of additives

Additives are indispensable in improving the functional performance of fracturing fluids, despite the fact that their quantity typically accounts for only a minor percentage of the total volume. Therefore, it is critical to clarify each additive for the purpose of classification and characterization of different types of fracturing fluids. Some of the more commonly applied additives include:

Acids dissolve rock and create paths to transport formation water and shale gas. Hydrochloric acid, sometimes combined with acetic or formic acid, is typically introduced into fracturing fluids which target limestone formations. Normally, acids are substantially diluted to 1,000 times weaker than the concentrated versions before injection (Donaldson et al., 2014).

Biocides control the growth of bacteria which can secrete enzymes that rapidly break down the gelling agent and polymers and lead to reduced fluid viscosity. Additionally, biocides control corrosion, which is enhanced by the biogenic formation of H_2S in the reservoir and biofilms on metallic surfaces (Spellman, 2012).

Considering that the pad of the fracturing fluids might be obtained from different water bodies in which the population of microbes is significant, it is important to apply biocides that can quickly kill a wide range of bacteria. The biocide should not contain any corrosive property and should be low in toxicity for human beings (Fink, 2013). Studies have investigated various biocides, including bronopol, glutaraldehyde, a glutaraldehyde/quaternary ammonium compound blend, isothiazolin, tetrakishydromethylphosphoniumsulfate, and 2, 2-dibromo-3-nitrilopropionamide. It has been shown that tetrakishydromethylphosphoniumsulfate had the best performance in terms of bacteria instant control as well as long-term preservation of the fluid (Johnson et al., 2008; Fichter et al., 2009).

Breakers bridge pore channels created by fracturing and further recover the fluids by decreasing their viscosity. Breakers enhance the degradation of the polymers introduced with the fracturing fluids and allow their pumping back from previously formed factures. Breakers can be mixed with fracturing fluids and delivered simultaneously or injected at a desired time stage when fractures have formed. Approaches to controlling the time of functionalizing breakers include encapsulation and granule additions.

Acids, oxidizers, and enzymes are among the most common types of breakers. Hazardous constituents such as ammonium persulfate, ammonium sulfate, copper compounds, ethylene glycol, and glycol ethers may also be contained in different types of breakers (Spellman, 2012). Interactions between enzyme breakers and other fluid additives, including biocides, clay stabilizers, and certain types of resin-coated proppants, have also been reported (Fink, 2013).

Shale stability, an important issue during fracturing operations, is often impeded by clay swelling. This extremely undesirable phenomenon caused by the subsurface hydration of clay results in volume expansion and the migration of fine clay particles and leads to the instability of shale. **Clay stabilizers** mitigate these effects, especially when formation brine cannot be accessed at the pad of fracturing fluids.

Common clay stabilizers include salts, quaternary ammonium salts, saccharide derivatives, sulfonated asphalt, grafted copolymers, anionic polymers, and guanidyl copolymer. Special clay stabilizers have been synthesized as high-molecular-weight cationic organic polymers, which can be used in conjunction with acidizing under a lower salt concentration (Montgomery, 2013). Liquid products have also proven to be environmentally compatible and biodegradable in their diluted form.

Corrosion inhibitors are required when acidic fluids are involved in order to mitigate the corrosion of steel tubing, well casings, tools, and tanks under acidic environments. Acetone is a common additive as the solvent of corrosion inhibitors. Corrosion inhibitors are quite hazardous even though only small quantities are required in fracturing operations (Singh and Quraishi, 2015).

Crosslinking effects are important in increasing the viscosity of fracturing fluids to improve proppant transportation. Common **crosslinking agents** include boric acid, titanium compounds, zirconium compounds, guar gum, and hydroxypropyl guar.

Usually delayed crosslinking is more desirable in order to pump down the fluids in an easier and smoother way. Glyoxal is effective in triggering a retarded crosslinking reaction by adjusting the pH levels of the solution. Other alternatives include polyols and chelating agents for magnesium ions (Legemah et al., 2014).

Defoamers reduce the amount of foams which might be introduced at an earlier stage to prompt proppant transportation so that the surface tension could be lowered to release the trapped gas.

The active ingredients of defoamers may be liquids or solids. Based on the hydrophobic liquid phase components, defoamers can be classified as hydrocarbons, poly(ether)s, silicones, or fluorocarbons. As for applications in nonaqueous systems, a silicone antifoaming agent such as poly(dimethylsiloxane) provides a solution when it is compounded with a hydrophobic-modified silica (Fink, 2013).

Foaming can considerably increase the viscosity of the fluids and decrease the tendency of leakage based on liquid fracturing operations. Foams can also benefit the recovery of residual fracturing fluids with a sudden expansion of gas within the foams when fracturing has been completed. Surfactants are known for their ability to form foams; however, the degradability and toxicity of certain types of surfactants remain an environmental concern. An environmentally friendly **foaming agent** is commercially available by the hydrolysis of hoof and horn meal to produce a free-flowing powder that contains about 85 percent protein. As another alternative, foamed nitrogen in liquid CO_2 can also be used for fracturing purposes (Montgomery, 2013).

Fracturing fluid loss is extremely undesirable considering the high cost of producing the fluids and their corresponding environmental risks. This may occur, however, when the fluid passes through a porous formation. The extent of fluid loss is closely related to the nature of the fluid, the permeability of the formation, and operational conditions.

Fluid-loss additives rapidly form a filter cake with low permeability that can control fluid leakage. Granular starch and enzymes are described as two important components of fluid-loss additives. Starches are usually a mixture of natural and chemically modified starches, and enzymes help to degrade the starches at a later stage by oxidation or microbes. Other fluid-loss additives include succinoglycan, scleroglucan, poly(orthoester)s, poly(hydroxyacetic) acid, polyphenolics, and viscoelastic additives (Crews et al., 2010; Fink, 2013).

Friction reducers are introduced to improve the rheological properties of fracturing fluids, such that energy loss due to fluid transportation through tubular structures can be reduced and operational horsepower saved. Polymers are frequently used as friction reducers. However, incompatibility between anionic friction reducers and quaternary surfactants, which are also a common component of fracturing fluids, might inhibit the performance of friction reducers (Sun et al., 2010).

Gel stabilizers ensure the best performance of crosslinked gels, which is challenged by pH variation and elevated temperature during fracturing operations. O_2 is also detrimental to the polymers at high temperatures. Sodium thiosulfate can be an ideal O_2 scavenger. Methanol, diethanolamine, ethylenediamine, n-butylamine, and mixtures from these compounds are recommended as high-temperature gel stabilizers (Fink, 2013).

pH buffers, important for the stability of gels, often control the retarding of crosslinking effects. Some typically applied buffers for HF operations are low molecular weight organic acids, bicarbonate, carbonate, and hydroxide (Montgomery, 2013).

Proppant selection is based on the attributes of high permeability, high resistance to compression, low density, and good resistance to acid. Sand, ceramic pellets, or other small incompressible particles are good candidates for fracturing fluids. In particular, sand is the simplest and most common proppant introduced after the formation of fractures to generate slurry, such that the fractures can remain open to ensure maximum permeability even when the pumping pressure has been released (Donaldson et al., 2014).

To avoid flowback of the proppant with the produced fluids, coatings are also widely applied to proppant surfaces. These coatings can be thermoplastic films functional over a wide range of temperatures, or adhesive materials which mechanically interact with the proppant particles. Magnetized materials provide another option to prevent proppant flowback by forming clusters in the voids or channels (Arthur et al., 2009).

Scale inhibitors prevent the build-up of mineral scale that can potentially block fluid and gas transportation through the pipes. Acids can be used as a scale inhibitor. Poly(phosphate)s as well as sulfonated polymers can be suitable scale inhibitors but are not viable for different ranges of temperatures. Copolymers have been particularly useful in this regard (Fitzgerald and Cowie, 2008; Fink, 2013).

Surfactants play various roles in improving hydraulic fluid performance. Their deployment is usually accompanied by other types of additives to improve the compatibility of aqueous fluids with hydrocarbons, generate foams and emulsions, and enhance the remediation of contaminated sites during and after fracturing operations (Liu et al., 2010).

The components of surfactants vary from case to case; however, some common environmental concerns associated with the application of surfactants need to be considered, especially toxicity and degradability.

The chemical additives typically used in fracturing fluids are summarized in Table 6.1. Considering that many types of additives are toxic and potentially hazardous to the environment, it is important to rationally select these additives and control their quantities while preparing the fluids.

For the specific site conditions in Western Newfoundland, sea water might be the water supply for operation locations near the coast, especially when the clay content in the subsurface profile is low, and the addition of no or low-dosage clay stabilizers is recommended. The quantity of other chemical additives can also be adjusted on the basis of the specific geological and operational conditions.

Table 6.1. Representative major chemical additives used in fracturing fluids (adapted from Precht and Dempster, 2015 a, b, c; USDOE, 2009).

ADDITIVE TYPE	MAIN COMPOUND(S)	PURPOSE	COMMON USE OF MAIN COMPOUND
Diluted acid (15% HCl)	Hydrochloric acid	Helps dissolve minerals and initiate cracks in the rock	Swimming pool chemical and cleaner
Biocide	Glutaraldehyde	Eliminates bacteria in water that produce corrosive by-products	Disinfectant, sterilizing medical and dental equipment
Breaker	Ammonium persulfate	Allows a delayed breakdown of gel polymer chains that help suspend the proppant	Bleaching agent in detergent and hair cosmetics, manufacture of household plastics
Corrosion inhibitor	N,n-dimethyl formamide	Prevents corrosion of the pipe	Used in pharmaceuticals, acrylic fibres, plastics
Crosslinker	Borate salts	Maintains fluid viscosity as temperature increases	Laundry detergents, hand soaps, and cosmetics
Friction reducer	Polyacrylamide, Mineral oil	Minimizes friction between fluid and pipe	Water treatment, soil conditioner Makeup remover, laxatives, and candy
Gel	Guar gum or hydroxyethyl cellulose	Thickens water in order to suspend the proppant	Cosmetics, toothpaste, sauces, baked goods, and ice cream
Iron control	Citric acid	Prevents precipitation of metal oxides	Food additive, flavouring in food and beverages, lemon juice ~7% citric acid
KCl	Potassium chloride	Creates a brine carrier fluid	Low sodium table salt substitute
O_2 scavenger	Ammonium bisulphite	Removes oxygen from the water to protect the pipe from corrosion	Cosmetics, food and beverage processing, water treatment
pH adjusting agent	Sodium or potassium carbonate	Maintains the effectiveness of other components, such as crosslinkers	Washing soda, detergents, soap, water softener, glass and ceramics
Proppant	Silica, quartz sand, ceramic beads	Allows the fractures to remain open so the oil or gas can escape	Drinking water filtration, play sand, concrete, and brick mortar
Scale inhibitor	Ethylene glycol	Prevents scale deposits in the pipe	Automotive antifreeze, household cleansers, and de-icing agent
Surfactant	Isopropanol	Used to increase the viscosity of the fracture fluid	Glass cleaner, antiperspirant, and hair colour

6.2 Potential Risks

Environmental impacts and risks commonly exist during HF operations as described in Figure 3.1. Among different types of fracturing waste, flowback water is a major concern in terms of a potential hazard to the location environment. There is also a risk of human exposure to such hazardous waste (Rassenfoss, 2011).

For fracturing systems that rely on water-based fluids, the introduced water is intrinsically non-hazardous regardless of the source. Despite the fact that some of the additives are commonly found in our drinking water and are considered benign at a low dosage, most categories of chemical additives in fracturing fluids might be detrimental or even toxic to humans if they receive excessive exposure to these additives. The chemical composition of HF fluids and the corresponding hazards based on Material Safety Data Sheets (MSDSs) are given in Table 6.2.

Table 6.2. Characteristics of undiluted chemicals found in HF fluids (adapted from Donaldson et al., 2014).

PRODUCT	CHEMICAL COMPOSITION INFORMATION	HAZARDS INFORMATION
Linear gel delivery agent	1. 30-60% by wt. Guar gum derivative 2. 60-100% by wt. Diesel	Harmful if swallowed Combustible
Water gelling agent	1. 60-100% by wt. Guar gum derivative 2. 5-10% by wt. Water 3. 0.5-1.5% by wt. Fumaric acid	May be mildly irritating to eye
Linear gel polymer	1. <2% by wt. Fumaric acid 2. <2% by wt. Adipic acid	Flammable vapours
Linear gel polymer slurry	1. 30-60% by wt. Diesel oil #2	Causes irritation if swallowed
Crosslinker	1. 10-30% by wt. Boric acid 2. 10-30% by wt. Ethylene glycol 3. 10-30% by wt. Monoethanolamine	Harmful if swallowed Combustible
Crosslinker	1. 10-30% by wt. Sodium tetraboratedecahydrate	May be mildly irritating to eye
Foaming Agent	1. 10-30% by wt. Isopropanol 2. 10-30% by wt. Salt of alkylamines 3. 1-5% by wt. Diethanolamine	Harmful if swallowed Highly flammable
Foaming Agent	1. 10-30% by wt. Ethanol 2. 10-30% by wt. 2-Butoxyethanol 3. 25-55% by wt. Ester salt 4. 0.1-10% by wt. Polyglycol ether 5. 10-30% by wt. Water	Harmful if swallowed or absorbed through skin
Treatment – hydrochloric acid	1. 30-60% by wt. Hydrochloric acid	May cause eye, skin, and respiratory burns
Treatment – formic acid	1. 85% by wt. Formic acid	May cause mouth, throat, stomach, skin, and respiratory burns
Breaker fluid	1. 40-100% by wt. Diammoniumperoxidisulfate	May cause respiratory tract, eye, or skin irritation Harmful if swallowed
Microbicide	1. 60-100% by wt. 2-Bromo-2-nitrol, 3 propanedol	May cause eye or skin irritation
Biocide	1. 60-100% by wt. 2,2-Dibrom 3-nitrilopropionide 2. 1.5% by wt. 2-Bromo-3-nitrilopropionamide	Causes severe burns Harmful if swallowed May cause allergic reaction
Corrosion inhibitor	1. 30-60% by wt. Methanol 2. 5-10% by wt. Propargyl alcohol	May cause eye or skin irritation May be fatal if swallowed
Corrosion inhibitor	1. 30-60% by wt. Pyridinium, 2. 1- (phenylmethyl)-, ethyl methyl derivatives, chlorides 3. 15% by wt. Thiourea 4. 5-10% Propan-2-ol 5. 1-5% by wt. Poly (oxy-1,2-eth-anediyl)-noniphenyl-hydtoxy 6. 10-30% by wt. Water	Cancer hazard Causes severe burns to respiratory tract, eyes, and skin Harmful if swallowed or absorbed through skin

In addition to the recovery of the original components in fracturing fluids, flowback water could also bring up minerals and hydrocarbons inside the created fractures of the formations, as well as the by-products of subsurface reactions or degradations. The composition of flowback water varies with location and time, although it partially includes those fracturing fluids that were pumped into the well initially. In general, it may contain a high volume of dissolved solids and a high concentration of barium, bromide, calcium, chloride, iron, magnesium, sodium, strontium, and bicarbonate ions. VOCs including but not limited to benzene, toluene, xylenes, and acetones, as well as radionuclides, are also found in flowback water (Spellman, 2012). These compounds exhibit serious detrimental effects on surface and subsurface environments. Therefore, operators and stakeholders must be cautious about the potential environmental impacts and risks related to flowback water, and treat it responsibly.

The environmental risks related to the handling of fracturing fluids and wastewater can be ascertained from the aspects described below.

6.2.1 Surface spills

Spills may occur during the storage, transport, operation, and treatment of fracturing fluids and flowback water. These spills endanger the local environments by seeping into shallow groundwater aquifers, flowing into surface waters, evaporating into the air, or remaining on the ground surface, depending on the fluids' characteristics and local geographic conditions. It is difficult to quantify the environmental risks that result from a spill event; each event needs to be assessed case by case. Nevertheless, it is essential to identify the possible causes of surface spills and derive mitigation plans.

Many factors lead to surface spills: the rupture of storage tanks, malfunction of pumps, structural failures of pipework, overfilling of impoundment pits, or improper operations (Donaldson et al., 2014). These factors can be controlled by:

- Providing adequate training for the crew handling the equipment and chemicals,
- Using more environmentally friendly chemicals or their substitute,
- Using double-walled tanks to limit the accidental rupture of single walls,
- Preparing site-specific spill prevention and responding plans, and
- Monitoring and inspecting the site at regular intervals.

6.2.2 Subsurface leakages

Contamination of groundwater from subsurface fracturing fluids/flowback water leakages is a major environmental concern. Considering that the perforation and production zone is normally located far below the freshwater aquifer, the likelihood of groundwater contamination from uplifting fluid wastes is extremely low. However, accidents may occur and lead to subsurface leakages. Hence, attention needs to be paid to properly insulating the injection wells with multiple strings of casing and layers of cement as well as to the production tubing.

Each string of casing serves as a layer of protection, separating the fluids inside and outside the casing and preventing them from coming into contact with each other. As illustrated in Figure 6.1, these structures should be well maintained and monitored to ensure that they are of sufficient strength and to prevent the contamination of freshwater aquifers due to subsurface leakages of fracturing fluids or flowback water. Monitoring measures normally include acoustic cement bond logs as well as pressure testing (Spellman, 2012). Certain technical criteria regulate the depth of protective casings and cement setting times, which might be modified according to specific regional conditions.

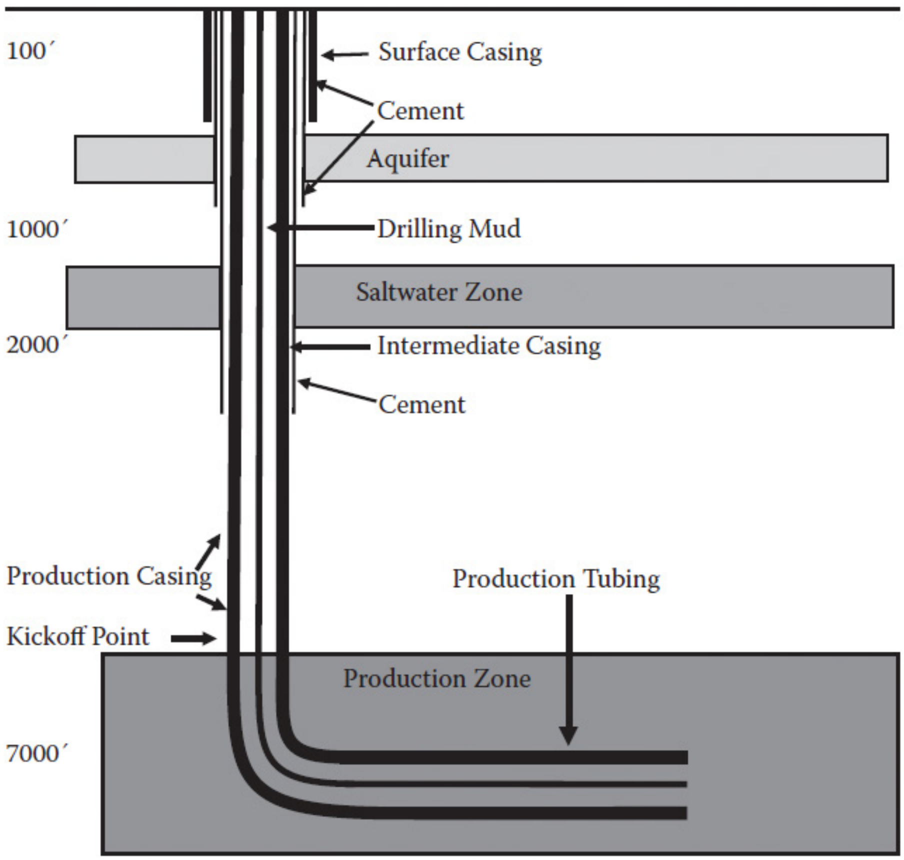

Figure 6.6.2. Subsurface casing and cementing for HF operations (adapted from Spellman, 2012).

6.2.3 Disposal

Direct land disposal or the discharge of wastes from HF operations into waterways is forbidden. However, illegal dumps of fracturing waste still exist. For example, fracturing wastes were illegally discharged at multiple times into the municipal water storage pond of Dawson Creek, British Columbia (Linnitt, 2014).

Indeed, disposal is an option for fracturing waste management only in places where deep-well injections are feasible. When designing an underground disposal well, it is critical that the geological conditions are evaluated closely to ensure that there is no slip or that no earthquakes might be caused by HF operations. The subsurface formation selected for waste disposal should have high porosity and permeability but with impermeable zones above it to isolate the waste from shallow-water aquifers. The installation of monitoring wells is also recommended to detect any leaks or migration of the injected waste fluids (Haluszczak et al., 2013).

6.3 Flowback Water Management

The proper handling of waste materials associated with HF is essential throughout the lifecycle of the operations. In particular, flowback water, which typically accounts for 15 to 80 percent of the fracturing fluids' returning to the surface after the initial injection, contains various hazardous chemicals that severely endanger the environments and human beings who receive excessive exposure to them (Ferrar et al., 2013).

A common onshore practice involves separating free water from the solids, burying the solids in a suitably lined pit (usually the reserve pit at a drilling site), filling that pit with soil, and covering it with topsoil. The water is treated to the necessary standards for disposal into local systems or pumped into injection wells to depths safely below freshwater aquifers. The separation of free water from the solids often is aided by chemical flocculants; their environmental acceptability must also be assessed.

In order to mitigate the environmental impacts and risks, three approaches are generally employed to manage flowback water: direct disposal by deep-well injection, recycling and reuse, and treatment for discharge. Table 6.3 presents examples of current US fracturing waste management plans.

Table 6.3. Current fracturing waste management approaches in the United States by shale gas basins (adapted from G.W.P. Council, 2009).

SHALE GAS BASIN	WATER MANAGEMENT TECHNOLOGY	AVAILABILITY	COMMENTS
Barnett Shale	Injection wells	Commercial and non-commercial	Disposal into the Barnett and Underling Ellenberger Group
	Recycling	On-site treatment and recycling	For reuse in subsequent fracturing jobs
Fayetteville Shale	Injection wells	Non-commercial	Water is transported to two injection wells owned and operated by a single producing company
	Recycling	On-site recycling	For reuse in subsequent fracturing jobs
Haynsville Shale	Injection wells	Commercial and non-commercial	
Marcellus Shale	Injection wells	Commercial and non-commercial	Limited use of Class II injection wells
	Treatment and discharge	Municipal wastewater treatment facilities, commercial facilities reportedly contemplated	Primarily in Pennsylvania
	Recycling	On-site recycling	For reuse in subsequent fracturing jobs
Woodford Shale	Injection wells	Commercial and non-commercial	Disposal into multiple confining formations
	Land application		Permit required through the Oklahoma Corporation Commission
	Recycling	Non-commercial	Water recycling and storage facilities at a central location
Antrim Shale	Injection wells	Commercial and non-commercial	
New Albany Shale	Injection wells	Commercial and non-commercial	

6.3.1 Injection wells

Disposal of flowback fluids through injection, where an injection zone is available, is widely recognized as being environmentally sound, is well regulated, and has proven to be effective.

Another method sometimes used is annular injection. Originally, mud was pumped into the annulus of the well for permanent disposal. Both freshwater aquifers and hydrocarbon-producing reservoirs are protected by cement and pipework. Casing depths and injection pressures often are regulated by state and/or local agencies. Recent improvements on this technique involve grinding and slurring of the cuttings, followed by pressurized injection into the formations. Annular injection leaves almost no footprint at the rig site and greatly reduces the potential of surface and/or groundwater contamination. It cannot be used in some areas because of down-hole formations or proscription by agencies (Vengosh et al., 2014).

6.3.2 Recycling/Reuse

The transportation and processing of the large amounts of water required for HF is expensive. Moreover, the strict environmental regulations on the injection of flowback and produced water are considerably costly (Montgomery and Smith, 2010). For these reasons, the industry started using water produced from HF treatments. In some parts of the world where water is scarce, this approach is even more attractive (Gregory et al., 2011).

A system for reclaiming flowback or produced water typically includes anaerobic digestion, followed by aerating the water to enhance biological digestion. The water is then separated by using a flotation operation that effectively removes the spent friction-reducing agents and allows the treated water to be reclaimed and reused as fracturing water. In a separate branch of the unit, a three-stage process occurs. It passes through the sand pack filter, which is followed by bioreactors, and finally through a boron treatment unit before being safely discharged to the environment (Hickenbottom et al., 2013).

Reusing flowback or produced water may present microbial, salinity, and hardness issues. All these may require higher loadings of biocides, polymers, friction reducers, or other additives to achieve the desired viscosities and transport proppant or maintain pumping pressures. All this ultimately adds to the pre-treatment cost (Watts, 2013).

6.3.3 Treatment facilities

Flowback or produced water can be treated on-site for reuse or transported to off-site treatment facilities. Some common technologies for wastewater treatment also apply to flowback and produced water.

For instance, Reverse Osmosis (RO) technology is a well-known water treatment method which has been widely implemented to produce high-quality municipal and industrial water. Wastewater passes through a semi-permeable membrane under pressure in an RO system, from which suspended particulates, organic molecules, or even undesired ions are removed. Despite the fact that trials using RO systems in treating HF flowback water led to a dramatic decrease in the volume of waste concentrate to be disposed, the intensive energy requirements impeded the scaled application for the treatment of high Total Dissolved Solids (TDS) flowback water in practice (Gregory et al., 2011).

Vibratory shear-enhanced processing (VSEP) is another technical option that can be applied, together with membrane technologies, for high-TDS flowback-water treatment. In VSEP, gaskets separate the flat membranes, which are arranged in parallel. A leaf element tangent to the membrane surface vibrates to create shear, which lifts solids and fouling material off the membrane surface; as a consequence, colloidal fouling and polarization of the membrane are reduced. VSEP technologies have been successfully used in offshore produced-water treatment (Gregory et al., 2011; Shi and Benjamin, 2011).

For operations in Western Newfoundland, the choice of flowback-water management plans to a large extent depends on the specific conditions of HF: whether the site is suitable for deep-well injection, the supply of water is scarce, and the temporal and spatial requirements of waste treatment facilities can be satisfied.

6.4 Regulations and Best Practices

Sections 82 to 84 of the Petroleum Drilling Regulations (NLR 1150/96) provide the general requirements for waste collection, storage, and disposal. Fundamentally, operators are required to store, treat, and dispose waste in a manner that does not lead to a hazard to safety, health, or the environment. In addition, waste oil must be collected in a closed system and not burned at the drill site. The provision of chemical disclosure of fracturing fluids is not specified in Newfoundland and Labrador O&G regulations. However, the operating practices recommended by CAPP include:

Disclose Fracturing Fluid Additives

To assure the safe application of HF technology, this practice outlines the requirements for HF operators to disclose, on their own websites or on a third-party website, for each well undergoing HF:

- The trade name of each additive and its general purpose in the fracturing process,
- The name and the chemical abstracts service number of each chemical ingredient listed on the MSDS for each additive, and
- The concentration of each reportable chemical ingredient.

Risk Assessment and Management

To better identify and manage the potential health and environmental risks associated with fracturing fluids, this practice outlines the requirements for the risk-based assessment and management of fracturing-fluid additives, and thereby selecting fracturing fluids with lower risk profiles, where possible.

Baseline Groundwater Testing

In order to establish the baseline characteristics of the groundwater predevelopment, and to analyze whether there have been changes over time, this practice outlines the requirements for HF operators to test water quality within 250 metres of shale gas, tight gas, and tight oil development and to participate in long-term regional groundwater monitoring programs.

Wellbore Construction and Quality Assurance

This practice outlines the requirements for O&G operators to ensure that all wellbores are designed, installed, and maintained to ensure wellbore integrity prior to initiating HF operations in order to prevent any fluids from migrating into groundwater zones.

Water Sourcing, Measurement and Reuse

This practice outlines the requirements for O&G operators to safeguard water quantity through the assessment and measurement of available water supply sources and water use, and reusing water as much as practical in HF operations.

Fluid Transport, Handling, Storage and Disposal

This practice outlines the requirements for O&G operators to transport, handle, store, and dispose all fluids and fracturing-fluid waste in a manner that is safe and environmentally responsible. It also requires the operator to identify, evaluate, and mitigate potential risks related to fluid transport, handling, storage, and disposal and to respond quickly and effectively to an accidental spill of fluids (including remediation of the spill site).

CAPP strongly recommends that O&G operators adopt these practices. A regulator such as the Government of Newfoundland and Labrador would have the authority to review and implement these practices.

7.0 SITE RESTORATION

When drilling activities have been completed, the areas surrounding the well pad must be restored as closely as possible to pre-drilling conditions. This generally involves landscaping and contouring the property, removing infrastructure, and assessing soil remediation, if necessary, and long-term monitoring at the site. The following section elaborates on potential remediation technologies and site-decommissioning procedures.

7.1 Potential Remediation Technologies

Based on current remediation technologies, Figures 7.1 and 7.2 present a review and classification of currently adopted remediation technologies based on their application and cost respectively. From Figure 7.2 it can be observed that the remediation technologies within Category A refer to confined or stabilized contaminants in-situ, such as solidification and stabilization. Although these technologies prevent contaminants from further entering the groundwater and downstream environment, the contaminants remain in-situ. Category B technologies are those through which contaminants will be degraded chemically and biologically in-situ. On the other hand, Category C removes contaminants ex-situ by extracting them using air, water, or chemical solvents. In Category D technology, soil will be excavated and treated ex-situ using physical, chemical, or biological methods.
The remediation cost for these technologies depends on the location of the contaminated site and the required cleanup time. Generally, the longer the duration of the remediation project, the lower the required cost. Additionally, the cost for contaminated sites in cold regions is much more expensive than those in a temperate zone. The following sections present a review of soil and groundwater remediation technologies suitable for application in Western Newfoundland.

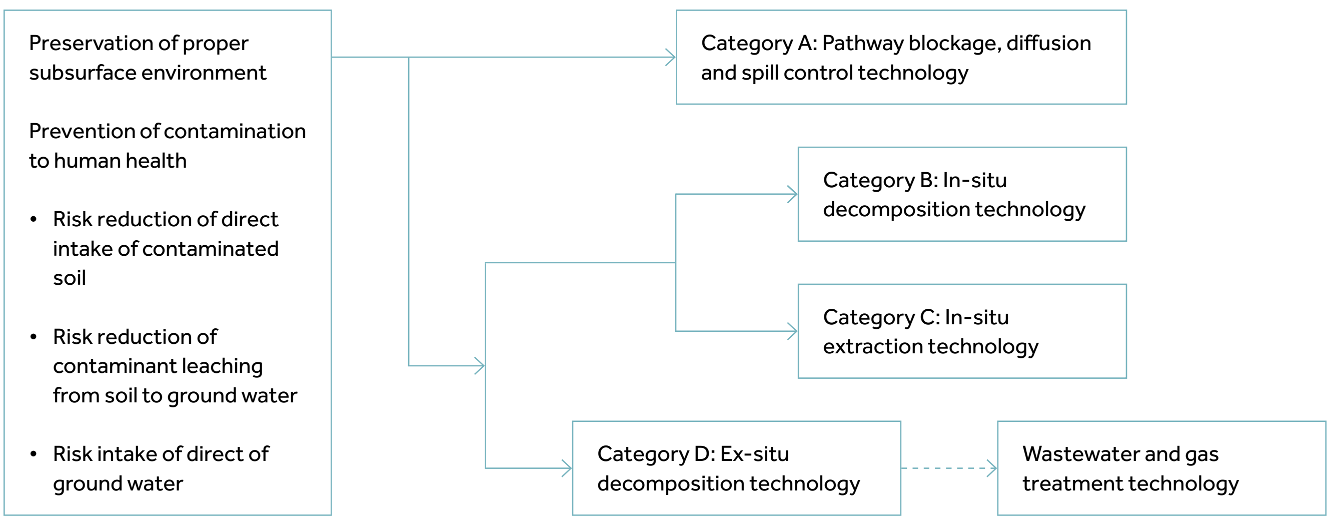

Figure 7.7.1. Review of soil remediation technologies.

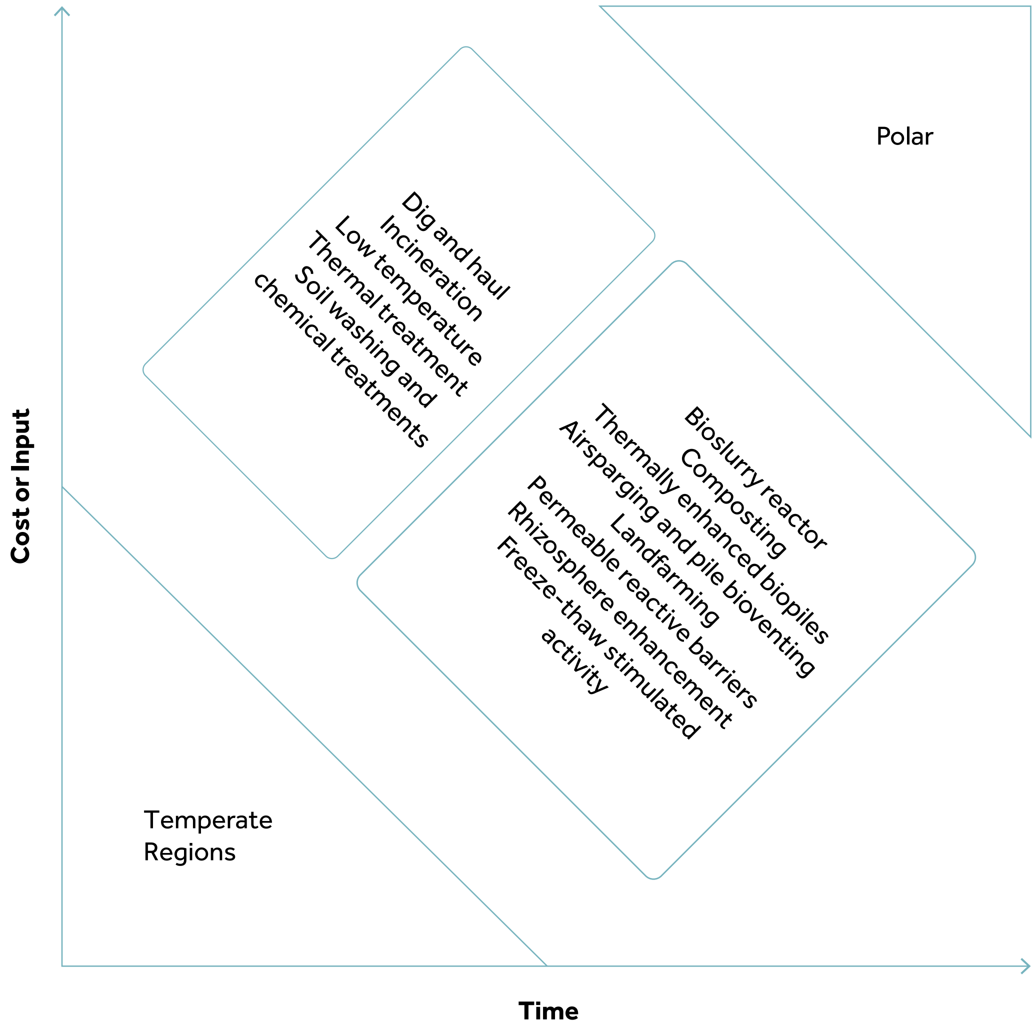

Figure 7.7.2. Cost and time effect of soil remediation technologies.

7.1.1 Soil Remediation

Soil Washing

Soil washing (SW) is a water-based process for removing contaminants from soil particles. Water is mainly adopted as the washing agent; solvents will also be considered based on the physicochemical characterization of the contaminant and the environmental conditions in the contaminated area. Based on the characterization of the target component, a SW system can be attached as pre- or post-treatment systems and thereby minimizing or eliminating secondary waste. A significant volume reduction of contaminant can be achieved through this technology. As an alternative to slow remediation processes such as biological treatments (e.g., enhanced natural attenuation) or costly soil-denaturing processes (e.g., thermal treatments), SW can be used as an on-site and mobile system. There are no stringent permit requirements for such activities. It appears to be a reliable technique (Mousset et al., 2014) and a number of USEPA superfund sites have adopted SW as the cleanup technology of choice. Table 7.1 presents those parameters that need to be identified before the application of SW.

Table 7.1. Parameters for determining the treatability of a contaminated site (Suer, 1995).

KEY PHYSICAL	
Particle Size Distribution	
>2mm	Oversize pre-treatment requirements.
0.25-2 mm	Effective soil washing.
0.063-0.25 mm	Limited soil washing.
<0.063 mm	Clay and silt fraction-difficult soil washing.
Other Physical	
Type, physical form, handing properties	Affects pre-treatment and transfer requirement.
Moisture content	Affects pre-treatment and transfer requirements.
Key Chemical	
Organics Concentration Volatility Partition coefficient	Determine contaminants and assess separation and washing efficiency, hydrophobic interaction, washing fluid compatibility, changes in washing fluid with changes in contaminants. May require pre-blending for consistent feed. Use the jar test protocol to determine contaminant partitioning.
Metals	Concentration and species of constituents (specific jar test) will determine washing fluid compatibility, mobility of metals, posttreatment.
Humic acid	Organic content will affect adsorption characteristics of contaminants on soil. Important in wetland sites.
Other Chemical	
pH, buffering capacity	May affect pre-treatment requirements, compatibility with equipment materials of construction, wash fluid compatibility.

Based on Table 7.1, SW can be considered a promising soil-remediation technology in Newfoundland for the following reasons:

1. **Treatability of potential target compounds:** Given the complex composition of petroleum products generated on-site, and the variety of injection solution for operation, the remediation technology could effectively remove all the target compounds if a spill accident happens. SW exhibits considerable potential in cleaning up soil contaminated with a wide variety of organic and inorganic contaminants, such as semi-volatile organic compounds (SVOCs), petroleum and fuel residuals, polychlorinated biphenyl (PCB), polycyclic aromatic hydrocarbon (PAH), heavy metals, and radionuclides. A combination of solvents or a sub-sequential washing process may be required due to the waste-stream mixture. Additionally, washing water needs to be further treated before its disposal.

2. **Efficient and economical for a large contaminated site:** Figure 7.2 shows that SW technology can be considered an effective remediation technology in the cleanup of contaminants, especially in a cold region such as Western Newfoundland. According to USEPA, the average cost of an SW project is approximately $150 to $250 per ton, yet the remediation cost is significantly reduced to one-third of its original cost as the soil volume increases. Therefore, SW would be a cost-effective approach to cleaning up a large contaminated project site.

3. **Feasibility of soil texture:** SW is most effective for soil that does not contain a large amount of silt and clay. In a previous section it was noted that most sites in Western Newfoundland are sandy loam or have a high content of sand, and thus SW is a promising candidate for the removal of possible contaminants in these drilling sites.

Soil Flushing

This technology is accomplished by passing the extraction fluid through in-place soils using an injection or infiltration process. Extraction fluids must be recovered from the underlying aquifer and, when possible, they are recycled. Similar to SW, soil flushing applies to almost all types of soil contaminants and is generally used in conjunction with other remediation technologies such as activated carbon, biodegradation, and pump and treat (Khan et al., 2004). Other than the advantages mentioned above that suit it for application in Newfoundland and Labrador, soil flushing further reduces the need for the excavation, handling, or transportation of hazardous substances by conducting the remediation task on-site.

Chemical Oxidation

Chemical oxidation involves the delivery of oxidants into soil and groundwater to destroy organic chemical contaminants. The most commonly employed oxidant includes catalyzed hydrogen peroxide (H_2O_2) (modified Fenton's), activated sodium perfulfate ($Na_2S_2O_8$), potassium or sodium permanganate ($KMnO_4$, $NaMnO_4$), or O_3. These oxidants can efficiently destroy many toxic organic contaminants (with a ratio for over 90 percent destruction in a minute) with well-established reaction stoichiometries, pathways, and kinetics over a wide range of contaminants. In one soil remediation project in New Jersey, $Na_2S_2O_8$ was adopted as the oxidant to clean up VOC-contaminated soil and groundwater. Over 5,000 tons of soil was treated within two days, and the concentration of the contaminant dropped from 100-200 parts per million total VOCs in the groundwater to less than 0.1 parts per million within one week.

Factors affecting the application of chemical oxidation in Western Newfoundland:

1. Soil texture in Newfoundland and Labrador: The soil type and subsurface lithology will impact the effectiveness of chemical oxidation. The type of soil (sand, silt, clay, or gravel) will largely determine the amount of water that the soil can hold (pore space volume) and the velocity at which the groundwater can travel through the soil (permeability). The mass transfer of contaminant and oxidant in high permeability soils (e.g., sand) is dictated by dispersion/advection. The mass transfer of contaminant and oxidant in low permeability soils (clay) is dictated by diffusion. The length of time and the plausibility that the oxidant will come in contact with the contaminant will be governed by the lithology. The oxidant will travel through sandy lenses more quickly than through clay lenses. Fractures provide preferential pathways that bypass pockets of contamination.

2. Clays and silts tend to bind contaminants to their surfaces more tightly than sands. If this is not considered in the delivery design across heterogeneous lenses, the chemical oxidant will circumvent the low permeable clay and silt lenses in favour of the more highly permeable sands. The oxidant will not make contact with the residual non-aqueous phase liquid (NAPL) and the treatment will fail. If the lenses are well characterized, then the injection of the oxidant can be directly targeted to tighter soils by the use of special injection tools. However, it should be recognized that it is difficult to obtain an adequate distribution of oxidant in clays without applying the oxidant in closely spaced, multiple injection points. In addition, some aquifers and soils will have a greater competing background or natural oxidant demand than others. Generally, the longer it takes the chemical oxidant to travel through the soil, the greater the oxidant consumed by competing demands. Furthermore, tighter soils tend to have a higher native organic content with which the oxidant might react. The special considerations given to fracture sedimentary rock and fractured clay such as saprolite are discussed later in this report. The outcome is a function of how well the fractured areas containing these sources can be identified and then how well those fractures are targeted. Channeling will occur through more highly permeable fractures at the expense of less permeable fractures.

3. Site structures/impediments: Site infrastructure such as buildings and utilities need to be identified and evaluated for chemical oxidation. Utility corridors may serve as preferential pathways for oxidant delivery if not properly

planned for. Safety considerations must be addressed when injecting oxidants under and around buildings and other structures, particularly when treating shallow contamination. A geotechnical evaluation may be warranted prior to injecting large volumes of solution directly underneath footings and foundations. Obviously, surface structures may also limit the feasibility of reaching all of the contamination, depending on the method of delivery and, hence, the success of the project. The alkaline chemistry of RegenOx® is more chemically compatible with typical site infrastructure than most other chemical oxidants. As mentioned previously, Fenton's type chemistry and activated persulfate typically require acidic conditions that can be very corrosive. For this reason, Fenton's type remediation is not recommended near tanks or the pumping islands of commercial gasoline stations.

4. Selection of oxidant and delivery system: The selection of a proper oxidant and in-situ delivery system on the basis of target contaminants and site conditions is the key to its successful implementation. The rate and extent of degradation of a target contaminant are dictated by the properties of the chemical itself and its susceptibility to oxidative degradation as well as the matrix conditions, most notably, pH, temperature, oxidant concentration, and the concentration of other oxidant-consuming substances such as natural organic matter and reduced minerals as well as carbonate and other free radical scavengers. Given the relatively indiscriminate and rapid rate of reaction of the oxidants with reduced substances, the method of delivery and distribution throughout a subsurface region is of paramount importance. Oxidant delivery systems often employ vertical or horizontal injection wells and sparge points with forced advection to rapidly move the oxidant into the subsurface.

5. Additionally, the integration of chemical oxidation and in-situ bioremediation has long been recognized as a very cost-effective technology for achieving low contaminant concentrations when applied to dissolved phase contaminant plumes. The more readily degraded by-product due to chemical oxidation that can be metabolized by microbes in the subsurface may be a very successful and cost-effective strategy.

6. However, engineering of in-situ chemical oxidation must be done with due attention paid to reaction chemistry and transport processes. It is also critical that close attention be paid to worker training and the safe handling of process chemicals as well as the proper management of remediation wastes. The design and implementation process should rely on an integrated effort involving screening-level characterization tests and reaction transport modeling combined with treatability studies at the laboratory and field scale.

Bioremediation

Figure 7.2 shows that bioremediation is more cost-efficient than other technologies. Bioremediation through the metabolic process of living organisms, primarily microorganisms, to degrade toxic contaminants into less toxic forms has proven to be a promising technology. Heavy metals, which are not biodegradable, can be accumulated by microorganisms, and transformed either by a redox process or by alkylation, which thereby changes their mobility and toxicity. Bioremediation can be classified into in-situ and ex-situ bioremediation depending on the place and the soil handling/conditioning process. In-situ bioremediation is a biological process where microorganisms flourish and metabolize organic contaminants into harmless products on-site with minimum disturbance to the environment. Ex-situ techniques remove the contaminants off-site via extraction (soil) or pump (water). The second remediation technique is useful for treating contaminated sites with low hydraulic conductivity, low permeability combined with high concentration of recalcitrant contaminants, and contaminated sites that require a short remediation time. In-situ bioremediation, on the other hand, is a relatively long-term remediation process which is less costly and has potentially remarkable efficiency in cleaning up contaminated sites without producing toxic by-products; it has gained increasingly attention in the last few decades. To improve the efficiency of bioremediation and to reduce the remediation duration, working conditions at the site will be designed or engineered; this is termed engineered or enhanced in-situ bioremediation.

Generally, bioremediation is still a site-dependent approach, and environmental factors have a significant role in controlling the effectiveness of the technology. The removal of oil and heavy metal contamination in cold regions has been recognized as an area of particular importance. Bioremediation is appealing to the industry due to its potential efficiency and cost-effectiveness. Although the extreme habitats in Western Newfoundland are a challenge for bioremediation, with proper design and the integration of other remediation technologies, a satisfactory result can be achieved.

Factors affecting the application of bioremediation in Western Newfoundland:

1. **Identification of indigenous cold-adapted microorganisms.** Using indigenous cold-adapted microorganisms is important for in-situ bioremediation in a cold environment. Cold-adapted microorganisms, including bacteria, fungi, and algae, have been screened and identified as having the ability to metabolize aliphatic and aromatic hydrocarbons in cold regions, even in areas that have not previously experienced oil-spill pollution. Whereas different microbial communities have specific metabolic capabilities and can only degrade limited hydrocarbons, a diverse population of microorganisms is required to attack complex mixtures of hydrocarbons in a specific environment. Although the establishment of diverse microbial communities remains a challenge for engineers due to limited bioavailability and permeability in a cold climate, Cai et al. (2014) and Cai et al. (2015) have identified over 150 indigenous bio surfactant-producing and oil-degrading bacteria in Newfoundland's coastal area; this indicates the existence of numerous indigenous cold-adapted microorganisms in this region and a great potential for the application of bioremediation.

2. **Availability of nutrient.** The nutrient content of a contaminated site directly impacts microbial activity and biodegradation efficiency. Nutrient elements or organic compounds act as donors/accepters of carbon or electrons in bioremediation. Nevertheless, it is generally accepted that soils in cold regions are low in nutrients; the bioremediation of contaminants will further deplete such limited nutrients as nitrogen and phosphorus. The addition of nitrogen and/or phosphorus to cold region soil systems can enhance the rate of bioremediation. Reported optimum C/N ratios vary from 9:1 to 200:1, which largely depend on soil type. In order to enhance bioremediation in the cold region of Western Newfoundland, nutrient addition should be considered. Additionally, reports indicated that, due to lower water-holding capacities, sites with sand and loamy sand characteristics, such as the region of Western Newfoundland, are more sensitive to over-fertilization, and thus a proper nutrient ratio should be examined.

3. **The influence of ambient temperature on the extent of microbial hydrocarbon metabolism.** Weather conditions in Western Newfoundland generally result in a short summer and an extremely cold winter. Historical weather data indicates that the average temperatures are less than 10°C during most of the year except during the short summer (May-September). Temperature fluctuations greatly affect the physical nature and chemical composition of the spilled oil. A decrease in temperature leads to an increase in oil viscosity and reduced volatilization of low-molecular-weight compounds, thereby delaying the activation of oil biodegradation. Temperature is also proportional to the physicochemical characteristics of the environment and contaminants, thus affecting the bioavailability, diffusion, and volatilization of contaminants. Provided that the contaminants have a low solubility, the biodegradation rate of pollutants is largely dictated by the limitations of mass transfer. Low temperatures, especially those of frozen soils in winter, severely inhibit the mass transfer of the contaminant, thus reducing the bioavailability of pollutants. The application of additives, especially those with a low toxicity and high activity such as a bio surfactant can be used in bioremediation. Zhang and Zhu (2012) have demonstrated the feasibility of bio surfactant-enhanced in-situ bioremediation of a contaminated site in Newfoundland and Labrador in a pilot study. As previously mentioned, more than 150 bio surfactant-producing and oil-degrading strains have been identified by their research group, which exhibits a great potential for the application of bioremediation in Western Newfoundland.

7.1.2 Groundwater Remediation

Pump and Treat

Pump and treat is a common technology to treat contaminated groundwater (Khan et al., 2004). Various wells are installed in the contaminated aquifer area; contaminated water is carried away by fresh water and further treated on-site to remove the contaminants. Treated water is directly injected back into the aquifer or discharged to municipal wastewater treatment plants. The use of pump and treat alone is inefficient; it can be combined with enhanced or advanced technologies to improve its efficiency. This technology itself can be designed to prevent the spread of contaminants and to treat a contaminated water body in deep areas.

Application of Pump and Treat

Pump and treat utilizes high pressure fresh water injected into a contaminated groundwater body to bring the plume to surface treatment facilities. Two advantages of this technology: it can be used for treating wide target compounds such as VOCs, SVOCs, and heavy metals, and its flexibility allows it to be combined with other technologies. Although it is a time-consuming technology, it has produced a significant effect on highly contaminated sites (USEPA, 1996).

In-Situ Treatment Wall

An in-situ treatment wall, a relatively new technology, has been developed and utilized in the past 20 years. Treatment walls are generally used in the treatment of contaminated groundwater. The mechanisms include degradation and sorption: in degradation, the filling materials react with contaminants in the water and transfer them into a harmless or less harmful formation; and sorption adsorbs contaminants onto the walls by the high surface area and multi-pore structures of the material. Detailed applications, mechanism, and filling materials are listed in Table 7.2.
Application of treatment walls

Depending on the filling material, the target contaminants of treatment walls can be divided into inorganic and organic contaminants. Table 7.2 shows the main target compounds and filling media that are generally utilized in treatment walls.

Table 7.2. Major target compound and filling materials of treatment walls.

<table>
<tr><th>ORGANIC COMPOUNDS</th><th>MECHANISM</th><th>FILLING MATERIALS</th></tr>
<tr><td rowspan="6">BTEX
PAHs, PCBs
Perchloroethylene (PCE), Trichloroethylene (TCE), Dichloroethene (DCE), Trichloroacetate (TCA), Dichloroacetate (DCA)</td><td rowspan="3">Degradation</td><td>Zero-valent iron</td></tr>
<tr><td>Microorganisms</td></tr>
<tr><td>Oxidizer</td></tr>
<tr><td rowspan="3">Sorption</td><td>Activated carbon</td></tr>
<tr><td>Zeolite</td></tr>
<tr><td>Bentonite</td></tr>
<tr><td>Inorganic compounds</td><td></td><td></td></tr>
<tr><td rowspan="5">Heavy metals
Radioactive metals</td><td rowspan="3">Sorption</td><td>Bentonite</td></tr>
<tr><td>Zeolites</td></tr>
<tr><td>Modified activated carbon</td></tr>
<tr><td rowspan="2">Precipitation</td><td>Zero-valent iron</td></tr>
<tr><td>Limestone</td></tr>
</table>

In a HF site, various treatment walls can be applied based on different contaminants types. Table 7.2 indicates that bentonite, zeolite, and activated carbon can be applied to organic and inorganic compounds, and, due to the physical sorption mechanism, both materials could passively adsorb contaminants without any specific conditions (such as pH, temperature, and pressure) being required; however, the disposal of treated walls could be a concern due to a high concentration of contaminants.

7.2 Site Decommissioning

7.2.1 Exploitation Period

The decommissioning procedure after the exploitation period can be divided into two processes: a non-commercial quality reservoir and a commercially available reservoir. As the first does not contain sufficient hydrocarbons for commercial purposes, it would be abandoned. The second, containing hydrocarbons, is economically commercially available. This site would be further exploited for production, and before production the site should be properly preserved to prevent uncontrollable contamination.

Non-Commercial Quality Reservoir

After exploitation drilling, if there is no commercial quality reservoir available in a specific site, the proper decommissioning procedure is required. Drilling rigs must be removed if there is to be no more exploitation in the area. All access roads to the abandoned site should be properly closed and locked.

Pre-Production Period

During the period between exploitation and production, if the site is not used before production, it needs to be properly protected and access to it should be strictly prohibited.

7.2.2 Post Production – Abandonment Period

Rigs and Infrastructure

All drilling equipment should be disassembled and removed from the site. Wellheads must be properly sealed and buried under the surface. All drilling holes should be resealed and monitored to prevent facility aging and leakages.

Fluid Tanks

Fluid tanks are utilized to store fracturing fluid, which is mainly water. After the abandonment of wells, all fluid tanks can be recycled and reused for the next wells or for other purposes. Only during the fracturing period is there a high water consumption; after this period, the demand for water can be reduced, and the fracturing fluid storage tanks can be cleaned and reused as water tanks or as temporary oil storage tanks. When a site is to be abandoned, portable oil tanks can be trucked and moved to other sites. Leaking tanks need to be cleaned and fixed.

7.3 Monitoring

Air, groundwater, soil, and seismicity are four major concerns for a HF site. A monitoring program will focus on these parameters. Regulations, BMPs, and technologies have been developed for groundwater and seismicity monitoring.

Groundwater Monitoring

Seven operating practices were developed to fulfill CAPP's requirements for shale and shale gas HF. These practices were developed by all CAPP companies and are Canada-wide and include baseline groundwater testing (BGWT), water sourcing, measurement, and reuse (CAPP, 2012b). BGWT requires baseline data of the groundwater within a 250-metre radius of the project site before drilling exploration as background data; during the project period, water will be periodically sampled to trace changes in water quality and levels.

For private wells, CH_4 contamination has been reported in some sites in the US. Table 7.3 lists the basic criteria for domestic (private) well monitoring from an operating practice (CAPP, 2012a):

Table 7.3. Criteria of domestic well monitoring.

CATEGORIES	REQUIREMENTS
Distance	within 250 m from the project site
Chemical analysis	basic drinking water related test following guidelines from Health Canada and fracturing related organic and inorganic compounds
Physical analysis	water pressure and water level of the well
Procedure	background data acquiring, continuously monitoring program after production

Before exploration and after production, a complete site investigation needs to be done to determine post-project differences. This can include the surface and subsurface environment, ecology habitat, wildlife access, and vegetation. CH_4 contamination has been reported in various US fracturing sites. As shown in Figure 3.2 of the potential hydrocarbon reservoirs in Western Newfoundland, only the DLB region contains both shale oil and natural gas resources; other possible reservoirs may only contain shale oil. Monitoring wells may be required to ensure that the groundwater near the project site is free of contaminant. This monitoring should be applied at the beginning of the exploration period due to potential well blowout during drilling. Poor well integration, migration from fractured rocks, and pipe leakage are three other possible causes of CH_4 contamination. Table 7.4 lists the main parameters recommended by FracFocus US.

Table 7.4. Suggested groundwater parameters recommended by US FracFocus (US FracFocus, 2015).

CHARACTERISTICS	TDS, Specific Conductance and pH
Organic compounds	BTEX, diesel range hydrocarbon, gasoline range hydrocarbon, total petroleum hydrocarbon, and dissolved CH_4
Metals	Fe, Mg, Ca, Se, B, Na, and K
Hazardous metals	As and Cr
Radioactive material	Ba and U
Other	Major ions and cations

Canada FracFocus (2015) also suggests that TDS is the main target parameter in groundwater monitoring. In natural groundwater, the average TDS level is about 4,000 parts per million, while in contaminated water it can be greater than 10,000 parts per million.

Land Monitoring

Soil contamination could occur from accidental blowout, failure of the wellbore, and improper protection of wastewater pits. Additional monitoring wells are required to provide real-time monitoring of subsurface pressure during drilling and production periods; the abnormal pressure could potentially be the cause of blowout. Regular soil and water sampling around wastewater pits is necessary to detect any leakage or damage of the pits' containment. A monitoring well may be required for shale gas to find the source and the migration of CH_4, and thus to prevent the contamination of ground- or surface water. Field soil sampling for VOCs, SVOCs, PAH, metals, and radioactive metals is needed to continuously determine the quality of the soil surrounding the well and if there is any pipeline leaking or wellbore failure. Monitoring the diversity of vegetation and wildlife can be an indicator of surface or subsurface hydrocarbon leakage (Elliott, 2014).

Seismicity Monitoring

A seismograph can be set up around the project site to provide real-time subsurface seismic events.

Monitoring Health and Social Impacts

Assessments should evaluate short-term, cumulative, and long-term health and social impacts and consider mechanisms for enhancing health equity and the unique health and social needs of vulnerable populations. Specific monitoring of the impacts on Aboriginal peoples' physical and mental health, social well-being, quality of life, and the ecological systems on which they depend is therefore essential. This includes not only the impacts of shale gas development directly on their health, communities, and cultures, but also the indirect and long-term impacts of intrusion into traditional territories and economic and social activities (Council of Canadian Academies, 2014).

Surface Water Monitoring

Linkages between surface water and groundwater are seldom sufficiently understood (Council of Canadian Academies, 2014). As much as possible baseline data for the surface water around the well site is required.

7.4 Monitoring Program for Existing Sites

HF has been operated and developed in Alberta for over 60 years. Alberta Environment and Parks (AEP) illustrated that currently over 250 groundwater monitoring wells have been drilled in the province to provide near real-time data.

Due to the different environment, habitat, ecosystem, and vegetation in every project, it is difficult for decision makers to develop one generalized monitoring protocol. An indicator-based monitoring program was developed to help decision makers focus on the most important factors in a specific project. This monitoring technology has been utilized in Alberta for in-situ oil-sands monitoring. Decision makers give different weights for all elements affected in the site area, and then generally eight indicators will be chosen based on a consideration of time and economic and social effects. Decision makers can focus on the chosen indicators to prioritize assessment and practice in a specific project (Antoniuk et al., 2009).

Four forms of indicators are listed below:

- Physical and chemical indicators: air and water quality; animal body burden based on direct measurements or modelled conditions;
- Ecological indicators: habitat quality; species presence or relative abundance; biodiversity present in a defined area;
- Social indicators: economic performance, population dynamics, infrastructure and service availability, resource use, or individual or community well-being; and
- Land and resource use indicators: human activity intensity; direct and indirect footprint associated with linear corridors, clearings, industrial and commercial facilities, and residential and recreational sites.
- Project specific and general indicators can be generated from these four criteria.

- A seismic mapping network could help in seismicity monitoring, and monitoring sites are required to be in at least a 5-kilometre radius from the well. In the Fox Creek site alone, over 40 monitoring sites were set up to give accurate and precise seismic activity (AER, 2015).

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 Air Quality

The impact of HF operations on air quality is of high magnitude when compared to conventional O&G operations. These include emissions of criteria pollutants such as PM_{10}, $PM_{2.5}$, NO_x, SO_2 and CO. Other emissions include BTEX, which is occupational health hazard and CH_4 contributes to global warming. A preliminary dispersion modelling on selected criteria pollutants was undertaken in a small domain in the Western Newfoundland. A hypothetical release scenario was developed based on previous drilling studies. The modelling exercise revealed that all pollutants were below NL air quality standards, however peak concentrations of NO_2 were relatively high. In addition to its adverse effect on human health, NO_2 plays significant role in the formation of O_3. Hence it is highly recommended that a photochemical modelling must be performed to study the regional ozone formation.

The following mitigation measures are recommended to minimize the impact of HF activities on air quality:

- Operators must conduct a baseline air-quality study in conjunction with periodic, site-specific air-quality monitoring at their facilities for various criteria pollutants.
- GHG emissions must be minimized by setting the emission limits, creating inventories, modeling and monitoring the emissions, and employing green completion techniques in HF operations.
- Operators planning to conduct HF in Newfoundland must prepare, adopt, and follow a fugitive emissions management plan for the construction, completion, and operation of well drilling and well completion.
- Venting must be avoided; the operators must prepare, adopt, and follow a venting management plan.

8.2 Land

The land requirements for a HF drilling pad and supporting facilities is not large; however, constructing an access road might require a considerable area. As many areas in Western Newfoundland are not currently connected by roads, the construction of an access road is needed if drilling is to be performed in those areas.

Western Newfoundland is rich in flora and fauna, and it is likely that HF activities will inevitably disturb or destroy both. Several ecological reserves and protected areas exist in this region, including Gros Morne National Park, a UNESCO heritage site. These reserves are host to many threatened species of plants and animals. Considering its impacts on land, HF may be undertaken if these recommendations are strictly followed:

- Designated restricted/prohibited areas must be avoided;
- NL's guidelines on the proximity distances of archaeological sites, provincial parks, etc., must be followed;
- If the surface vegetation is removed, re-vegetation or any measures to prevent soil erosion must be undertaken;
- Areas of threatened species must be absolutely avoided;
- Utmost care must be taken to avoid an invasion of alien species into the region; and
- Hydraulic fluid additives must be properly handled and stored to minimize contamination of the soil and vegetation.

8.3 Waste Management

Fluid waste could lead to a wide range of environmental concerns if it is not properly managed. Finding environmental friendly hydraulic additives and the subsequent treatment and management of flowback water has been the subject of research for a long time. Regulations and best practices are in place for the storage and handling of fluids and the management of produced and flowback water. Hence, in the context of Western Newfoundland HF, fluid waste is not a major concern when proper regulations are practiced and BMPs are implemented as outlined below:

- Operators must disclose the trade name of each fracturing fluid additive and the concentration of chemical ingredients;
- Operators must also present the results of environmental risks associated with fracturing fluids;
- Establish baseline data for surface water and groundwater so that the pollution due to additives could be monitored;
- To prevent any fluids from migrating into groundwater zones, proper quality assurance must be employed for wellbores; and
- Operators must ensure the proper transport, handling, storage, and disposal of all fluids and fracturing fluid waste in a manner that is safe and environmentally responsible.

8.4 Site Restoration

When drilling activities have been completed, the areas surrounding the well pad must be restored as closely as possible to their pre-drilling conditions. This generally involves landscaping and contouring the property, removal of infrastructure, assessment of soil, remediation, if necessary, and long-term monitoring at the site. Well-established regulations and BMPs are in place with respect to activities associated with site restoration such as well decommissioning and infrastructural removal. These regulations and BMPs are also applicable to the Western Newfoundland region. Innovative and proven soil assessment and remediation technologies (e.g., bioremediation) particularly for harsh climates are available in the province and can conveniently be applied if the need arises when site-restoration activities are undertaken in Western Newfoundland. If any contamination of the soil and or groundwater occurs, locally available, proven, and environmentally friendly technologies should be used to minimize any major impact to the environment.

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APPENDIX A: CANADIAN AND INTERNATIONAL REGULATIONS RELATED TO O&G AND HF OPERATIONS

CANADA REGULATIONS

Federal

The federal government regulates O&G activities on frontier lands, certain offshore and territorial lands, and those lands set aside for First Nations people. Each province with O&G production has its own specific regulations governing these requirements. Four principal acts govern O&G activities in frontier Canada (PTAC, 2012):

- The Canada Oil and Gas Operations Act (National Energy Board [NEB])
- Canadian Environmental Assessment Act (CEAA)
- Canada-Newfoundland Atlantic Accord Implementation Act (Canada-Newfoundland and Labrador Offshore Petroleum Board [C-NLOPB])
- Petroleum Resources Accord Implementation Act (Canada-Nova Scotia Offshore Petroleum Board [CNSOPB])

Canada Oil and Gas Operations Act

The Canada Oil and Gas Operations Act (COGOA), along with the National Energy Board Act, the Canadian Environmental Assessment Act, the Northern Pipeline Act, and certain provisions under the Canada Petroleum Resources Act, assigns certain responsibilities to the National Energy Board (NEB). The NEB is an independent federal agency that is responsible for regulating international and interprovincial aspects of the O&G industry (NEBC, 2011). The primary regulatory responsibilities of the NEB include the following:

- Interprovincial and international powerlines and pipelines,
- Imports and exports of natural gas and oil,
- Energy studies and advisory functions, and
- Frontier O&G.

Canada Oil and Gas Drilling and Production, made pursuant to COGOA, deals with well development, production, and completion activities. It requires that, upon completion of the production, the well site must be reclaimed to "leave the site as nearly as possible in the condition encountered when operation were commenced."

Canadian Environmental Assessment Act

The Canadian Environmental Assessment Act (CEAA) requires that all projects where a federal department or agency has a decision-making authority need an environmental assessment (EA) (OAGC, 2009).

The federal decision-making authority is responsible for carrying out the EA process, including the scoping, public consultation, assessment, and evaluation of the significance of environmental effects and mitigations.

Four types of EAs exist under CEAA:
1. Screenings,
2. Comprehensive studies,
3. Panel reviews, and
4. Mediations.

Screenings and comprehensive studies are self-directed and must be completed by the responsible authority or delegated to a third party. Panel reviews and mediations are done by an unbiased mediator or independent review panel (PTAC, 2012).

Canada-Newfoundland Atlantic Accord Implementation Act

The Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) is comprised of seven members: three from the federal government, three from the provincial government, and one non-governmental member elected by the other six members as the Chief Executive Officer (CEO). C-NLOPB was created in 1986 through the Atlantic Accord for the purposes of regulating the O&G industry offshore Newfoundland and Labrador. It oversees legislative and regulatory compliance related to safety, environmental protection, resource management, and industrial benefits within the offshore areas covered under the agreement (C-NLOPB Website).

There are currently no shale gas prospects in the offshore areas of Newfoundland. However, if shale gas resources are discovered, the Canada-Newfoundland Atlantic Accord Implementation Act (Atlantic Accord) regulations would initially be used to cover the development of the resource, and specific modifications could be implemented to address the resource development. The Atlantic Accord is an agreement between the Government of Canada and the Government of Newfoundland and Labrador on the management of O&G resources and revenue sharing for offshore reserves (PTAC, 2012).

C-NLOPB has regulatory standards in place in various sections of the Drilling and Production Regulations that contain minimum casing and cementing requirements. In addition to these regulations, a set of guidelines are available to provide assistance in understanding how the requirements of the regulations can be met (DPG, 2011).

Both a project-specific EA and an Environmental Protection Plan (EPP) are required for well operations. The project-specific EA, required under both the Atlantic Accord and the CEAA, is comprised of a technical report that investigates the impact on the environment and also the impact of the environment on the operations. A requirement of the EA is public consultation with potentially impacted parties.

An application must be submitted for each well to be drilled and approved by C-NLOPB prior to initiating operations. The approval to Drill a Well (ADW) must contain detailed information regarding well design, equipment specifications, and geological prognosis. Casing and cementing program specifications, testing programs, drilling fluid programs, and other information are also required (Turner et al., 2010).

Canada-Nova Scotia Offshore Petroleum Resources Accord Implementation Act

The Canada-Nova Scotia Offshore Petroleum Board (CNSOPB) is an independent joint agency of the governments of Canada and Nova Scotia established in 1990 pursuant to the Canada-Nova Scotia Offshore Petroleum Accord Implementation Act (CNSOPB, 2011). There are currently no shale gas prospects in the offshore areas of Nova Scotia (PTAC, 2012). However, if shale gas resources are discovered, the Canada-Nova Scotia Offshore Petroleum Accord Implementation Act would initially be used to cover the development of the resource, and specific modifications may be implemented in the future to address the resource.

CNSOPB is a Federal Authority under the CEAA and follows the requirements outlined in CEAA, such that all operators are required to submit an EA prior to the authorization of any proposed offshore petroleum work or activity. The operator must also submit an EPP and a spill response plan.

Provincial

Alberta

O&G development in Alberta is regulated by the Alberta Energy Regulator (AER) pursuant to the Energy Resources Conservation Act. Alberta has extensive regulatory standards for casing and cementing to protect aquifers during HF. These standards can be found in various sections of the Oil and Gas Conservation Act (OGCA). In August 2009, AER issued Directive 27 for Shallow Fracturing Operations. Under this directive, HF cannot occur within 50 metres of the vertical depth of any water well within a 200-metre radius. HF at depths less than 200 metres requires a full assessment of potential impacts prior to initiating a fracturing program (Directive 27).

Fracturing is also prohibited within 50 metres of bedrock surface, even if the depth exceeds 200 metres (Directive 27). The depth of bedrock for all wells where shallow fracturing has occurred must be determined through water-well drilling reports, bedrock topography maps, or another acceptable method and maintained in operator files. In addition to the above requirements, Directive 27 requires the use of only non-toxic fracture fluids above the base of groundwater protection. An operator, upon request, must provide the AER with the composition of the fracture fluids for all shallow HF operations. Fracture treatments must be designed to prevent contamination of non-saline water zones.

Directive 50 sets out the requirements for the treatment and disposal of drilling waste such as mud and cuttings. It states that, due to significant land disturbance, operators are required to reclaim the affected site if mix-bury-cover, landspread, and biodegradation are used to manage drilling waste (AER, 2015).

Directive 58 deals with a wide range of issues related to oilfield waste management, including collection, treatment, and disposal. It also specifies a series of requirements for oilfield waste characterization and classification, waste manifesting and tracking, oilfield waste management facilities, application requirements for oilfield waste management facilities, and waste management and disposal options (AER, 2006).

Directive 59 requires that O&G operators in Alberta submit well drilling, completion, reconditioning, and abandonment data to AER in a timely manner. The chemical composition of fracture fluid has to be disclosed to AER, and it will be accessible for public through Fracfocus.ca.

Directive 55 outlines the requirements for material and waste storage to ensure that the stored materials are safely contained to prevent their migration to soil, surface water, and groundwater. This regulation specifies the minimum expected practices for the use of storage facilities, including:

- Sitting
- Spill prevention (primary and secondary containment)
- Storage duration
- Equipment spacing
- Leak detection
- Weather protection
- Inspection, monitoring, and record keeping

Once a well has been abandoned, O&G companies operating in Alberta must restore the site to its original state; this process must be completed before the company is allowed to leave the well site. Once site restoration has been completed, the operator can request a reclamation certificate from AER, but it is issued only after it is satisfied that the site has been properly reclaimed. Directive 20 outlines the minimum requirements regarding well abandonment, casing removal, and zonal abandonment (AER, 2010). IL 98-2 details the requirements and regulations to be complied with for well site decontamination and land reclamation (AER, 1998).

For air quality, Alberta Environment and Parks (AEP) established the ambient air-quality standards documented in Alberta Ambient Air Quality Objectives and Guidelines, which are applicable to HF activities. The intent of these standards is to protect Alberta's atmospheric environment through informing the public about air quality, regulating industrial activities, evaluating proposed projects, and accessing the emission compliance. AEP also enacted the Climate Change and Emissions Management Act to regulate GHG emission. If flaring or incineration is used during a HF operation, the requirements documented in AER's Directive 60: Upstream Petroleum Industry Flaring, Incinerating and Venting must be met.

British Columbia

British Columbia's Provincial Cabinet introduced the Oil and Gas Activities Act (OGAA) General Regulation, Environmental Protection and Management Regulation, and the Drilling and Production Regulation (DPR) to ensure public safety. DPR issues the requirements for O&G well permitting, operation, and decommission activities. According to the regulation, the operator is prohibited from conducting a fracturing operation at a depth less than 600 metres below ground level unless such operations are permitted by the well permit (AER, 2015). The following information must be included in any application where fracturing is proposed at less than 600 metres (PTAC, 2012):

- The fracture program design, including proposed pumping rates, volumes, pressures, and fracturing fluids;
- Estimation of the maximum fracture propagation;
- Assessment of groundwater resources in the area;
- Identification and depth of all wells within 200 metres of the proposed shallow fracturing operations;
- Verification of cement integrity through available public data of all wells under the Commission's jurisdiction within a 200-metre radius of the well to be fractured;
- Notification of water-well owners within 200 metres of the proposed fracturing operations;
- Pre- and post-fracture sampling of water wells within 200 metres of the proposed fracturing operations where agreed to by water-well owners;
- Bedrock depth; and
- Assessment of the suitability of the candidate well for the proposed fracturing operations, including casing and cement integrity.

Although the term hydraulic fracturing is not directly used in British Columbia's regulatory legislation, to complement its regulatory legislation the province has issued a series of supplementary regulatory instructions that directly address various aspects of HF; they include:

- Safety Advisory 2010 – 03 – Communication during Fracturing Stimulation[9]
- Consultation and Notification Manual – February 2013[10]
- IL # OGC 09-07 – Storage of Fluid Returns from Hydraulic Fracturing Operations
- Oil and Gas Water Use in BC – August 2010[11]
- Well Completion, Maintenance and Abandonment Guideline – Updated to April 2013
- Well Drilling Guideline – August 2012
- Well Permit Application Guideline – April 2013

The earthen pit for storing liquid waste from a well-drilling operation must not be located within 100 metres of the natural boundary of a water body and not within 200 metres of a water supply well. In addition, the operator is responsible for preventing domestic livestock from ingesting the fluid stored in earthen pits (AER, 2015).

Flaring may be permitted for emergency purposes or during maintenance, but the cumulative quantity of gas flared must not exceed 50,000 cubic metres in one year. After well production has been completed, DPR requires immediate site restoration, once weather and ground conditions permit (AER, 2015).

British Columbia is the first jurisdiction in Canada to mandate the public disclosure of chemicals used in a HF fluid. Disclosure reports must be submitted to the Oil & Gas Commission (OGC) within 30 days of finishing operations at a well and the report will be posted to www.fracfocus.ca by OGC immediately upon receipt.

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9 www.bcogc.ca/publications/safety-advisories/2010
10 www.bcogc.ca/content/consultation-and-notification-manual
11 www.bcogc.ca/content/oil-and-gas-water-use-bc

New Brunswick

New Brunswick, a small producer of natural gas and oil, has relied to date on its existing regulatory framework to regulate the production of gas and oil. In February 2013, the New Brunswick Government, under its "Responsible Environmental Management of Oil and Natural Gas Activities" initiative, published its "Rules for Industry," which addressed air emissions, including GHG. These rules addressed emission limits, identifying emission sources, predicting, modelling and monitoring emissions, and planning for emission reductions. These rules also specified that each operator must have a GHG reduction plan and must consider alternatives to diesel fuel for drilling rig compressors (e.g., electricity, natural gas) at locations where these alternatives are available.

Nova Scotia

Onshore O&G activities are administered by the Nova Scotia Department of Energy. The Petroleum Resources Act and Regulations provide the regulatory framework for the management and allocation of petroleum rights (NSDOE, 2010).

In Nova Scotia, regulations require that any well that is drilled is cased in steel to prevent fluids from traveling to formations. The casing must also be cemented for additional aquifer protection. Details of the casing and cementing program must be submitted for the approval of the Department of Energy. A separate application must be made for HF. The relevant government departments and an independent engineer review the application and the operator is required to hold a public open house and obtain landowner approval if the proposed activity is to occur on private land (PTAC, 2012).

Ontario

O&G wells in Ontario are regulated pursuant to the Oil, Gas and Salt Resources Act (OGSRA), which became effective June 27, 1997 (OMAFRA, 1999). The Ministry of Natural Resources (MNR) is responsible for maintaining the safe and sustainable development of hydrocarbon resources. There are currently no shale gas prospects being actively pursued in Ontario (PTAC, 2012).

The Provincial Operating Standards in Ontario outline the casing and cementing requirements that would protect groundwater during HF operations. Casing and cementing must be installed to protect all water zones and all potential oil- or gas-bearing formations encountered during drilling operations. The casing and cement must prevent the migration of oil, gas, or water from one horizon to another (OMNR, 2002).

All HF stimulation descriptions must be revealed on a Daily Record, which is a report of all the events that are performed during a given day (OMNR, 2002). Stimulation fluids recovered from a well must be kept separate from oilfield fluid and disposed of in accordance with the Environmental Protection Act.

Newfoundland and Labrador

Newfoundland and Labrador legislation related to HF operations has been discussed broadly by Precht and Dempster (2015 b) in the document Newfoundland & Labrador: Basis for Development of Guidance Related to Hydraulic Fracturing: Part 3. An overview of their discussion is given below.

Petroleum Drilling Regulations

Drilling Regulations Section 21 requires that a drilling base used in a drilling program be designed and constructed so that it can:

- Withstand the environmental conditions and effects that may reasonably be anticipated,
- Provide a base on which drilling and related operations can be conducted safely and efficiently, and
- Protect against erosion and corrosion.

Section 27 states that "The location of a well is subject to the approval of the director"; this approval requirement can be used to reduce and mitigate the effects of HF operations on nearby residents, communities, and municipalities. Section 28 includes specific provisions relating to the proximity to surface improvements, including:

- Prohibiting the drilling of a well within 100 metres of a surface improvement unless the director is satisfied that the operation can be conducted without damage or threat to the surface improvement. Under these guidelines, the director will prohibit HF within 250 metres of a surface improvement
- Prohibiting the drilling of a well that may penetrate a mineral deposit where there are mining operations or where mining operations may be undertaken, unless the measures are satisfactory to the director

Section 32 authorizes the director to approve an application for an authority to drill a well. The well must be drilled in accordance with the detailed description required in the application (sections 29 and 30) as submitted by the operator, unless otherwise authorized by the director. Newfoundland and Labrador's legislation allows the director to add additional terms and conditions to his or her approval to drill a well, and these conditions could include requirements regarding the release of emissions to the atmosphere from HF operations.

Sections 82 to 84 provide general requirements for waste collection, storage, and disposal. Fundamentally, operators are required to store, treat, and dispose waste in a manner that does not lead to a hazard to safety, health, or the environment. In addition, waste oil must be collected in a closed system and not burned at the drill site.

Part III of the Petroleum Drilling Regulations includes requirements for well termination. Section 117 states that the operator must clear the surface of the drill site and carry out restoration to the satisfaction of the director.

Environmental Protection Act

Under the Environmental Protection Act, the definition of "environment," in addition to "air, land and water, plant and animal life," more specifically includes:

- Human life;
- The social, economic, recreational, cultural, and aesthetic conditions and factors that influence the life of humans or a community; and
- A building, structure, machine, or other device or thing made by humans.

Thus, many considerations relating to surface infrastructure must be addressed within an environmental impact statement. The Minister of Environment and Conservation may require that these issues be addressed in an environmental impact statement, and they may be subject to conditions that he or she may attach to the release of the undertaking.

Water Resources Act

The Water Resources Act includes provisions to protect water that may affect the location of surface infrastructure.

Section 30 authorizes the Minister of Environment and Conservation to classify wetlands, flood plains, shorelines, coastal waters, and other aquatic systems according to their sensitivity and productivity, and to control and determine the use of, or modifications to, wetlands where there may be an impact on the hydrology of that wetland or its recreational, aesthetic, or other natural functions and uses.

Section 33 authorizes the Minister to designate flood risk areas and regulate land development in these designated areas, in consultation with municipal authorities and other government departments.

Section 39 authorizes the Minister to designate an area surrounding a present or potential source of public water and to regulate resource development and other activities in a designated public water supply area that may impair the quality of the water.

Section 61 authorizes the Minister to define and establish a protection zone around a groundwater well used for non-domestic purposes in order to protect that well from pollution, prohibit the placement or deposit of material in the area which might impair the quality of the groundwater, and prohibit development activity in the area.

Petroleum and Natural Gas Act

Section 10 of the Petroleum and Natural Gas Act provides that a person involved in petroleum exploration, development, or production activities:

- Must provide satisfactory proof of financial responsibility to the Minister of Finance in an amount prescribed by the regulations, sufficient to meet the costs of cleanup and rehabilitation incurred as a result of the activities, and
- Is strictly liable for any loss which may occur as a result of the pollution caused and the costs of cleanup and rehabilitation incurred by the province or another person.

Subsection 33(1) of Petroleum Regulations addresses a development plan that will include, among other things (NLR, 1150/96),

- An environmental impact statement, where required, under the Environmental Assessment Act,
- A description of the proposed mitigative measures designed to reduce the impact of the proposed development on the environment, and
- Other information the Minister may require.

Subsection 35(1) authorizes the Minister to:

- Approve the development plan subject to the terms or conditions that the Minister considers appropriate, or
- Reject the development plan.

Subsection 35(2) and 35(1) states that the Minister will consider, among other things, whether:

- The proposed technology for petroleum production allows for safe production in the lease or proposed lease area, or whether more appropriate production alternatives exist, and
- Sufficient environmental, social, and economic impact studies have been undertaken by the proponent to provide a basis for the establishment of production guidelines.

The Minister must consider safety and environmental impacts in approving a development plan and is authorized to make his or her approval subject to terms and conditions. The Minister has the authority to ensure that HF operations are conducted in manner that protects air quality.

Newfoundland and Labrador Ambient Air Quality Standards

All HF operators must comply with Newfoundland and Labrador's Air Pollution Control Regulations, Section 4 (NLR 39/04). These regulations prohibit air contaminants from HF operations from exceeding the ambient air quality standards prescribed in Schedule A.

Best Available Control Technology

All HF operators must comply with Newfoundland and Labrador's Air Pollution Control Regulations, Section 6 (1 (NLR 39/04). The regulation in 6 (1) states that "An owner or operator who installs a new or modified emission source shall employ the best available control technology."

Burning of Graded Fuel

All HF operators must comply with Newfoundland and Labrador's Air Pollution Control Regulations, Section 14 (NLR 39/04). A regulation in 14 commencing January 1, 2005, states that "a person shall not burn, or permit the burning of any fuel, grade numbers 4, 5 or 6."

Operation of Motorized Vehicles

All HF operators must comply with Newfoundland and Labrador's Air Pollution Control Regulations, Section 16 (1) (NLR 39/04). A regulation in 16 (1) states, "A person shall not operate or permit the operation of a light duty motorized vehicle having an emission in excess of the standards prescribed in Schedule F."

Air-Quality Standards in Newfoundland and Labrador

The air quality across the province is generally considered to be good as the ambient air quality standards are rarely exceeded for the pollutants being measured. Five categories of pollutants are measured at the province's monitoring networks: sulfur dioxide (SO_2), oxides of nitrogen (NOx) (which includes nitric oxide [NO] and nitrogen dioxide [NO2]), carbon monoxide (CO), particulate matter (PM) (which includes particles less than 2.5 micrometres (PM2.5], particles less than 10 micrometres [PM10], and total particulate matter [TPM]), and ozone (O3). Volatile organic compounds (VOCs) are also measured periodically.

Regulatory Comparisons

Regulation of HF has been done for decades under existing federal, provincial, and territorial regulations in Canada. PTAC (2012) developed a comparison of different regulations in Canada. Table A1 outlines the federal and provincial regulations in Canada related to HF operations.

Table A1. Regulatory comparisons for Canadian territories and provinces (PTAC, 2012).

"G" – Generally addressed in Regulations; "S" – Specifically addressed in Regulations; "F" – Covered by Federal Regulation		FEDERAL REGULATION					PROVINCIAL REGULATION									
		Newfoundland & Labrador Offshore	Nova Scotia Offshore	Northwest Territories	Nunavut Territory	Yukon Territories	Alberta	British Columbia	Manitoba	New Brunswick	Newfoundland & Labrador	Nova Scotia	Ontario	Prince Edward Island	Quebec	Saskatchewan
HYDRAULIC FRACTURING OPERATIONS	Regulatory Notification	S	S	G	G	G	S	S	S	S	S	S	S	S	S	S
	Fracturing Plan	S	G	G	G	G	S	G	G	S	G	S	G	G	S	G
	Public Notification	G	G	G	G	G	S	S	F	F	F	S	F	F	F	S
	Reporting	S	S	G	G	G	S	S	S	S	S	S	S	S	S	S
	Fracture Fluid Chemical Disclosure	S	S	G	G	G	S	S	S	S	G	G	G	G	S	S

Specific Regulations Related to Air, Land, Waste Management and Site Restoration

Air

Air emissions from HF activities are regulated by the Air Pollution Control Regulations under the Environmental Protection Act. It includes the following applicable requirements:

- *Section 3. (1) The concentration of air contaminants due to all sources shall not exceed the standards prescribed in Schedule A*
- *Section 6. (1) An owner or operator who installs a new or modified emission source shall employ the best available control technology*
- *Section 12. (1) A person shall not burn or permit the burning of any material listed in Schedule E in a fire such as:*
  - > *trash, garbage, or other waste from commercial, industrial or municipal operations*
  - > *fuel and lubricant containers*
  - > *used oil*
- *Section 14. Commencing January 1, 2005, a person shall not burn, or permit the burning of any fuel, grade numbers 4, 5, or 6*
- *Section 16. (1) A person shall not operate or permit the operation of a light duty motorized vehicle having an emission in excess of the standards prescribed in Schedule F.*

Waste

Provision of chemical disclosure of fracturing fluid is not specified in Newfoundland and Labrador's O&G regulations. However, Section 7 of the Petroleum Regulations states that the Minister may initiate public briefing or hearing covering the proposed petroleum operation. In addition, the Petroleum Regulations have the following provisions:

- *Section 33*
  - *a detailed description of the proposed method for petroleum recovery and the estimated recovery factor;*
  - *an environmental impact statement, where required under the Environmental Assessment Act; and*
  - *any other information the Minister may require.*

- *Section 54*
  - *The Minister may publish, in general form, with the prior approval of the interest holder, reports based on information submitted by an interest holder, where the Minister considers the release of the information to be in the public interest.*

These regulations imply that the Minister has the authority to require the operator to disclose the chemical composition data to public.

Sections 82 to 84 of the Petroleum Drilling Regulations provide the general requirements for waste collection, storage, and disposal. Fundamentally, operators are required to store, treat, and dispose waste in a manner that does not lead to a hazard to safety, health, or the environment. In addition, waste oil must be collected in a closed system and not burned at the drill site.

Land

Section 16 of the Petroleum Drilling Regulations states that drilling activities should be carried out so as to minimize disturbance of the ground surface and vegetation and changes in the thermal regime of the ground in the area of the drill site.

Site Restoration

Part III of the Petroleum Drilling Regulations includes requirements for well termination. Section 117 states that the operator must clear the surface of the drill site and carry out restoration to the satisfaction of the director.

UNITED STATES REGULATIONS

Federal

In the United States, HF developments are regulated by a series of federal laws. The Clean Water Act (CWA) provides requirements for surface-water discharges, including oil drilling and production. It sets national effluent guidelines for industrial wastewater to be discharged to surface waters and municipal sewage treatment plants (Spellman, 2012).

HF can generate considerable amounts of wastewater, including flowback along with formation water. The flowback typically contains proppant, trace chemicals from fracturing fluid, salts, and metals, and possibly radioactive materials naturally present in formation. Formation brine water is usually generated throughout the well production lifespan (Vann et al., 2014). The constituents present in the wastewater are potentially harmful to human health and the environment. According to CWA's Section 301(a), any direct discharge from a point source to navigable water without a permit from the National Pollutant Discharge Elimination System (NPDES) will be considered as unlawful (USEPA, 2015a).

The NPDES permit program, as authorized by CWA, regulates the discharge of pollutants into surface water (USEPA, 2014). Direct discharges from hydraulic fracturing to navigable waters must comply with 40 CFR Part 122. General Pre-treatment Regulations (40 CFR Part 403) regulate indirect discharges to publicly owned treatment works (POTWs).

USEPA proposes pre-treatment standards (40 CFR Part 435) that deal with the discharge of effluents from onshore unconventional O&G extraction facilities. Part 435 prohibits the direct discharge of wastewater, unless the water quality meets the requirements for agricultural irrigation or wildlife propagation. USEPA requires certain oil drilling facilities to prepare and implement Spill Prevention, Control and Countermeasure (SPCC) plans to prevent the discharge of oil into navigable waters or adjoining shorelines (USEPA, 2015 a).

The Safe Drinking Water Act (SDWA) is the main federal law that protects drinking water from contamination. For unconventional O&G exploration, underground injection is a common method for the disposal of unwanted flowback. Such disposal is regulated by an Underground Injection Control (UIC) program to prevent the contamination of underground sources of drinking water (USDW) (USEPA, 2012). UIC is promulgated under SDWA, which regulates the injection of substances into the subsurface. However, the underground injection of proppant (except diesel fuel) is excluded from the definition of "underground injection."

The Resource Conservation and Recovery Act (RCRA) is one of most important federal laws for the proper management of hazardous and non-hazardous waste. As HF generates a large amount of flowback and other wastes, temporary land-based pits or tanks are commonly used to store these wastes. The proper management of oil and gas exploration and production waste under RCRA provides recommendations for handling the waste generated during operation (USEPA, 2014). It should also be noted that many wastes generated from HF are exempt from the definition of hazardous wastes under the RCRA definition (USEPA, 2014).

Air emissions from HF are regulated via the Clean Air Act (CAA). Under CAA, EPA has enacted a set of regulations and technique guidelines for controlling gaseous emissions from O&G extraction activities, especially for methane and VOC. In 2012, EPA issued its final New Source Performance Standards (NSPS) for the oil and natural gas industry including the VOCs and methane from HF operations (USEPA, 2012). On September 18, 2015, EPA proposed Draft Techniques Guidelines to assist regulatory agencies in selecting a reasonably available control technology (RACT) for reducing VOC emissions from certain O&G industry emission sources (USEPA, 2015c).

To promote transparency and outreach to the public, various organizations and the industrial sectors, USEPA issued an Advance Notice of Proposed Rulemaking (ANPR) under Section 8 of the Toxic Substances Control Act (TSCA) to seek public comment on accessing information on the chemicals and mixtures used in HF activities (USEPA, 2015c).

States

Individual states have the right to set their own HF regulations as long as they meet the minimum requirements of federal regulations. Consequently, O&G companies face varying levels of complexity regarding the regulatory process in different states. Some states have specific laws and regulations for HF activities; others may solely provide general O&G regulations (Brady, 2012).

Some regulations are similar among states; for example, many states require the use of open pits for storing waste. Fundamentally, open pits should be properly designed, lined and constructed to protect the health, safety, and welfare of the public as well as the environment. Some states, such as Colorado (COGCC, 2015), Texas (Railroad Commission of Texas, 2015), and Wyoming (WOGCC, 2008), require a permit for open pits. On the other hand, certain regulations vary among states. For instance, Pennsylvania requires that "No well site may be prepared or well drilled within 100 feet measured horizontally from any stream, spring or body of water ... or within 100 feet of any wetlands greater than one acre in size" (PDEP, 2015). New York's Department of Environmental Conservation (DEC) proposed a regulation that prohibits the drilling of wells within 500 feet of a private water well or within 2,000 feet of a public drinking-water supply well or reservoir for at least three years (Brady, 2012).

Disclosure of fracturing chemicals can help landowners, water users, and regulatory agencies in understanding the potential problems that upcoming HF may have and aid in tracking and identifying any contamination. However, a small number of states require the advanced notice of proposed HF operations. Colorado and West Virginia are the only two states that require the provision of notification to landowners. Five states, including Arkansas, Wyoming, (West) Virginia, Indiana, and Montana provide varying levels of pre-fracturing chemical disclosure. A1 shows the status of state regulations regarding the pre-disclosure of fracturing chemicals.

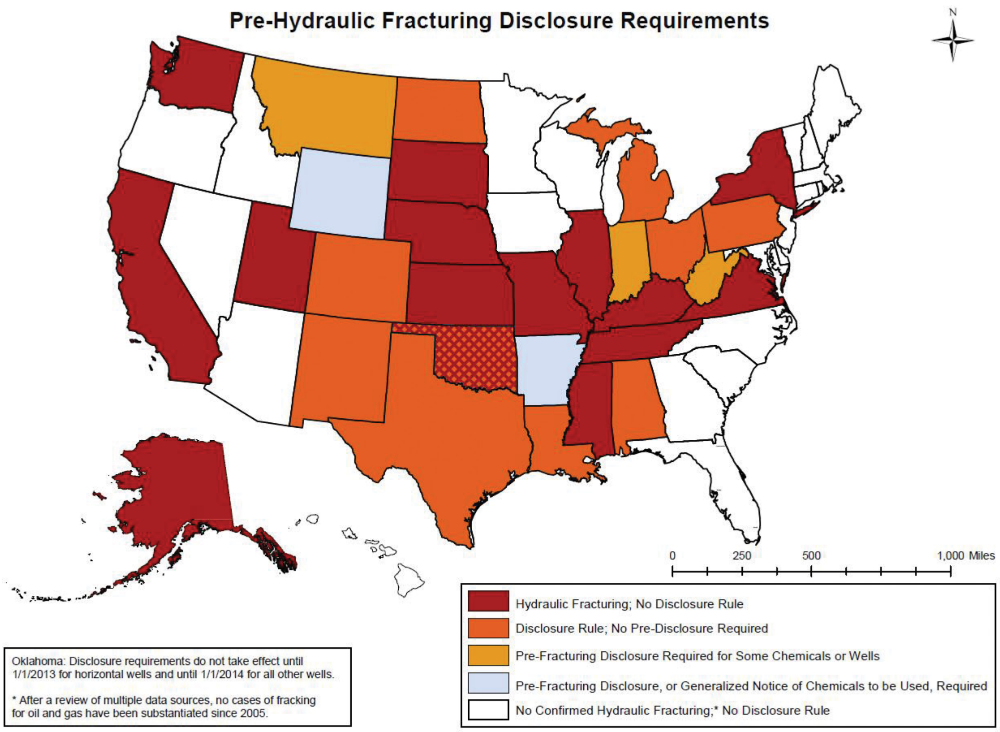

Figure A1. Pre-hydraulic fracturing disclosure requirements by state (McFeeley, 2012).

APPENDIX B: BEST MANAGEMENT PRACTICES

A recent report by PTAC (2012) suggests implementing BMPs as an effective mechanism to reduce and mitigate the risks associated with HF operations. PTAC describes different BMP technologies, methods, and procedures that are site-specific, economically feasible, generally voluntary, and usable for guidance or help in achieving a desired outcome. These BMP technologies can be found elsewhere in the PTAC website. Although the PTAC (2012) report mainly focuses on identifying areas for adopting BMPs, many of these provisions and requirements could be incorporated into the regulations as mandatory requirements.

CAPP is responsible for both large and small companies that explore, develop, and produce natural gas and crude oil throughout Canada. Recently, it has developed comprehensive guiding principles and operating procedures to support an emergency air-quality monitoring procedure that can be utilized as a responsible approach for HF operations. According to CAPP (2014), the air-quality parameters that should be measured and documented include the following.

Concentration data: The target concentrations monitored depend on the nature of the chemical or condition being evaluated, the focus of concern (i.e., safety, health, and the environment), and the sensitivity of the monitor. A device that is capable of measuring specific chemicals or chemical mixtures at peak concentrations or concentrations over a range of averaging periods (e.g., 15 minutes) for concentration levels have been referred to in published standards (i.e., regulatory requirements). Concentration levels reported by specific devices reflect the sensitivity of the device.

Location: The location of the measurement and an understanding of the surrounding topography enable the data to be interpreted in the appropriate context. Location data may be obtained and documented using Global Positioning Satellite (GPS) systems or through written descriptions relative to local features or coordinate information.

Meteorological conditions: Wind direction, wind speed, temperature, and atmospheric stability determine the transport and the dilution of the released substance. These conditions can be estimated by observation or determined by measurements.

Air monitoring and related equipment: A broad range of monitoring equipment is used to detect the presence of gases, vapours, and particulates and to describe the location and movement of these substances in the atmosphere. Air monitoring and related equipment must be:

Fit for purpose: The technology, accuracy, precision, sensitivity and responsiveness, ruggedness and reliability, ease of use, and options selected must match the hazards present on-site and in the environment where the device will be used.

Calibrated on a regular schedule: Calibration should be according to the manufacturer's specifications and appropriate documentation must be available to verify the testing and calibration requirements.

Familiar to the user: Before using any air-monitoring equipment, the user should be familiar with its specific purpose, limitations, and operating practices.

Specialized service firms should be engaged for air-quality monitoring services as their personnel will be familiar with more complex air-quality measurement equipment and the related technologies.

Minimization of GHG

HF fluid and related wastewater can emit natural gas and other contaminants to the atmosphere, including chemical additives from the fracturing fluid and vapour from the shale formation.

Once a well has been completed, fluids that return to the surface include HF flowback fluids and gas from the producing formation, along with a small amount of granular proppant (CCA, 2014). Until recently, the standard practice in the United States was to direct the flowback water into storage and vent or flare the natural gas as the equipment used was not designed to handle the abrasive mixture of flowback water, sand, and gas (CCA, 2014). CH_4 gas may be emitted by the HF process, but an ongoing debate exists about whether the amount is more or less than that from conventional gas operations (Cathles et al., 2012; O'Sullivan and Paltsev, 2012). If CH_4 leakage is high, then shale gas operations have the potential for a larger GHG footprint than coal (Healy, 2012). Because of the risk to air quality and the atmosphere, industry best practices aim to limit air pollution and minimize GHG emissions during the completion and testing of HF wells.

Conserving petroleum is another part of a sound air-quality strategy. Operators who follow best practices know all the potential emission sources in their operations. They predict and then monitor emissions so that they operate within the set limits. Even before the well begins operation, they keep emissions at a minimum by using "green completion" techniques to trap emissions that would otherwise have escaped or been flared off.

To limit emissions, minimize GHG emissions and conserve petroleum during the completion and testing of HF wells. The operator is required to:

- Set emission limits,
- Create inventories of emission sources,
- Model and monitor emissions, and
- Reduce emissions using "green" completion techniques.

AER Draft Directive 60: Upstream Petroleum Industry Flaring, Incinerating, and Venting (AER Directive 60, 2013) provides the requirements for the flaring, incinerating, and venting activities conducted in Alberta at all upstream petroleum industry wells and facilities. These requirements were developed to eliminate or reduce the potential impacts associated with these activities and to ensure that public safety concerns and environmental impacts were addressed prior to commencing flaring, incinerating, and venting activities. Directive 60 requires operators to address and evaluate the following three questions, in this sequence:

- Can flaring, incinerating, and venting be eliminated?
- If it cannot be eliminated, can flaring, incinerating, and venting be reduced?
- If it cannot be reduced, will flaring, incinerating, and venting meet performance standards?

The director of the HF operations will require operators planning to conduct HF operations in Newfoundland and Labrador to address these questions and adopt acceptable goals and standards respecting flaring, incinerating, and venting arising from HF operations in the province. If the flaring and venting arises from HF for crude oil production, Newfoundland and Labrador is signature to the World Bank Standard for Global Gas Flaring and Venting Reduction. This is a voluntary standard that provides guidance on reducing flaring and venting of gas associated with crude oil production and, ultimately, in minimizing the continuous and non-continuous production flaring and venting of associated gas.

Establishing Best Practices

Canadian regulators and the country's O&G industry are focused on the protection of groundwater and the environment and the mitigation of risk. In addition to CAPP's Operating Practices for HF (2013), the Petroleum Services Association of Canada (2013) has released a HF code of conduct for the Canadian O&G services sector.

All Canadian jurisdictions regulate the interface between water, the environment, and industry. The application of evolving HF techniques for unconventional O&G development is no exception. These regulations are set and administered by federal and provincial ministries, including environment, natural resources, sustainable development, energy, transport, industry, and others. In addition, major producing jurisdictions have O&G regulatory entities – either provincial boards or the federal National Energy Board. The following suggestions have been compiled from published literature.

PTAC's Recommended Areas for Adopting BMPs

A recent PTAC (2012) report suggests implementing BMPs as an effective mechanism to reduce and mitigate the risks associated with HF operations. It recommends that BMPs be adopted in the following areas:

- Review of Baseline Conditions: identify potential problems that could occur during HF operations; evaluate nearby O&G wells to identify issues that may require mitigation before commencing HF operations; evaluate baseline water samples from nearby water sources to provide the well operator, regulatory agency, and landowners with baseline water quality information; identification of geologic hazards is integral to proper design, completion, and stimulation of a well;

- Appropriate Wellbore Construction – design and construction of the wellbore is a crucial part of mitigating the impacts associated with HF;

- Fracture Evaluation – use of wireline tracer surveys to determine the height of fractures created during hydraulic stimulation procedures;

- Use of Green Fracturing Chemicals – use of chemicals formulated with non-toxic substances or designed to break down into non-toxic substances in the environment after they have performed their intended task can reduce the hazards associated with surface spills and subsurface migration of fluids to groundwater resources;

- Reduction of Chemical Usage – closely reviewing the effectiveness and necessity of each chemical additive to decide which one to use in order to reduce the overall risk of chemical usage;

- Cement Integrity Logging – use integrity logging methods to evaluate and confirm the cement integrity and ensure that the cement has formed a competent seal between the casing and the surrounding rock to prevent the flow of fluids behind the casing;

- Well Integrity Testing – use of a casing pressure test, after the casing has been installed and cemented into place, to ensure that the casing integrity is adequate to meet the HF objectives planned for the well; in addition to the casing pressure test, use of a shoe test or leak-off test after drilling out the casing strings;

- Fracturing Treatment Design – use of site-specific data gathered during construction and logging of the well prior to stimulation to design and model the fracturing treatment to site-specific conditions;

- Pre-Fracturing Treatment and Analysis – use of a mini-frac test prior to initiating a full-scale HF treatment can provide site-specific details of the formation being treated to determine the breakdown pressure of the formation;

- Monitoring during HF – real-time monitoring and control of treatment progression and fracturing geometry can identify potential problems with the HF stimulation and allow operators to stop them before they cause harm;

- Post-Fracture Modeling – use of information collected from a HF treatment can provide information not otherwise available to make improvements and changes to future stimulation design; and

- Information Exchange – information should be freely exchanged between the operators, public, and regulators when developing a resource and especially when developing in a new area, to help remove fear of the unknown and to promote cooperation.

The BMPs described by PTAC are voluntary; however, many of their provisions and requirements could be incorporated in the regulations as mandatory requirements. The Government of Newfoundland and Labrador can review the outcomes of these BMPs and could add/amend its regulations.

CAPP's Recommended Operating Practices

In support of an accountable approach to HF, CAPP has developed the following guiding principles and operating procedures (www.capp.ca):

- Safeguard the quality of surface and groundwater resources through sound wellbore construction practices, sourcing freshwater alternatives where appropriate, and recycling water for reuse as much as practical;
- Measure and disclose water use with the goal of continuing to reduce effects on the environment;
- Support the development of fracturing fluid additives with the least environmental risk;
- Support the disclosure of fracturing fluid additives; and
- Continue to advance technologies and best practices that reduce the potential environmental risks of HF.

CAPP has also established a series of Hydraulic Fracturing Operating Practices that are outlined below (www.capp.ca):

Disclose Fracturing Fluid Additives

To reassure the safe application of HF technology, this practice outlines the requirements for HF operators to disclose, on their own websites or on a third-party website, for each well undergoing HF:

- The trade name of each additive and its general purpose in the fracturing process,
- The name and the Chemical Abstracts Service number of each chemical ingredient listed on the Material Safety Data Sheet (MSDS) for each additive, and
- The concentration of each reportable chemical ingredient.

Risk Assessment and Management

To better identify and manage the potential health and environmental risks associated with fracturing fluids, this practice outlines the requirements for a risk-based assessment and management of fracturing fluid additives, and thereby selecting fracturing fluids with lower risk profiles, where possible.

Baseline Groundwater Testing

In order to establish the baseline characteristics of the groundwater predevelopment, and to analyze whether changes have occurred over time, this practice outlines the requirements for HF operators to test the quality of the water within 250 metres of shale gas, tight gas, and tight oil development and to participate in long-term regional groundwater monitoring programs.

Wellbore Construction and Quality Assurance

This practice outlines the requirements for O&G operators to ensure that all wellbores are designed, installed, and maintained to guarantee wellbore integrity prior to initiating HF operations in order to prevent any fluids from migrating into groundwater zones.

Water Sourcing, Measurement and Reuse

This practice outlines the requirements for O&G operators to safeguard water quality and quantity through the assessment and measurement of available water supply sources and water use, and reusing water as much as practical in HF operations.

Fluid Transport, Handling, Storage and Disposal

This practice outlines the requirements for O&G operators to transport, handle, store, and dispose all fluids and fracturing fluid waste in a manner that is safe and environmentally responsible. It also requires the operator to identify, evaluate, and mitigate potential risks related to fluid transport, handling, storage, and disposal and respond quickly and effectively to an accidental spill of fluids (including remediation of the spill site).

Assessment, Monitoring, Mitigation and Response

To reassure the safe application of HF technology, this practice outlines the requirements for HF operators to assess the potential for anomalous induced seismicity and, where necessary, to:

- Evaluate wellbore placement and drilling design to account for geologic conditions,
- Communicate and prepare on-site personnel for the possibility of irregular induced seismicity,
- Establish procedures to monitor for induced seismicity, and
- Establish procedures to mitigate and respond to induced seismicity.

CAPP strongly recommends that O&G operators adopt these practices. A regulator such as the Government of Newfoundland and Labrador would have the authority to review and implement these practices.
The regulations are extracted from that report and summarized below.

On-Site Storage System
Earthen pits used to store liquid waste must be:

- Located more than 100 metres from the natural boundary of a water body,
- Located more than 200 metres from a water supply well,
- Constructed of clay or other impermeable material with the pit bottom above groundwater level,
- Located or ditched so that it will not collect natural run-off water,
- Filled less than 1 metre below the point of overflow at any given time,
- Completely emptied and any excavation filled without unreasonable delay,
- Fracture fluid returns may be stored in closed top tanks only,
- Slick water fracture fluid returns may be stored in open top tanks or lined, earthen excavations, and
- Storage of fracture fluid returns in open and closed top tanks is limited to 90 days from the completion of servicing operations unless otherwise approved.

Use of Tank: Requirements

- Sites must be bermed to ensure that fracture fluids will not migrate off-site in the event of tank failure. The berm may surround the entire site or tanks only.
- Open top tanks must maintain at least 1 metre of freeboard at all times.
- The primary containment for open top tanks may be provided by an impermeable synthetic liner, if its design has been certified by a professional engineer.
- Open top tanks must be inspected monthly for leakage and damage.

Use of Lined, Earthen Excavations: Requirements

- Must be constructed with a primary containment device and a secondary containment device, both of which are constructed of impervious synthetic liners, and a leak detection system between the primary and secondary containment devices.
- Adequate fencing to prevent wildlife access and unauthorized dumping.
- Signage at the access point identifying the operator and the location.
- Design must be certified by a professional engineer.
- Must include measures to ensure that synthetic liners are not damaged during the operations.
- Must provide a contingency plan for the collection and containment of spills during loading and unloading.
- Minimum 1 metre of freeboard must be maintained.
- Excavation must be sloped, with the low point being down gradient of the directional flow of groundwater.
- Mitigative measures to prevent damage to the waterfowl protective netting.
- Removal of accumulated sheen.
- Must include the treatment and removal of hydrocarbons.

Pipeline Systems

- If pipelines are used, they must be approved, usually temporary, on surface.
- Saline water may be disposed of into the same reservoir as it was obtained.

Techniques to Treat, Dispose and Recycle Used Water

- Flowback may be disposed of or treated and reused in subsequent fracture operations.
- Treatment at licensed waste treatment facility injection to the subsurface through a licensed disposal well.
- Tanks may be closed top, open top, and lined, earthen excavations.
- No surface discharge of produced water.
- Flowback may be stored in closed top tanks.
- Only slick water flowback may be stored in open top tanks or in lined, earthen excavations.
- Registration of earthen excavations is required.

Techniques for Berms and Tanks with Liners

- Secondary containment for tanks with a volume less than 45.4 cubic metres storing chemicals, fuel, or other products on a well site equalling 110 percent of tank.
- Tanks with a volume less than 1 barrel do not require secondary containment.
  (Tanks with a volume greater than 45.4 cubic metres require dyking or berming.)

Storage Ponds

- Must be lined.
- Must be engineered with dual synthetic liners.