AN ACCIDENTAL RELEASE OF FLOWBACK WATER FROM STORAGE SYSTEM: A RISK ASSESSMENT STUDY

by

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The undersigned certify that they have read, and recommend to the College of Graduate Studies for acceptance, a thesis entitled:

AN ACCIDENTAL RELEASE OF FLOWBACK WATER FROM STORAGE SYSTEM: A RISK ASSESSMENT STUDY

Submitted by Himani Rajiv Gandhi in partial fulfillment of the requirements for the degree of Master of Applied Science.

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ABSTRACT

In the last decade, extraction of unconventional oil and gas (UOG) has rapidly increased in Canada. One of the major concerns related to UOG extraction is the risk of accidental releases during wastewater management. UOG extraction uses technologies of horizontal drilling and hydraulic fracturing. Flowback and produced water are generated as wastewater and may contain high concentrations of salts, metals, oil, grease, and organic compounds. Flowback water is stored on site before being transported for treatment, reuse or disposal. It is stored in containment pond, above ground walled storage systems (AWSS) or storage tanks. A comprehensive risk assessment has been carried out for the accidental release of flowback water during the storage. Two components of risk namely probability of failure and consequence assessment on the ecology have been examined using the frameworks of Backward Integrated Analysis (BIA) and Ecological Risk Assessment (ERA), respectively. In BIA, failure modes were identified for an uncontrolled release of flowback water due to AWSS failure by developing a fault tree. The probability of failure of the system was calculated and its failure modes were ranked by assigning risk priority number (RPN). To assess the consequence of the accidental release, the toxicity and exposure of the flowback water components to the aquatic ecology were examined through ERA. Toxicity of each constituent of flowback water was assessed by developing species sensitivity distribution curves. An exposure model using dilution factor and adsorption coefficient of the flowback water constituents is proposed and risk quotient was used to characterize ecological risk. To demonstrate the methodology, a case study in Montney unconventional play in Northern BC was carried out. The risk to the aquatic ecology was found to be very low, however, scenario analysis and uncertainty analysis prove that the risk cannot be completely overlooked. A review of the regulations for storage systems was carried out and they were assessed in light of the results of the study. Enforcing regulations pertaining to the quality of water stored, citing of the storage system with respect to the water body and making secondary system mandatory were realized to be the most beneficial.

PREFACE

All the frameworks development was conducted by Mrs. Gandhi under the supervision of Drs Rehan Sadiq and Kasun Hewage. Portions of this research have been submitted to a scientific journal for publication. The papers are written by Himani Gandhi under the supervision of Drs. Rehan Sadiq and Kasun Hewage. Dr. Guangji Hu is also an author on these paper due to his contribution in the review of the papers. Parts of Chapter 2, Chapter 3 and Chapter 4 of this thesis are:

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- Working Paper: Gandhi, H., Sadiq, R., Guangji, H., & Hewage, K. (2017). *Assessing failure of the above ground walled storage systems for UOG production: An effectiveness of the provincial regulations in Canada*.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

λ	Component failure rate per time t
ρ	Soil bulk density
AER	Alberta Energy Regulator
A_i	Amount of adsorbate
ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resources Management Council of Australia and New Zealand
ARI	Advanced Resources International
A_{soil}	Area of contaminated soil
AWSS	Above Ground Walled Storage System
BAF	Bioavailable fraction
BC	British Columbia
BC MOE	British Columbia Ministry of Environment
Bcf/day	Billion cubic feet per day
BCOGC	British Columbia Oil and Gas Commission
BIA	Backward Integrated Analysis
C_∞	Final contaminant concentration in receiving water body
CBM	Coalbed Methane
CCA	Council of Canadian Academies
CCME	Canadian Council of Ministers of the Environment
CCREM	Canadian Council of Resource and Environmental Ministers
CEAA	Canadian Environmental Assessment Agency
CEQG	Canadian Environmental Quality Guidelines
C_i	Concentration remaining in solution after adsorption
C_o	Concentration of contaminant in spilled water
COG	Conventional Oil and Gas
COGDPR	Canadian Drilling and Production Regulation
COGOA	Canadian Oil and Gas Operations
CSUG	Canadian Society of Unconventional Gas
C_w	Background contaminant concentration in receiving water body

CWQG-PAL	Canadian Water Quality Guidelines for Protection of Aquatic Life
d	Distance between AWSS and water stream
D	Detection
EC_{50}	Effect Concentration 50
EC_n	Effect concentration of the n^{th}contaminant
EDF	Empirical Distribution Function
EEC_n	Estimated exposure concentration of the n^{th} contaminant
EMA	Environmental Management Act
ERA	Ecological Risk Assessment
FIA	Forward Integrated Analysis
FMEA	Failure Mode and Effects Analysis
FTA	Fault tree Analysis
GHG	Green House Gas
GWPC	Groundwater Protection Council
IOGCC	Interstate Oil and Gas Compact Commission
K_d	Adsorption Coefficient
km	Kilometer
L	Litre
LC_{50}	Lethal Concentration 50
$\log K_{ow}$	Log octanol water partition coefficient
m^3	cubic meter
mD	Millidarcy
mg/L	milligram per litre
Mm^3/day	Million cubic meter per day
M_{soil}	Mass of soil contaminated
NEB	National Energy Board
NORM	Naturally Occurring Radioactive Material
NRCAN	Natural Resource Canada
O	Occurrence
OGAA	Oil and Gas Activity Act
p	Probability of exposure

P	Probability of failure
PI	Prediction Interval
Q_w	Creek discharge
Q_s	Flowback water discharge
R	Risk quotient
RPN	Risk Probability Number
S	Severity
SSD	Species Sensitivity Distribution
T	Component exposure time
tcf	Trillion cubic feet
tcm	Trillion cubic meter
TDS	Total Dissolved Solids
UOG	Unconventional Oil and Gas
US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VOC	Volatile Organic Compound
V_s	Volume of flowback water spilled

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DEDICATION

For my father

CHAPTER 1. INTRODUCTION

1.1 Background

The hydrocarbon production from shale or tight formation has been rising in Canada since 2005 and is expected to present 80% of Canada's natural gas production by 2035 (NRCAN, 2016b; Rivard et al., 2014). For economic extraction of oil and gas from these formations, directional drilling, and hydraulic fracturing is used. These processes use water in huge quantities and produce a large volume of wastewater. The water produced from well immediately after hydraulic fracturing is known as flowback water (Jiang et al., 2014; Kondash & Vengosh, 2015; Ziemkiewicz et al., 2014).

The flowback water may contain salts, metals, oil, greases, volatile and semi-volatile organic compounds (Gregory et al., 2011). Since a large volume of flowback water is generated and has high concentration of dissolved solids and a complex physicochemical composition, the flowback water creates potential risk to human health and the environment in an event of accidental or uncontrolled release into the environment (Gregory et al., 2011; Kargbo et al., 2010; Lester et al., 2015; Vengosh et al., 2014).

Flowback water is stored on site before being transported for reuse or disposal. Historical data show that majority of the flowback water release incidents constitute about 46% by a number of spills and 75% by volume of spills, have been reported during storage (US EPA, 2015). Various studies have pointed out that the accidental release of the hydraulic fracturing fluid chemicals and generated flowback water may affect surface water resources (Barbot et al., 2013; Becklumb, 2015; Burton et al., 2014; Ewen, Borchardt et al., 2012; Gagnon et al., 2016; Rozell & Reaven, 2012; Torres et al., 2015; Vengosh et al., 2014; Ziemkiewicz et al., 2014).

It has become a pressing concern to assess the integrity of the storage systems used for flowback water, investigate the causes to reduce the probability of its failure, and analyze the ecological consequences if it happens. The uptake of the flowback water constituents by the aquatic organisms can cause lethal and sub-lethal effects to the native species resulting in serious environmental consequences (Siegel, 2007; US EPA, 2007). Thus, it is critical to assess the risks to the receiving aquatic system and to identify areas requiring mitigative actions in lieu of the growing unconventional oil and gas (UOG) industry.

1.2 Research Objectives

The main objective of this study is to quantify the risk to the aquatic ecosystem caused by the accidental release of flowback water due to storage system failure. The objective of quantifying the risk is achieved through assessing the two major components of risk, the probability of failure and consequences of failure. They have been assessed using Backward Integrated Analysis (BIA) and Ecological Risk Assessment (ERA) frameworks respectively. These frameworks use techniques such as fault tree analysis (FTA), failure mode effect analysis (FMEA), regression based species sensitivity distribution (SSD) curves, dilution and distribution coefficient, risk quotient and Monte Carlo simulations to assess the risk as shown in Figure 1.1.

BIA is used to calculate the probability of the failure of the storage system and rank the failure modes. ERA helped to assess the exposure and effect of the flowback water contaminants on the aquatic ecology. The probability is input in the ERA framework to estimate the risk. Uncertainty, sensitivity and scenario analysis is done to obtain the full range of risk estimate, to determine the parameters contributing to the uncertainty and derive the relationship between spill volume and receiving aquatic body discharge. This method is applied to a creek in Montney unconventional play in Northern BC, Canada to assess its effectiveness.

The results, thus computed, will help to identify the failure modes, determine the probability of failure of the system, rank the failure modes, assess the toxicity of the flowback water, quantify exposure to the aquatic ecosystem, and characterize the overall risk to the system. The framework will provide useful information to facilitate in devising guidelines for flowback water management to reduce the risk to the aquatic ecology.

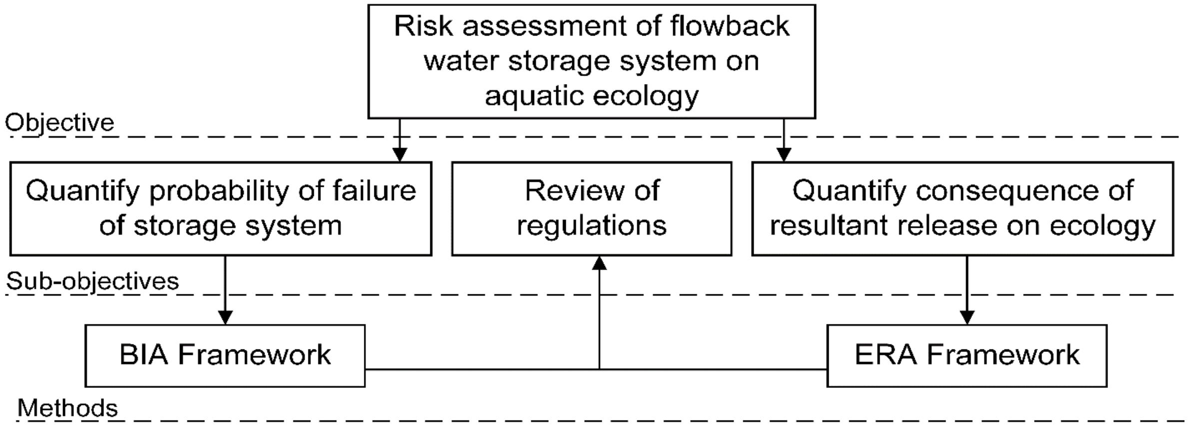


Figure 1-1 Objectives, sub-objectives and methodology of the assessment

1.3 Thesis Outline

This thesis consists of five chapters. This first chapter briefly introduces the problem and outlines the objectives of this research. Chapter 2 reviews the literature of UOG industry in Canada, flowback water quality and volume generated, adverse environmental effects, risk assessment frameworks and techniques, and flowback water storage regulations. Chapter 3 proposes the methodology to assess risk using BIA and ERA frameworks and discusses techniques used in each framework. Chapter 4 includes a hypothetical case study to demonstrate the developed methodology. The hypothetical case study includes data collection, site description, identification of failure modes and the assessment of the ecological risk. The results are discussed and assessed in lieu of the current provincial regulations. Chapter 5 provides limitations, conclusions, and recommendations for future research.

CHAPTER 2. LITERATURE REVIEW

2.1 Unconventional Gas Industry in Canada

Canada ranks fifth in the production of natural gas on a global scale and accounts for five percent of the global production (NEB, 2017b). Current natural gas supply far exceeds the domestic demand allowing export of the surplus gas which makes Canada fourth largest exporter of natural gas in the world (NRCAN, 2015). It is the common fuel of choice in applications related to residential, commercial, and industrial as well as for electricity generation (NEB, 2009). Natural gas makes important contributions to the economy and labour force of Canada (CAPP, 2017).

Natural gas resources can be categorized into conventional resources and unconventional resources. Classification is made based on the permeability of the reservoirs in which the gas is entrapped. Reservoirs having a permeability of more than 1 millidarcy (>1 mD), can produce resources at economical flowrates and volumes using traditional techniques like vertical drilling into the pools of oil and gas and extracting them via pumping. The oil and gas resources extracted in such a manner are conventional resources (McGlade et al., 2013; Speight, 2013). While unconventional gas resources are those that are extracted from relatively low permeability reservoirs (<1 mD) requiring special techniques, such as hydraulic fracturing, horizontal drilling, and multilateral well bores, for economic extraction (McGlade et al., 2013). NEB (2017a) defines unconventional gas as:

"*Natural gas that can be produced at commercial rates only after the extensive use of technology. It may be that the gas is held by the matrix material such as coal, ice, or shale; or where the reservoir has an unusually low amount of porosity and permeability*."

The examples of unconventional gas resources include tight gas, coalbed methane (CBM), and shale gas. Tight gas is commonly found in limestone or sandstone, CBM is found entrapped in coal seams, while shale gas is found in shale sedimentary rock (McGlade et al., 2013).

2.1.1 Global resource overview

In 2015, the total unconventional oil and gas (UOG) global production accounted for 9% and 27% of the annual oil and gas production. These resources are having a profound impact on the global supply and demand structure and are becoming alternative to the conventional resources (Wang et al., 2016). Wang et al. (2016) systematically estimated technically recoverable UOG to be 442.1 billion tons and 227 trillion cubic meters (tcm) respectively, globally. The estimate includes shale gas, tight gas, and CBM, which account for 71.1%, 7%, and 21.7% respectively. The top five countries with the largest unconventional resource are shown in Table 2.1. Technically recoverable is an estimate of the volume of oil or gas that could be recovered using current technology, without accounting for the economic conditions (NRCAN, 2016). Canada ranks fourth in terms of the recoverable unconventional natural gas in the world and contains 7% of the global resource, as shown in Table 2.1.

Table 2-1 An estimate of top 5 countries with the highest recoverable unconventional natural gas resources (Wang et al., 2016)

Country	Recoverable unconventional natural gas (tcm)	% of total global resource
United States	39	17.4
China	31	13.9
Russia	29	12.6
Canada	16	7.0
Australia	16	6.4

2.1.2 Canada’s resource overview

Canada has 16 trillion cubic meters (tcm) of recoverable unconventional gas reserves found in the form of tight gas, shale gas, and CBM (Cherry et al., 2014; Chong & Simikian, 2014; Wang et al., 2016). Canadian society of unconventional gas (CSUG) has provided an estimate of marketable gas in Canada for coalbed methane, tight gas, and shale gas. The estimate is shown in Table 2.2. They have defined marketable gas as (Heffernan & Dawson, 2010):

“The volume of gas that can be sold to the market after allowing for removal of impurities and after accounting for any volumes used to fuel surface facilities”

Table 2-2 Total marketable gas from unconventional sources (Heffernan & Dawson, 2010)

Unconventional gas resource type	Estimate Range (Tcm)
Coalbed Methane	1-3.6
Tight Gas	6.1-13.5
Shale Gas	3.6-9.7

Most of the estimated unconventional gas resources are tight gas and shale gas. Province wise distribution of the ultimate marketable recoverable gas in Canada is shown in Figure 2.1. The total unconventional gas in British Columbia consists of about 66% of the total estimated reserves, followed by Alberta, Northwest territories, Quebec and Yukon at 23%, 6%, 4% and 1% respectively (ARI, 2013; NEB, 2016). Major shale and tight gas plays include the Horn River Basin and Montney Play Trend in British Columbia, the Cretaceous Colorado Group in Alberta and Saskatchewan, the Utica Shale in Quebec, and the Horton Bluff Shale in New Brunswick and Nova Scotia (NEB, 2009).

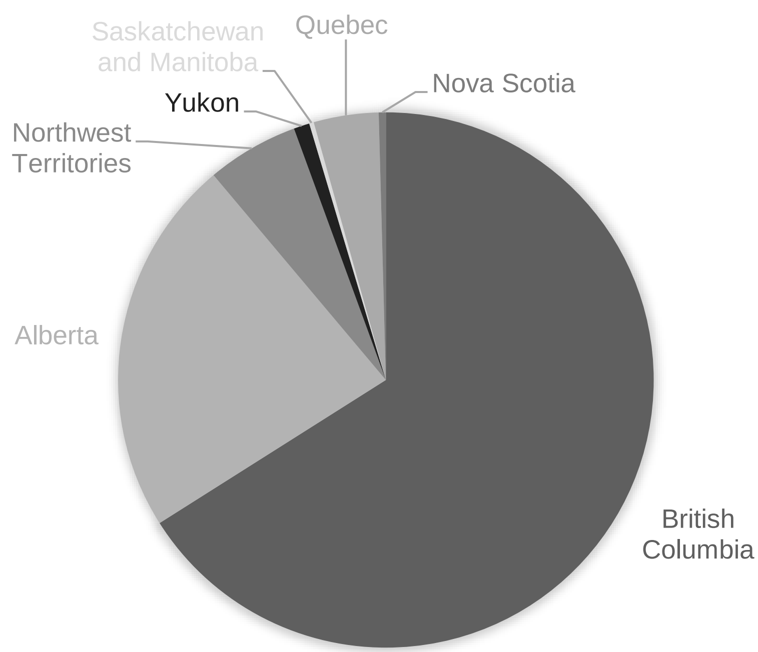


Figure 2-1 Ultimate marketable recoverable shale and tight gas in Canada (ARI, 2013; NEB, 2016)

However, UOG extraction activities are not carried out in all provinces. It is banned in Nova Scotia, New Brunswick, Newfoundland, and Labrador until further research is done (Atherton & Macintosh, 2014; Gosine et al., 2016; NRCAN, 2016d). In Manitoba, there are thirteen active oil fields but the unconventional gas is not presently exploited (NRCAN, 2016c). Unconventional gas or oil are not being extracted anywhere in Ontario (McKinley, 2015; NRCAN, 2016f). In Quebec, 29 wells were drilled from 2006-2010 in Utica shale until a moratorium was imposed in 2013 (NRCAN, 2016f).

Alberta has drilled over 180,000 oil and gas wells using hydraulic fracturing completion. Apart from CBM and shale gas, a significant amount of natural gas liquids and oil are found in the formations. The complete unconventional oil and gas potential of Alberta is still being assessed. In 2013, CBM and shale gas contributed 8% to the total gas supply and are expected to contribute increasingly higher percentage in the coming years (AER, 2014).

2.1.3 British Columbia's resource overview

In British Columbia (BC), the unconventional portion has continued to increase since 2005. By the end of 2015, it accounted for about 80% of total gas production in BC (NRCAN, 2016a). The Montney and Horn River Basin are the most active unconventional gas plays that contributed to the daily production level of 3.4 billion cubic feet/day (Bcf/d) and 0.365 Bcf/d in 2015, respectively (NRCAN, 2016a). The Cordova Embayment and the Liard Basin shale plays in BC are in the early stages of development with predicted marketable natural gas production of 0.3106 Mm^3/d (million cubic meters per day) from Cordova and 0.9106 Mm^3/d from the Liard Basin by 2040 (NEB, 2016a).

These plays reside within the Western Canadian sedimentary basin in British Columbia and are chiefly gas-charged system, black oil being a smaller constituent of the overall hydrocarbon generation. Montney Basin is a mixture of tight and natural gas liquids play in the mid-Triassic, over-pressured siltstones (NRCAN, 2016b). Montney also has a marketable, technically recoverable natural gas liquid (NGL) resource potential estimated at 12.6 billion barrels (NRCAN, 2016b).

As of January 2017, Montney reached production levels of 127 Mm^3/d represented one third of the total Canadian natural gas production. Also, due to continual application and experience gained, technological improvements have helped achieve more productivity at lower cost. These improvements include advances in geoscience and engineering, longer horizontal legs, number of fracture stages in a well, and the use of more fluid and/or proppant (NEB, 2017b).

The predicted increase in the unconventional gas production will help in filling the gap created due to decline in conventional resources. This can result in larger growth opportunities and lower natural gas prices. Despite potential economic benefits, unconventional oil and gas production has faced criticism and is banned in many provinces (Chong & Simikian, 2014). Concerns unique to the unconventional gas process circumscribe about the special completion techniques used for unconventional production like hydraulic fracturing and horizontal drilling technologies. These processes and related concerns are discussed in depth in the following sections.

2.2 Hydraulic Fracturing

A typical shale formation can be a hundred metres to a few kilometres thick and may spread over extensive geographic areas (CCA, 2014). The resources are extensively spread over wide areas instead of being concentrated in definite places. Shale gas tends to remain where it was first generated and is often found as free gas trapped in pores, cracks or fissures, as adsorbed gas or as dissolved in organic matter (NEB, 2009). The pores in the shale formation can be up to 10^3 times smaller than in the most conventional formations. Hence, shale gas is unconventional gas form and requires special completion, stimulation, and/or production techniques, such as hydraulic fracturing, to be economically produced (King, 2012). The unconventional and conventional gas well stages are shown in Figure 2.2.

The upstream and downstream stages of the conventional and unconventional stages are similar. Site preparation, infrastructure construction, drilling, hydrocarbon production, processing, transportation and well closure stages are carried out in both conventional and unconventional production. The unconventional production required few additional steps. The drilling for unconventional gas extraction can go up to 4 km in depth.

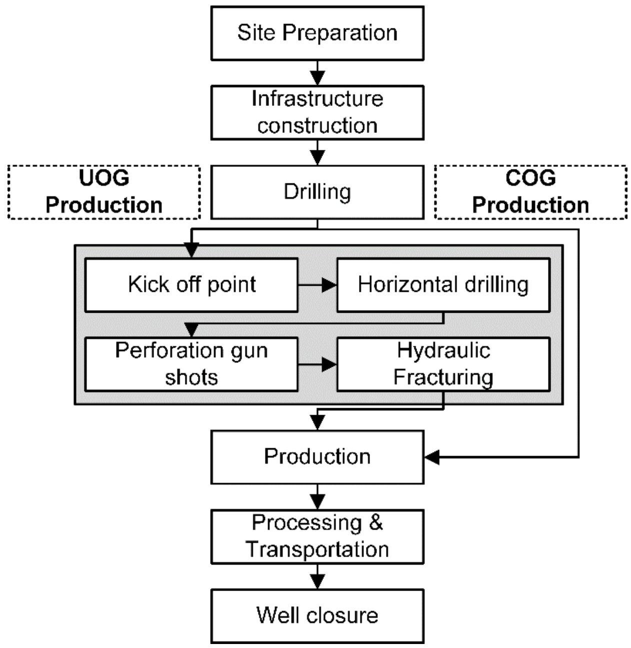


Figure 2-2 Unconventional (UOG) and conventional (COG) well production stages

Once the required vertical depth is reached through drilling production zone is connected to the surface, it is turned horizontal into the pay zone (also known as a kick off point). The horizontal drilling continues until 610 m to 1500 m or more. The shape of the horizontal segment can be lateral or continuously slanting (Cherry et al., 2014; King, 2012; US EPA, 2016c). The well construction is then completed by placing production casing which is cemented to the surface. In case of multi stage fracturing, the drilled hole is left open at the bottom of the well which is known as open-hole completion. On a multi well pad, the drilling rig is positioned next to the conductor pipe, and the entire process of horizontal drilling and well completion is carried out until all the wells are drilled (CCA, 2014; King, 2012).

Once the drilling is completed and casing installed, a perforation gun is inserted and brought in a predetermined position in the pay zone and small holes are shot through casing and cement. Then water, acid or propane based fluids are pumped at high pressure to create fracturing in the holes previously created within the rock surface. The tiny hair-like cracks are created, which facilitate in the flow of oil and gas through the rocks and is collected at the well head (CCA, 2014; King, 2012; US EPA, 2016c).

Hydraulic fracturing input fluids can be water-based, gel-based, acid-based, foams, emulsions of nitrogen, carbon dioxide, other such liquid or gas hydrocarbons (US EPA, 2016c). The most common type of hydraulic fracturing fluid is slick water formulation, which consists of a mixture of water and sand (98% - 99.9%) and three to twelve additive chemicals (2% - 0.1%) primarily friction reducers, biocides, stabilizers and corrosion preventers (GWPC, 2016). They help in preventing the corrosion of the pipe, scale downhole and in surface equipment, reduced friction, increased viscosity to suspend the proppants. The proppant sticks in between the fractures and facilitate the flow of the oil and gas to the surface. High purity quartz sand with very durable and very round grains are used as proppants (USGS, 2015). After the hydraulic fracturing stimulation, the pressure is released and the fluid is allowed to flow back to the surface. The plug is then set at the fractured location and the perforating gun shoots holes through casing and cement, the gun is then moved upwards and more holes are shot by repeating the process (Kargbo et al., 2010). These steps are unique to the unconventional process and have distinctive concerns related to it. Its impact on air, water, land, human health and society are discussed in the following sections.

2.2.1 Impacts on air

Shale gas is mostly composed of methane, and its use can lead to the emission of methane and carbon dioxide, both these GHGs contribute to global warming. Methane is a potent GHG with a shorter lifetime in the atmosphere but more efficient at trapping radiation having an overall impact of more than 20 times than carbon dioxide on climate change over a 100-year period (Garvie et al., 2012). The major source of GHG emission in the shale gas well development process is the emissions caused by a large number of truck trips to deliver water, proppant, chemicals, cement, and transportation of huge volumes of flow back and produced water. A well with a single fracture needs nearly 2,000 one-way heavy commercial vehicle trips to deliver water and other supplies (CCA, 2014). Other sources of emissions include flaring or venting during drilling and well completion. However, as compared to the larger impact of the natural gas emissions during its life time, the contribution to GHG emissions from flaring completions gas is quite negligible. Methane emissions due to leakage during extraction, processing, and transport to market and methane emissions from well after abandonment also contribute to the emissions. The deterioration of the cement leads to the escape of the buoyant gas from the annulus of the production well casing (CCA, 2014; Jiang et al., 2011).

2.2.2 Impacts on land

The land and terrestrial ecosystem changes are caused primarily due to the development of energy resources (Northrup & Wittemyer, 2013). The related development involves extensive infrastructure for oil and gas energy source development. The infrastructure includes well pads, work camps, waste handling, pipelines, and roads. The associated infrastructure often take up more land than the well pads themselves (CCA, 2014). The oil and gas resources cover large geographical areas. However, in the case of unconventional shale development, multiple wells on a single well pad are developed. This is environmentally desirable as the land footprint is smaller (CCA, 2014).

Shale gas development needs proppant for hydraulic simulations, which has cause rise in the demand for high-quality silica, resulting in a large scale increase in sand mining. A 20,000 m^3 of hydraulic fracturing injection fluid can use up to 1.5 million kilograms of proppants (King, 2012). The environmental impacts of mining contribute to dust, noise, and scarring of land (CCA, 2014). The shale gas development activities can also affect forest ecosystems by intersecting and sub-dividing the forests with infrastructure like roads, pipelines and forming transition zones between disturbed and undisturbed habitats. The high scale development in previously unexplored areas can disrupt the ecosystem and affect resource availability for wildlife (CCA, 2014; Northrup & Wittemyer, 2013; Oswald et al., 2012).

Other land use impacts include the decrease in biomass productivity due to displacement and compaction of soil, increase in erosion causing transfer of sediment and soil nutrients to streams and other water bodies, altered streamflow, loss of aquatic habitat, restricted animal passage due to road and bridge infrastructure, increased aquatic and terrestrial biota mortality and non-lethal effects because of increased hunting and fishing (Cherry et al., 2014; Northrup & Wittemyer, 2013). There is a potential threat of induced seismicity due to the fluid injection activities of the disposal wells and hydraulic fracturing processes (Rutqvist et al., 2013).

2.2.3 Human health and social impacts

The impacts on human health can be due to the compromised groundwater, surface water quality or air quality. There are health risks to the workers due to inhalation of silica used as proppant which can cause lung cancer or silicosis. It has also been linked to diseases like tuberculosis, pulmonary and autoimmune diseases (CCA, 2014). Workers can be exposed to Naturally Occurring Radioactive Material (NORM) found in some of the flowback and produced water (CCA, 2014; King, 2012). The exposure to radioactive material like Radium-226 can cause lung, breast, thyroid, bone, digestive organs and skin cancer or leukaemia (Health Canada, 2017). A study was done in Pennsylvania to understand the impact of unconventional gas extraction activities on public health. The households within 1 km of a gas well reported higher health problems as compared to those residing more than 2 km away. Skin problems were the most common reported health related issues (Rabinowitz et al., 2015). Some of the most common contaminants produced during unconventional activities and the potential impacts on human health due to inhalation, ingestion and/or direct consumption are shown in Table 2.3.

Often, a boomtown phenomenon occurrence is observed due to the large-scale development in a short period of time due to production activities. Skilled labours are imported to the place temporarily increasing the demands due to the growth of population putting a lot of stress on the available resources. This can have a negative impact on the human health and can adversely affect the quality of life. The nuisances to the public due to increased noise, dust, odour, traffic and visual impacts causes irritability and nausea (CCA, 2014). Large truck traffic increases congestion and disturbs the daily life activities of the people living there. There are invisible losses to the community having a cascading effect on their cultural practices leading to an identity crisis. Soil vibrations from fracturing can lead to change in water color and increased turbidity (CCA, 2014; King, 2012; Oswald & Bamberger, 2012). Psychologically there is a huge anxiety among the general population about the use of chemicals in the hydraulic fracturing process.

Table 2-3 Contaminants produced from unconventional activities and effects on human health (Health Canada, 2017; US EPA, 2016c)

Common Contaminants		Potential Human Health Effects
Salt ions	Chloride	Physiological effects
	Bromide	Renal cell tumors
	Sulphate	Physiological effects
	Sodium	Physiological effects
	Magnesium	No evidence of adverse health effects
	Calcium	No evidence of adverse health effects
Metals	Barium	Increase in blood pressure, cardiovascular disease
	Manganese	Undesirable taste, laxative effect
	Iron	Haemochromatosis
	Strontium	Thyriod, lung, breast, digestive system or skin cancer or leukaemia
BTEX	Benzene	Bone Marrow changes, cancer, blood changes immunological responses
	Xylene	Adverse neuromuscular effects
	Toluene	Neurological disorders like vibration and auditory ailments, colour discrimination, attention and memory disorder
Radioactive material	Radium 226	Thyriod, lung, breast, digestive system or skin cancer or leukaemia

2.2.4 Impacts on water

Some of the major concerns related to hydraulic fracturing are the amount of water used and amount of wastewater generated. In 2014, 643 wells were fractured in British Columbia consuming 8,258,192 m^3 of water (BCOGC, 2015d). Water is directly consumed in the hydraulic fracturing, drilling, cementing and site preparation stages. Other than the direct water consumption, indirect water use for the production of materials used in the extraction process involves water-intensive industries, for instance, proppant, additives, and cement (Jiang et al., 2014). A study of life cycle water footprint of hydraulic fracturing was carried out for the United States and the water use intensity was compared with other energy extraction techniques, to conclude that the unconventional water use is lower as compared to the conventional counterparts (Kondash & Vengosh, 2015). Similar conclusions were also reinforced by Kuwayama et al. (2015) and was suggested that the water quality concerns can be more severe than water quantity issues.

The wastewater generated during hydraulic fracturing, the fluid used for hydraulic fracturing purposes, the chemicals used as additives in the fluids can accidently spill and can potentially deteriorate the quality of groundwater and surface water besides causing a threat to aquatic/marine ecology. Various studies have been carried out to assess the impacts on water quality like Bergmann et al. (2014); Gagnon et al. (2016); Reagan et al. (2015) using toxicological risk assessment and numerical simulation techniques. The studies analyse the data gaps that does not allow a profound risk assessment to propose technical controls.

Groundwater contamination or surface water contamination can also occur due to upward migration of fracturing fluids or methane gas and pathways created by defective or missing cement seals. They can be caused by the abandoned wells due to increase in pressure, along well annulus or the wellbore. These sources of gas leaks can contaminate the fresh water aquifers (CCA, 2014; Vengosh et al., 2014a). Minor earthquakes simulated by the hydraulic fracturing or by natural causes may lead to the activation of upward gas leakage along the faults. The occurrence of fugitive gas in shallow drinking water wells could cause increase in salinity and other changes in quality of water (Vengosh et al., 2014)

Spills and leaks of the wastewater generated contain high concentrations of potentially harmful organic and inorganic contaminants and need treatment before its reuse or discharge into the environment (Lester et al., 2015). The wastewater management includes activities like transportation, loading, unloading, treatment, storage, and disposal. There are challenges in the treatment of the wastewater produced as the quality of flowback water is highly variable across and within shale plays (Lester et al., 2015). The wastewater is often disposed of through deep injection well. This wastewater can percolate through the pervious layers contaminating the freshwater aquifers through leaking of injection wells (Lutz et al., 2013; Vengosh et al., 2014b). The generation of the wastewater, waste water volume and quality, its management and the potential modes of accidental release are discussed in the following sections.

2.3 Flowback Water

Once the hydraulic fracturing simulation is completed, the water that flows back to the surface immediately after the pressure is released is known as flow back water. Jiang et al. (2014) defined flowback water as:

"*The water that returns from the well during the flowback period, immediately after hydraulic fracturing and before gas production*"

The flowback period was considered as the first 10-14 days approximately after the hydraulic fracturing completion process. Along with gas and oil, water is generated as a by-product of the life of service of well. This is known as produced water. Produced water can be defined as (FracFocus, 2014):

"*The water extracted from the subsurface along with produced oil and gas, including water from the reservoir, water that has been injected into the formation, and any chemicals added during the production/treatment process*"

2.3.1 Flowback water quantity

About 5-75% of the injected water flows back to the surface (Jiang et al., 2011; Rivard et al., 2014; Vengosh et al., 2014; Ziemkiewicz et al., 2014). Table 2.4 gives a summary of the average water volume used for each well for hydraulic fracturing process and the total flowback and produced water recovered per well, from the unconventional plays in North America. The water recovered is expressed as the percentage of input water.

It can be seen from the table that the range of water used and water recovered is highly variable in various unconventional plays. The water use depends on factors like type of well (horizontal, lateral or vertical), length of horizontal or lateral, number of hydraulic fracturing stages and type of hydraulic fracturing fluid used (Scanlon et al., 2014).

Table 2-4 Water use for hydraulic fracturing per well and percentage total water recovered

Unconventional Play	Avg. Water use (m^3)	% Water recovered	References
Montney, BC	14,241	50-100	(BCOGC, 2015c; Rivard et al., 2014)
Horn River Basin, BC	88,634	-	(BCOGC, 2014)
Marcellus, PA	20,000	25	(Haluszczak et al., 2013; Jiang et al., 2011)
Barnett Shale, TX	15,250	9-29	(Nicot & Scanlon, 2012; US EPA, 2016c)
Woodford Shale, OK	16,000	-	(Murray, 2013)
Haynesville Shale, TX	21,500	5	(Nicot & Scanlon, 2012; US EPA, 2016c)
Eagle Ford, TX	16,100	6-20	(Nicot & Scanlon, 2012; US EPA, 2016c)
Niobrara, CO	13,000	30	(Vengosh et al., 2014)

The volume of water recovered from a well depends on the type and volume of hydraulic fracturing fluid injected, the type of liquid or gas hydrocarbon being extracted, the pressure in the formation, the reactions between the formation and injected fluid and the reactions within the reservoir. An unanticipated rise in the volume of water recovered can be due to the loss of mechanical integrity or miscommunication between well operators (US EPA, 2016c).

Typically, higher rates of flowback water are recovered in the immediate weeks following hydraulic fracturing and reduce by almost an order of magnitude with time. Generally, it can be said that the volume of flowback recovered during the flowback period can be considered equivalent to the volume of produced water generated over the life of the well. This indicates large volumes of flowback water return over a period of several weeks (US EPA, 2016c). It becomes a challenge to manage the amount of water thus produced.

2.3.2 Flowback water quality

The flowback water consists mainly of chemicals injected for fracturing and sometimes the formation chemicals (Vengosh et al., 2014). It mainly contains high concentrations of salts, metals, oil, grease, and organic compounds. Due to possible subsurface interactions, the composition of the flowback water depends on the injected fluid, the formation minerology, geochemistry, structure of the formation solids and flow patterns of water (Alley et al., 2011; Cherry et al., 2014). Alley et al. (2011) conducted a literature review of wastewater constituents generated from conventional and unconventional oil and gas extraction processes, as represented in Table 2.5.

Within the unconventional resources, shale and tight gas were similar, however, CBM contained a relatively low concentration of sulfate and magnesium. Also, shale gas flowback and produced water had a higher concentration of strontium (Sr), barium(Ba), and bromide(Br) (Alley et al., 2011). The variation in the quality of the generated water can be attributed to a mineralogical and geochemical characteristic of the formations. According to Health Canada (2001), total dissolved solids contains cations of calcium, magnesium, sodium and potassium and the anions of carbonate, bicarbonate, chloride, sulphate and sometimes nitrate. The concentration of the TDS is often expressed as the sum of its constituents. If the amount of TDS is less than 1000 mg/L, it is considered fresh or non-saline; 1001-3000 mg/L slightly saline; 3001-10,000 mg/L moderately saline or brackish; 10,001-100,000 saline and if greater than 100,000, then it is classified as brine (CCREM, 2008). Although there is a variation in the water salinity, flowback and produced water can be typically considered as saline (US EPA, 2016c).

In addition to the factors mentioned, the quality of flowback water also depends on factors like the injected hydraulic fracturing composition, the properties of the formation, the type of hydrocarbon product to be extracted, the time of contact of the fluid with the formation, temperature, pressure and other such factors (US EPA, 2016c). Generally, the flowback and produced water constitutes salt ions and metal ions like bromide, chloride, sulfate, phosphate, nitrate, sodium, magnesium, calcium, barium, manganese, iron, strontium, zinc and radioactive materials like radium-226 and radium-228, oil, grease, BTEX, hydraulic fracturing input chemicals and produced water treatment chemicals (US EPA, 2016c). The quality of the wastewater generated also changes with time. It has been observed that the concentration of metals, TDS, organic and NORM increases with time (Barbot et al., 2013; Gregory et al., 2011; Haluszczak et al., 2013).

Thus, the constituents of the flowback water range in concentrations and type. Within the scope of this research, only inorganic constituents, salts and metals are studied.

Table 2-5 Comparision of range of concentration of constituents of flowback and produced water for Conventional Natural Gas, Coalbed Methane, Shale Gas and Tight Gas (Alley et al., 2011)

Constituent (mg/L)	Conventional NG	CBM Gas	Shale Gas	Tight Gas
Nitrate	-	0.002-18.7	>2670	-
Phosphate	-	0.05-1.5	>5.3	-
Sulfate	1-47	0.01-5590	>3663	12-48
Oil and Grease	2.3-60	-	-	>42
Ra^{226} (pCi/g)	-	-	0.65-1.031	-
U	-	0.002-0.012	-	-
HCO_3	-	-	>4000	10-4040
Ammonium-N	-	1.05-59	-	>2.74
Al	0.4-83	0.5-5290	>5290	-
As	0.002-11	0.0001-0.06	-	>0.17
B	>58	0.002-2.4	0.12-24	-
Ba	0.091-17	0.01-190	>43700	-
Br	0038-349	0.002-300	>10600	-
Ca	>51300	0.8-5870	0.65-83950	3-74185
Cd	0.02-1.21	0.0001-0.01	-	>0.37
Cl	1400-190000	0.7-70100	48.9-212700	52-216000
Cr	0.002-0.231	0.001-0.053	-	>0.265
Cu	0.02-5	>0.06	>15	>0.539
F		0.05-15.22	>33	-
Fe	>1100	0.002-220	>2838	>0.015
K	0.458-669.9	0.3-186	0.21-5490	5-2500
Li	0.038-64	0.0002-6.88	>611	-
Mg	0.9-4300	0.2-1830	1.08-25340	2-8750
Mn	0.45-6.5	0.002-5.4	>96.5	>0.525
Na	520-120000	8..8-34100	10.04-204302	648-80000
Ni	0.002-0.303	0.0003-0.2	-	>0.123
Sr	0.084-917	0.032-565	0.03-1310	-
Zn	0.02-5	0.00002-0.59	>20	>0.076

2.3.3 Flowback water management and potential spill routes

The flowback water, when recovered, is collected in storage systems like containment ponds, above ground walled storage systems or storage tanks before being transported via pipelines or heavy commercial vehicles. Depending upon the characteristic of the water, it might be treated for reuse for the hydraulic fracturing or drilling process or it can be recycled for crop irrigation, or can be disposed of off-site using deep injection wells (Becklumb, 2015; Jiang et al., 2011;

Lutz et al., 2013; Rivard et al., 2014). Lester et al. (2015) have proposed a framework for assessing site-specific hydraulic fracturing wastewaters, techniques for their characterization and processes for guiding the selection of a custom treatment method.

The water thus treated can be reused for future fracturing operation or crop irrigation, livestock watering and indirect potable reuse. The use of flowback water outside the oil and gas industry will require a higher level of treatment (Lester et al., 2015). Closed loop systems to transfer produced water from well to the storage tanks via piping system might be used to decrease the number of heavy commercial vehicles transportation trips (GWPC and IOGCC, 2014). The water management activities for UOG extraction process is shown in Figure 2.3.

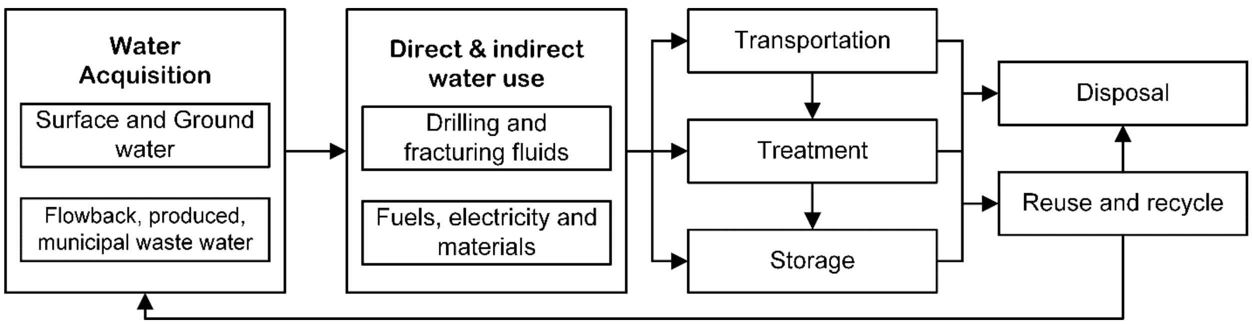


Figure 2-3 Water acquisition, use and wastewater management for UOG extraction process

Failure of the pipes and connections during the transportation process or the failure of a flowback water storage tank can cause accidental spills or release. Spills and leaks of the flowback and produced water during transportation, loading, unloading, and storage possibly percolating through the pervious layers, contaminating the freshwater aquifers (Lutz et al., 2013; Vengosh et al., 2014). Majority of the flowback water release incidents have been reported during its storage. About 46% by number of spills and 75% by volume of spills were related to the failure of storage container integrity, according to the spill data for hydraulic fracturing flowback water from 2006-2011 (US EPA, 2015). Flowback water release volume ranging from 5000 to less than 1 m^3 have been reported. An average spill volume of 288 m^3 has been reported from 2008-2011 in Colorado, Texas, and Arkansas during storage (US EPA, 2016c). In addition, over 18 spills have been recorded in Montney in 2010 due to containment pond failure (D. Scheck, personal communication, November 29, 2016).

The types of storage container typically used for storing flowback water include above ground walled storage system(AWSS or C-rings), in-ground containment ponds and storage tanks. The former two are lined containment systems and are often lined using materials like high-density polyethylene (HSPE) liners or other synthetic material (BCOGC, 2015a). The liners prevent the stored waste or waste water from contaminating the soil and groundwater at or surrounding the site. The storage systems are often installed on site for a period of 2 months to 2 years (BCOGC, 2015a).

Figure 2.4 shows an impounding containment pond with synthetic liners, drain and an inlet for flowback water loading. Figure 2.5 shows an above ground walled storage system which is a short cylindrical structure with open top and bottom with liner clamped on the structural wall, secondary containment system in form of a berm, inlet pipe, valve, and pump. These are the most commonly used storage systems in UOG industry currently (BCOGC, 2015b).

Common modes of failure for this storage system are reported as liner failure, overflow, slope stability, use of inferior soil quality for construction of the berms, the presence of debris, erosion of the berm, field compaction and other (US EPA, 2016c). Ziemkiewicz et al. (2014) studied 15 containment ponds in West Virginia and listed slope instability and liner deficiencies as the most frequent failure modes. Olawoyin et al. (2013) statistically analyzed storage systems in Pennsylvania and ranked structural instability, insufficient capacity, and erosion as the most frequent types of failure. These analyses were focused on the containment ponds. In the literature reviewed, the analysis for the failure of AWSS does not seem to have been carried out.

Various studies have pointed out that the accidental surface releases of fracturing fluids and wastewater may affect surface water resources (Becklumb, 2015; Burton et al., 2014; Ewen et al., 2012; Gagnon et al., 2016; Rozell & Reaven, 2012; Torres et al., 2015; Vengosh et al., 2014; Vidic et al., 2013; Ziemkiewicz et al., 2014). Kuwayama et al. (2015) suggested that the water quality issues related to fracturing to be more severe than water quantity issues and have determined the more conclusive association between shale gas development and impacts on surface water quality.

Blewett et al. (2017) conducted toxicity studies to understand the sub-lethal and reproductive effects of flowback water on water fleas, a species that is likely to be found in environments subjected to flowback water spill. The organic fractions and salt components were identified as main mediators of toxicity. Chloride is required to maintain normal physiological functions, but when exposed to widely changing chloride concentration, the organisms are vulnerable to survival, growth and reproduction risks (Siegel, 2007). Essential metals like iron and manganese, typically found in flowback water, are required for the biological functions of an organism, however, superfluous concentrations of these metals can result in adverse effects if they overwhelm an organism's homeostatic mechanisms (US EPA, 2007).

Ziemkiewicz et al. (2014) evaluated the integrity of impoundments used to store fluids produced by hydraulic fracturing and offered recommendations to reduce environmental risk. However, the investigation does not characterize the effect of flowback water on the aquatic ecology. Chen et al. (2017) studied ecological impact of flowback water on soil ecosystem, conducted a preliminary human health risk assessment and pointed out the need for holistic environmental assessment of the implications of the flowback water release. Due to large volume generated, historically relatively higher tendency for spill, the high concentration of dissolved solids, and the complex physicochemical composition of the flowback water, there is potential for human health and environmental impact in an event of accidental release of flowback water into the environment (Gregory et al., 2011; Kargbo et al., 2010; Lester et al., 2015; Vengosh et al., 2014).

From this, a need to conduct a holistic investigation of the adverse environmental effects on the aquatic ecology because of the possible failure of the storage system was realized. This assessment focuses on the assessment of the risk of an uncontrolled release of flowback water when stored near a surface fresh water body.

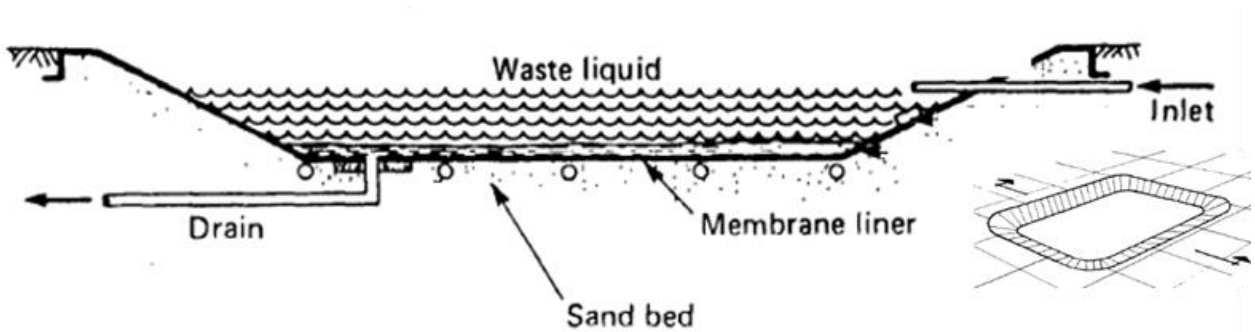


Figure 2-4 Containment pond and its components (US EPA, 1988a)

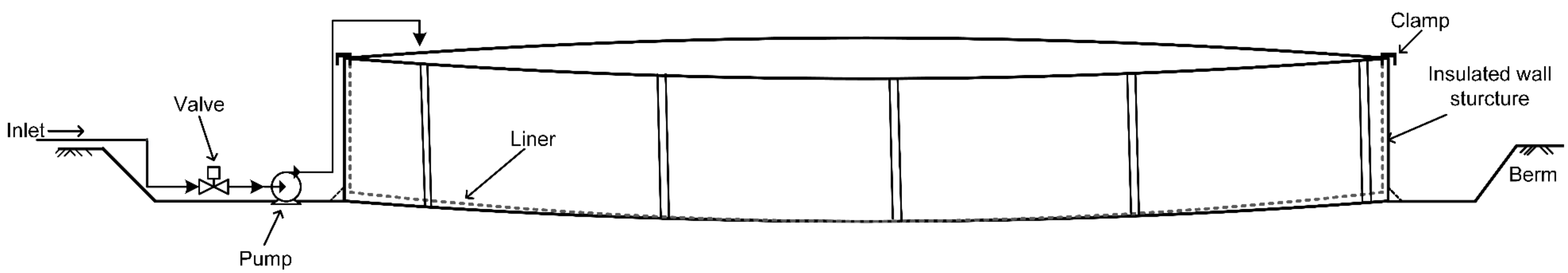


Figure 2-5 Above ground walled storage system and its components

2.4 Risk Assessment

Risk is most commonly defined as the possibility of adversely affecting something valued by humans from an event or an action (Pechan et al., 2011). Risk is related to the future and answers as to what can go wrong, the probability of that happening and the consequences arising out of it (Rausand, 2011d). The tool used for answering these questions is defined as risk analysis. When applied systematically, it can be used to assess the vulnerabilities of the system (Ostrom & Wilhelmsen, 2012). Risk analysis techniques can be qualitative or quantitative. When numerical estimates are provided for probabilities and consequences of the event, it is known as quantitative analysis (Rausand, 2011d).

Probability is defined as the likelihood that the event will occur (Ostrom & Wilhelmsen, 2012; Rausand, 2011e). A consequence is a specific damage to the asset(s). It can also be called adverse effects, impairment, impact or loss, while severity is the seriousness of the consequence (Rausand, 2011e). Risk can be defined as product of probability and severity of the consequence (Ericson II, 2005c)

$$Risk = Probability \times Consequence \tag{2.1}$$

Risk analysis evaluates the probability of failure and severity of the consequence of that failure. The risk analysis results are used in the risk characterization stage. Risk characterization evaluates the risk and compares it with the risk acceptance criteria (Rausand, 2011d). It articulates major assumptions and uncertainty in the assessment and describes the results such that they can be used in the risk management decision-making process (US EPA, 1998). A complete risk assessment comprises of risk analysis and risk characterization. While proposing, implementing, control and assessing the effectiveness of the control measures would be the part of the overall risk management framework. The distinction and the components of each risk analysis, risk characterization, risk assessment and risk management for this study are shown in Figure 2.6.

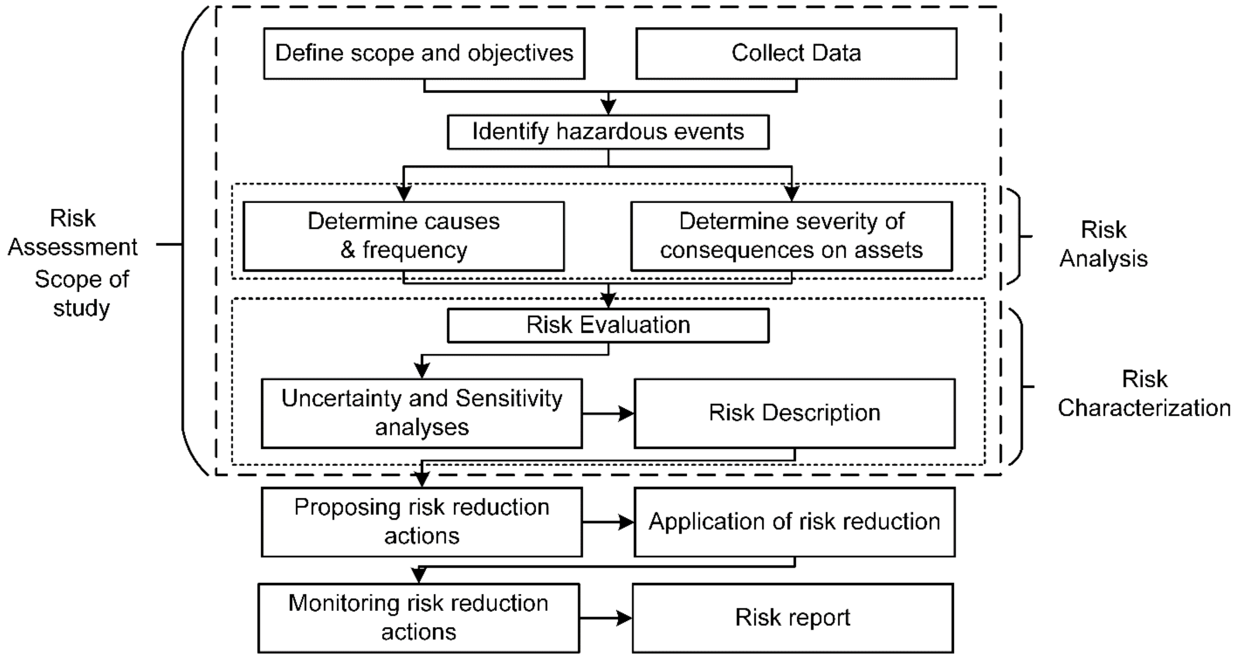


Figure 2-6 Typical components of risk management

Rausand (2011c) classified risk analyses based on three groups of hazards and their impacts on three groups of assets- the risk due to human activities or anthropogenic hazards; natural disasters; or hazardous material and their adverse effects on human health, environment and material or economy (Rausand, 2011d). Figure 2.6 is a generic framework which can be modified to assess the risk for each of the assets. The risk assessment carried out here is for assessing the impact of a flowback water storage system failure on the environment (aquatic ecology) due to uncontrolled release of flowback water caused by human, nature or toxicant. Some of the existing risk assessment studies for unconventional oil and gas activities are discussed here. The techniques specific to the assessing probability and adverse ecological effects are discussed.

2.4.1 Risk assessment studies for unconventional oil and gas development

Various risk assessment studies have been done in the past few years for analysing risks due to unconventional oil and gas development. Torres et al. (2016) reviewed risk assessment techniques that can be used for onshore UOG production to determine water quantity and quality risks related to hydraulic fracturing and flowback and produced water management. Techniques and frameworks like environmental (ecological) risk assessment, barrier, and other operational risk analysis, hazard identification, layers of protection analysis and quantitative risk assessment were enlisted as often used in the oil and gas industry. Engineering techniques like probability bounds analysis and binomial distribution models have been used for assessing the likelihood of water contamination (Rozell & Reaven, 2012; Ziemkiewicz et al., 2014).

Ziemkiewicz et al. (2014) have evaluated the flowback water containment ponds by conducting field evaluations using event tree analysis and mapped likelihood of problem occurrence for each identified storage system integrity problem. Further, a probability analysis using the binomial distribution to identify construction and maintenance efforts to minimize accidental release of hydraulic fracturing fluids to the environment was carried out. The analysis specifically focused on the liner failure of the pond containment storage system of the data collected from 71 sites (Ziemkiewicz et al., 2014). Other storage systems like above ground walled storage system, widely used in British Columbia and Alberta for temporary storage, were not assessed (BCOGC, 2015b).

Patterson et al. (2017) reviewed spills from 31,481 unconventional oil and gas wells in Colorado, New Mexico, North Dakota, and Pennsylvania. It was identified that 50% of spills were related to storage and moving fluids via flowlines and the spill volumes ranged from 0.5 m^3 to 4.9 m^3, the largest spills exceeding 100 m^3. The need to report spills in order to prevent spills and mitigate potential environmental damage was recognized and an interactive spills data visualization tool was designed.

Ingraffea et al. (2014) collected data from 41,381 COG and UOG wells in Pennsylvania to assess well casing and cement impairment issues. Cox proportional hazards model was used to measure the risk of damage to the casing which can lead to methane migration into the atmosphere and/or into underground potable wells.

Some human health risk assessment studies have also been done for unconventional oil and gas development. Human health risks for exposures to air emissions were studied by McKenzie et al. (2012) using human health risk assessment framework. Chronic and sub chronic non-cancer hazard indices and cancer risks from exposure to hydrocarbons were estimated. The preliminary results generated indicated the need for further studies. The studies carried out by Ferrar et al. (2013) affirmed this need. Interviews carried out with 53 participants attributed 59 unique health issues; stress was the most frequently-reported symptom. A need to address the identified health impacts and carry out exposure-based epidemiological studies were emphasized.

A detailed exposure based human health risk assessment carried out by Bunch et al. (2014). Community-wide exposures to volatile organic compounds (VOCs) in the Barnett Shale region due to the unconventional oil and gas activities were studied to assess potential acute and chronic health effects. A probabilistic and deterministic human health risk assessment was carried out based on more than 4.6 million data points which demonstrated that the exposure levels of the VOCs were below the threshold of posed health concern.

A new study by Elliott et al. (2017) identified 20 known or suspected carcinogens and addressed the need for investigation into the relationship between unconvetional oil and gas development and cancer risk in general and childhood leukemia in particular. Similar study was carried out by Werner et al. (2015) to review the existing literature on to identify the evidence of environmental health impacts. The paper highlighted concerns related to air and water quality. The evidence gathered in the scientific research is unsure of the actual environmental health impacts, however, a clear gap is recognized in the scientific knowledge.

Brittingham et al. (2014) reviewed the effects of unconvetional extraction activities on terrestrial and aquatic ecosystems in the United States. They identified the water quality and quantities as areas of concern for species like vernal pond inhabitants, and stream biota. Areas of futher research and monitoring were identified for developing effective policies to mitigate the adverse impacts on vulnerable species and ecosystems (Brittingham et al., 2014).

Some of the above discussed studies on unconventional oil and gas were carried out to assess evidence or compute risk related to human health and environmental impacts. Few studies analyse the failure modes to identify and prioritize the mitigating actions. The techniques that have been used requires intensive region specific historic data, the collection of which is not always feasible. In addition, such a large-scale development of the unconventional oil and gas is not prevalent in most parts of the world, hence, the required experience and skills for such analysis is straggling. Furthermore, the studies do not address the exposure in an event of accidental release while undertaking one or more oil and gas activities. The corresponding adverse effects on ecological or human health have also not been comprehensively studied. Overall, a need to undertake a holistic risk assessment to understand the impacts involved in all the stages of unconventional oil and gas production process and to prioritize them correctly was pointed out (Torres et al., 2015).

While it is difficult to address all the stages, storage stage of the production process has been ranked one of the most critical in terms of failure. Two main objectives to be achieved through this assessment are to evaluate the probability of failure of the AWSS type of storage system and the potential ecological adverse effects of storage failure on the aquatic system. The scope of the assessment does not include proposing, controlling and assessing the risk reduction action. The tools and techniques used for assessing probability and aquatic ecological effect are discussed in the following sections.

2.4.2 Assessment of probability of failure

To assess the probability of failure of an undesired event, it is required to identify and analyze the possible causes of the event. The cause of a system failure need to be identified and a logical sequence of the relations between the causes and the system failure needs to be established (Rausand, 2011c).

There are various techniques for frequency analysis, such as the cause and effect diagrams, fault tree analysis, a Bayesian network, Markov chains, and Petrinets. The Petrinets and Markov techniques are not suitable for identifying causes of the undesired events, while the cause and effect diagrams cannot provide quantitative estimates. Bayesian networks are flexible to use, but they are too complex and time consuming (Rausand, 2011b). Fault tree analysis (FTA) is the most commonly used technique for determining the root causes of an undesired event using a logical combination and graphical presentation of the various combinations of possible events occurring in a system (Ericson II, 2005b). FTA is a deductive analysis technique which transverses from the general problem to the specific causes known as basic events. It develops logical fault paths from a single undesired event at the top to all the possible basic events at the bottom (Ericson II, 2005b; US NRC, 1981).

FTA has been often used to analyse failure modes for the storage system. Choi & Chang (2016) analyzed the reliability of the sea-bed storage systems tanks using fault tree analysis. Shahriar et al. (2012) studied pipe-line failure using fuzzy based bow-tie analysis and developed fault tree for pipeline failure. Wang et al. (2013) conducted a fuzzy fault tree analysis for crude oil tank explosion. US EPA (2013) proposed techniques for hazardous waste tank failure using FTA. It included underground and in-gound storage tank and closed and open storage tank analyses. However, bottomless lined tanks are not analysed, though the guidelines are supportive of mostly all types of tanks.

An undesired event may be defined as an unwanted event, for example, an accident, a hazardous condition, or other such undesired failure modes. The graphical model can be interpreted as a mathematical model to calculate failure probabilities. FTA as an analytical technique uses logic theory, set theory, Boolean algebra, and reliability theory (CCPS, 2000b; Ericson II, 2005b).

Table 2-6 Basic terms used in FTA and their definitions (CCPS, 2000b; Ostrom & Wilhelmsen, 2012; Rausand, 2011e; US NRC, 1981)

Term	Definition
Failure	The inability of a system, subsystem, or component to perform its required function
Failure Modes	The way the item or operation potentially fails to meet or deliver the intended function
Probability	Likelihood that the event will occur
Undesirable/Top Event	It is the complete or catastrophic failure and constitutes the top event in the fault tree. FTA focuses on this particular event and the causes of this event are deduced logically
Basic Event	An initiating event requiring no further development
Intermediate Event	A failure event which can happen due to a combination of one or more basic events connected by logic gate
Minimal Cut Sets	It is the smallest combination of basic events that will cause the top event to occur. A top event can have many minimal cut sets, and each minimal cut set may have a different number of basic or undeveloped events. Each event in the minimal cut set is necessary for the top event to occur, and all events in the minimal cut set are sufficient for the undesired event to take place.

Once the undesired events have been identified, it is required to prioritize them to assess the problem that can proactively be used for suggesting risk reduction actions that have the most impact on the overall risk. The risk reduction actions can be based on either reactive or proactive approach. The actions taken to prevent or reduce the probability of an undesired event are proactive while the actions taken to reduce the severity of consequence are reactive (Rausand, 2011a). FTA requires minimal cut sets to rank and prioritize the identified failure modes. The number of cut sets can be large and can lead to complicated and tedious calculations. Also, the corrective actions thus prioritized does not take into consideration the severity of the effect of the failure mode or its detectability. The problem with high probability might have negligible severity on the overall system which affects the overall risk to the system.

The proactive actions use professional competences of the organization by a constructive approach to the problems and analysing the entire system to predict major adverse events and proactively implement changes to prevent them from occurring (Chiozza & Ponzetti, 2009). Failure Mode Effect Analysis (FMEA) is a proactive error prevention system that is designed to identify problems in infrastructure and systems before adverse events occur (Duwe, et al., 2005). FMEA is a technique used to identify and fully understand potential failure modes, their causes, the severity of the effects and their detectability. It assesses the risk associated with the effects, causes, detectability of the failure modes and ranks them in decreasing order of their risk. It can also identify and carry out corrective actions to address the most serious concerns proactively (Carlson, 2012). The basic definitions of the term often used in FMEA are explained in Table 2.6.

FMEA gives a systematic overview of failures in the system, thus, helping to assess the reliability of the system. FMEA provides less confidence that all the critical failure modes have been revealed, also human errors are often ignored. Accordingly, it is mostly used as a good basis for more comprehensive quantitative or qualitative analyses, such as fault tree analyses (Aven, 2015). Also in FMEA, all the failure modes are analysed and documented, including those having diminutive or insignificant consequences make it extremely demanding and extensive (Aven, 2015).

Fault tree technique is often used in conjunction with FMEA as they both compliment each other. Such a system is known as Integrated Analysis. In Backward Integrated Analysis (BIA), FTA is considered as the main technique followed by FMEA as supplementary (Hong & Binbin, 2009). Ideally, FMEA is used for hazard identification and FTA is developed using the failure modes identified in FMEA. Such framework is known as Forward Integrated Analysis (FIA). However, some researchers have found the FIA approach to be labour intensive and difficult to apply as compared to BIA (Hong & Binbin, 2009). Thus, a BIA is proposed to identify failure modes logically using FTA and then prioritize failure modes for directing corrective actions to reduce the overall risk to the system.

Table 2-7 Basic terms used in FMEA and their definitions (Carlson, 2012; Ericson II, 2005a)

Term	Definition
Occurrence (O)	A ranking number associated with the likelihood that the failure mode and its associated cause will be present in the item being analyzed. The occurrence ranking considers the likelihood of occurrence during the design life of the product.
Severity (S)	A ranking number associated with the most serious effect for a given failure mode, based on the criteria from a severity scale. It is a relative ranking within the scope of the specific FMEA and is determined without regard to the likelihood of occurrence or detection.
Detection (D)	The detection ranking considers the likelihood of detection of the failure mode/cause, according to defined criteria.
Risk Probability Number (RPN)	RPN is a numerical ranking of the risk of each potential failure mode/cause, made up of the arithmetic product of the three elements: severity (S), occurrence (O), and detectability (D) of the cause
Corrective Actions	Actions required to prevent or control the cause

2.4.3 Assessing adverse environmental effects

A typical environmental risk assessment framework would have four elements: hazard identification, toxicity assessment, exposure assessment, and risk characterization. The ecological risk assessment (ERA) framework proposed by US EPA (1998), provide detailed guidelines as to how to conduct each phase of the assessment. ERA evaluates the likelihood that adverse ecological effects might occur as a result of human activities and hence ecological risk assessment framework is used. It is conducted to offer information to the risk managers regarding the potential ecological effects of different management decisions (US EPA, 1998).

It is an iterative process which can continuously incorporate new information to improve environmental decisions. The assessment expresses deviations in ecological effects due to exposure to the contaminant. This capability may be useful to determine the degree of reduction to be applied to the contaminant to achieve required results. The ERA explicitly evaluates uncertainty. They provide a basis for comparing, ranking, and prioritizing risks and can be used to analyse the cost-effectiveness of each decision (US EPA, 1998). ERAs are conducted to transform the scientific data into meaningful information regarding the anthropogenic risks to the ecology. The result of the ERA helps the risk assessor and managers to make informed decisions regarding the environment.

The ERA identifies problems in the first stage which is problem formulation. In the second stage, it assesses the toxicity profile for the contaminant to evaluate the effect or benchmark concentration for a range of species. The concentration of the contaminant in the water, sediment or soil media to which the organism is exposed to and at which it is expected to produce lethal or sub-lethal response and the concentration exceeds a particular limit but will have no effect below this limit, is termed as threshold effects concentration (US EPA, 2016a). It has been referred to as effect concentration in this document. Next, the amount of actual exposure concentration to the species is estimated. This phase describes the sources of contamination, exposure pathways, fate and transport of the contaminant, and estimated likelihood of exposure. Exposure is contact or co-occurrence between a stressor and a receptor (US EPA, 1998).

Estimated exposure concentration (as the term used in the document) is the maximum concentration of the contaminant in the media (air, water, soil, sediment) that the species will be exposed to. The risk is then estimated by taking the ratio of the actual exposure concentration to the effect concentration. Risk calculation can be probabilistic or deterministic. A single point estimate of the ratio effect to exposure is taken for deterministic approach and for probabilistic approach, a range of possible environmental impacts and which ones are most likely to occur are derived so that they provide risk manager with a flexible tool for making decisions (US EPA, 2016h). Uncertainty analysis is carried out and the risk results are communicated for making informed decisions (US EPA, 1998).

As enlisted by Torres et al. (2016) ecological risk assessment is one of the most widely used techniques in oil and gas industry. It has been used by Sadiq (2001b) to assess the effect of offshore drilling waste discharge on aquatic life. Fugacity and aquivalence based approaches were used to evaluate the contaminant fate and exposure concentration, toxicity profile for drilling waste discharge was created using empirical distribution functions and risk quotient was derived by taking the ratio of exposure to effect. Nazir et al. (2008) conducted an ecological risk assessment of naphthalene and methane release in the marine environment. Xu et al. (2016) conducted an ecological risk assessment of the heavy metals in soils surrounding oil waste disposal areas by collecting soil samples. For conducting each phase of the ERA, various techniques are in place. The selection of techniques depends on factors like the characteristic of the contaminant, the representative species, assessment end, a measure of effect (lethal or sub lethal), exposure duration (acute and chronic) and other.

2.5 Regulatory Perspective

The use and permit for the construction of flowback water storage systems are regulated under jurisdiction to avoid contamination events. Regulations[1] are different in different provinces and they depend on the conditions in which storage systems are used, how they should be constructed, and their siting. For instance, regulations regarding the use of wastewater containment ponds in ecologically sensitive areas are in effect in almost all provinces. The role of the provincial and federal government, the regulatory structure, and current acts[2], corresponding regulations and guidelines[3] are studied.

2.5.1 National overview

In Canada, the National Energy Board (NEB) has regulatory responsibilities for oil and gas exploration and production activities under the Canadian Oil and Gas Operations Act (COGOA). This includes the drilling, well completion, hydraulic fracturing and formation flow testing as well as production from onshore unconventional reservoirs. However, the NEB does not have jurisdiction over onshore hydraulic fracturing in any of the provinces. The onshore areas where this act is applied are the parts of the onshore that is under the administration of a federal minister, Nunavut and Sable Island (NEB, 2016; NEB, 2015, R.S.C., 1985, c. O-7). The purpose

[1] The regulation(s) under the Act provide the details to give effect to the policy. Not all Acts have regulations. Sometimes regulations are used to bring Acts into force.
[2] Also called a statute. When a Bill (proposed law) passes third reading in the Legislative Assembly, and receives Royal Assent, it is thereby enacted and becomes an Act or law
[3] the requirements and expectations

of the act is to promote safety, protection of the environment and the conservation of oil and gas resources (R.S.C., 1985, c. O-7).

The Canadian oil and gas drilling and production regulations (COGDPR) under the COGOA, states (SOR/2009-315) that:

"…*the operator shall ensure that all chemical substances, including process fluids and diesel fuel, waste material, drilling fluid and drill cuttings generated at an installation, are handled in a way that does not create a hazard to safety or the environment*…"

In association with COGOA and COGDPR, NEB requires the use of Onshore Drilling Operations Involving Hydraulic Fracturing (Filing Requirements) for all cases where a proposed work or activity requiring an Operations Authorization (OA) involves hydraulic fracturing. These Filing Requirements focus on the unique elements of hydraulic fracturing (NEB, 2013). In addition, as a part of environmental protection, the NEB ensures that an environmental assessment (EA) is conducted for proposed activities in the Northwest Territories and Nunavut (NEB, 2013).

Furthermore, the federal government's jurisdiction would be triggered on the provincial land if the proposed hydraulic fracturing activities were to occur within a wildlife area or migratory bird sanctuary (Atherton & Macintosh, 2014). The provincial hydraulic fracturing requirements and regulations are controlled by the appropriate provincial authority. They have a very significant decision-making role regarding the management, control, and exploitation of natural resources within the provincial jurisdiction (Atherton & Macintosh, 2014).

In Nova Scotia, the hydraulic fracturing activities are currently banned but the province had approved some operations in the past. New Brunswick regulates on-shore oil and gas activity through a series of Departments and statutes, with its Department of Energy and Mines being a central authority. New Brunswick recently developed a "Blueprint" stating the rules for industry to oversee all oil and gas activity in the province, including the extraction of shale gas through hydraulic fracturing (Atherton & Macintosh, 2014). In Manitoba, the Petroleum Branch under Manitoba Mineral Resources, develops, recommends, implements and administers policies and legislation to provide for the sustainable development of Manitoba's oil and gas resources. The Branch deals with matters relating to well spacing, production allowable, pool designations, saltwater disposal, enhanced recovery projects and unitization (NRCAN, 2016d).

Hydraulic fracking for unconventional shale gas is currently not being used in Ontario. Shale gas or shale oil are not being extracted anywhere in Ontario (McKinley, 2015; NRCAN, 2016f). In Quebec, oil and gas exploration activities require the obtaining of permits and authorizations issued by the Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques (MDDELCC) and the Ministère de l'Énergie et des Ressources naturelles (MERN) (NRCAN, 2016g).

In Newfoundland and Labrador, Minister of Natural Resources has primary authority to regulate oil and gas activities under the Petroleum and Natural Gas Act and subordinate regulations. The Minister of Natural Resources appointed an independent panel to conduct a review of the socio-economic and environmental implications of hydraulic fracturing in western Newfoundland. The panel recommended that the hydraulic fracturing activity is paused in the western Newfoundland until the further examination is done (Gosine et al., 2016; NRCAN, 2016e).

Alberta and British Columbia are the most experienced with onshore oil and gas regulatory frameworks in Canada as they have a longer history of onshore oil and gas development. In Alberta, a single regulatory body, the Alberta Energy Regulator (AER), under the aegis of the Alberta Energy Ministry, is responsible for all aspects of oil and gas activities. In British Columbia, a single regulatory body, British Columbia Oil and Gas Commission (BCOGC), oversees all the oil and gas activities. (Atherton & Macintosh, 2014).

The regulations pertaining to a storage system for flowback water generated from hydraulic fracturing for the province of British Columbia are discussed in greater detail. The best practices voluntarily followed for the storage systems in U.S. are then discussed.

2.5.2 British Columbia overview

The scope of the regulatory review includes acts, supporting regulations and guidelines for containment ponds, AWSS, secondary containment system and liner. Regulations pertaining to pipe, valves, and pumps are not considered in the scope. Table 2.7 describes the acts and their corresponding regulations applicable to the storage systems in British Columbia. Table 2.8 discusses the recommended guidelines or advisory by the Oil and Gas Commission.

Drilling and Production regulation, Environmental Protection and Management regulation, Oil and Gas Waste regulation, Hazardous Waste regulation, contaminated sites regulations and spill reporting regulations under Oil and Gas Activity Act and Environmental Management Act dictate directives about siting, design, construction, operation, decommissioning, dismantle and disposal of the AWSS, pits and liner (BCOGC, 2015b). These are general regulations, not specific to the unique needs of hydraulic fracturing. Management of Saline Fluids for Hydraulic Fracturing guidelines and information letter #OGC 09-07 dictate precise guidelines related to storage of hydraulic fracturing flowback water. Some of the points discussed in the regulations are omitted in the discussion of guidelines.

2.5.3 Voluntary best practices in the US

A review was conducted by the Office of Resource Conservation and Recovery (ORCR) of the United States for the best voluntary management practices for oil and gas exploration and production waste. The review did not include provincial or federal regulations but was on such voluntary practices as they address pits, tanks, and land application/disposal (US EPA, 2014). Some of the best practices applicable to the flowback water storage guidelines are presented in Table 2.9. Best management guidelines recommend the use of AWSS storage system as compared to pits. Flowback water storage in pits is allowed in British Columbia, although the guidelines are rather strict, the regulations do not prevent the installation. The best practices suggest including the precipitation factor in the design of open tanks and considering storm run off for erosion safety of the storage containers. The closed loop systems have been given importance for reducing land footprint and environmental contamination. Alarms for overfill protection have been found to be beneficial in the event of the manual monitoring failure. The restriction for storing wastewater based on its quality parameters like pH, salinity, hydrocarbon content, NORM is in place. The BC guidelines recommend the removal of liquids and gas before storing waste water, however, other quality parameters are not taken into account.

Table 2-8 Acts and regulations pertaining to flowback water storage systems in BC (BCOGC, 2015b; Ernst and Young, 2015)

Act	Regulation	Description
Oil and Gas Activity Act [SBC 2008] (Chapter 36)		• Earthen Pits need to go through the permitting process under facilities approval • Prohibits spillage of harmful substances and requires the reporting, containment, elimination, and remediation in the event of a spill
	Drilling and Production Regulation (B.C. Reg. 282/2010)	• Should not contaminate any water supply well, usable aquifer, water body any land or public road, ice, or any water body merging in to any water body containing fish, aquatic plant or other aquatic biotas. • Earthen pit used for storage must be designed by a professional engineer and should be installed under their supervision. The pit should be approved under Oil and Gas Activity Act facility permit. • The pit should not be installed in the 100meters of the natural boundary of a water body unless it is a permitted location. • The structure should not be less than $6600m^3$ capacity • It should be located and constructed so that the fluid will not cross the site boundary • The structure must be able to bear the hydraulic pressure of the contained fluids at the designed capacity • The liner system must be installed such that the ground surface prep is satisfactory, the pond has a free board of 0.50m, is inspected and recorded daily for leaks, any sign of leakage is reported to the commission within 24 hours of discovery • The storage system must be uninstalled in after a year of first use. For the system to be used for a longer time, an impermeable secondary containment system having a capacity of 110% of the designed capacity of the primary system
	Environmental Protection and Management Regulation (B.C. Reg. 200/2010 O.C. 435/2010)	• Siting w.r.t water supply well or identified groundwater recharge area, watershed, or identified aquifer wildlife and wildlife habitat area, sensitive watershed, tree retention area, minimum riparian management and reserve distances • Maintain natural water flow in wetland • The waste materials or contaminants should not be dumped, accidently or otherwise, in the stream/lake
Environmental Management Act [SBC 2003] (Chapter 53)		• Without the approval or permit, the waste should not be dumped into the environment unless it occurs under permit, approval, or in accordance with a regulation under EMA
	Oil and Gas Waste Regulations (B.C. Reg. 254/2005 O.C. 541/2005)	• Any kind of unpleasant odor is prohibited outside the boundary of the site
	Hazardous Wastes Regulation (B.C. Reg. 63/88 O.C. 268/88)	• Make arrangements to allow for visual or any other form of manual inspection in an event of a leak • Make available and maintain an impervious secondary containment system of sufficient capacity to provide overflow protection, must provide a water tight hose connection • The piping system, containment, and all the equipment must be compatible with the type of the waste to be stored

Act	Regulation	Description
		• All waste transfer piping system must be equipped with automatic shutoff which can shut off the flow in an event of an accidental release if a secondary of containment is not provided • The waste water should be discharged into the environment, to the storm sewers or to a municipal or industrial treatment works, only if it meets the effluent safety criteria
	Contaminated Sites Regulations (B.C. Reg. 375/96 O.C. 1480/96)	• The site is contaminated only if the concentration of the contaminants exceed the background concentration of the contaminant at the site
	Spill Reporting Regulations (B.C. Reg. 263/90 O.C. 1223/90)	• Provides who will report the spill, how it will be reported and reportable levels for certain substances
Land Act [RSBC 1979] (Chapter 214)		• Needs to go through the permitting process for using the land for oil and gas activities • Siting. can be situated only with long term tenure
Heritage Act [RSBC 1996] (Chapter 187)		• Permit process required for use of areas of land considered to be heritage property

Table 2-9 Guidelines for flowback water storage systems in BC (BCOGC, 2009, 2015b)

Guideline	Description
Management of saline fluids, BCOGC, 2015	• Storage facilities must be further than 200m of supply well or groundwater capture zone or on top of aquifer or recharge zone, except with permission.
	• The site investigation to ensure the geotechnical and global stability of the containment pond must be carried out or certified by a professional engineer
	• Synthetic liners should not be undamaged and must have a quality assurance/quality control report • It must be at least 30 mils thick and must have hydraulic conductivity of less than or equal to 10-7cm/s • It must be designed for functional temperature
	• Proper ground surface preparation before installation. • Use of geotextile cushion, if needed
	• Berm or dikes surrounding the entire site or AWSS must be constructed
	• An impermeable secondary containment system must surround the AWSS if the AWSS is being used for more than a year. It must have a capacity of 110% of the designed capacity of the largest AWSS, • An AWSS must be situated at a site having a geologic unit of a minimum of 5m thickness and hydraulic conductivity of less than or equal to 10-6cm/s. Or it must have a barrier of compacted clay liner of thickness more than or equal to 30cm and hydraulic conductivity of less than or equal to 10-7cm/s; or any such liner of equal capabilities that act as a barrier between the ground and the contained fluid or waste
	• The service life of an AWSS must be greater than the design life of the liner. • The re-use of liners is no permitted and they are required to be recycled or disposed at permitted facility
	• A survey of the soils below the AWSS should be conducted after dismantling to check for soil contamination
	• A site-specific response plan to be in place to ensure the protection of groundwater resources
	• Containment pond will not be situated within a ravine, coulee, or gully, or within a 200-year floodplain or/and within 100m of normal high water mark of a natural water body
	• It must have a minimum safety factor of 1.5 and must be certified by professional engineer
	• Earthwork construction must be carried out only under non-frozen conditions or measures should be taken during construction to meet the design criteria.
	• Primary and secondary synthetic liners for containment pond must be a minimum 1.5 mm thick, have a hydraulic conductivity of less than or equal to 10-7cm/s and have density, tensile strength appropriate to the site and must be chemical resistance, tear or puncture resistance. They must be separated by an engineered seepage system
	• A leak detection system must be installed within the engineered seepage pathway and a sub drainage system below secondary liner which allows for water sampling
	• A minimum freeboard of 1.0 m must be always maintained in the pond.
	• The primary containment liner be regularly inspected and corrective actions be maintained and documented

Guideline	Description
Information Letter #OGC 09-07, BCOGC, 2009	• A groundwater monitoring program must be developed and the samples must be collected from the leak detection system and sub-drain for analyzing its quality every week. A summary of the information collected must be submitted annually
	• If a spill occurs through the synthetic liner into the soil, action leakage rates, and flow though the holes must be calculated. The spill must be reported if the leakage occurs for 3 or more consecutive days, or the chloride levels are in excess of 250mg/L from the samples collected from the sub-drain • The water must be passed through the separator to remove hydrocarbon liquids and gas
	• All types of liquid 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.
	• Registration of all lined earthen excavations is required
	• The flowback water must not be stored in open or closed tanks for more than 90 days from the last day of completion unless otherwise approved by the OGC. • The flowback water must be stored in lined containment ponds, the liner must be used only until the design life is not exceeded
	• An impermeable synthetic liner must be provided certified by a professional engineer
	• If applicable, groundwater monitoring records must be maintained until reclamation has been completed
	• The lined containment ponds must be reported on decommissioning

Table 2-10 Voluntary best storage practices followed in the US (US EPA, 2014)

Document	Section	Description
State Review of Oil and Natural Gas Environmental Regulations, Inc. - Guidelines for the Review of State Oil and Natural Gas Environmental Regulatory Programs, 2015	5.5.3 a	The open tank system must consider the precipitation factor while accounting for the capacity of the tank
	5.5.4 a	Restrictions pertaining to the quality of waste stored for parameters like pH, salinity, liquid or gas hydrocarbon content, presence of NORM, or other content which can be harmful to the environment should be considered
American Petroleum Institute (API) Guidance Document HF3 - Practices for Mitigating Surface Impacts Associated with Hydraulic Fracturing, January 2011	10.2	In order to avoid accidental spill, vital data must be maintained at the site regarding their site waste management and storage practices. The information must include capacity of each tank, capacity of secondary system, allowed accesses and restrictions and information about the liners
American Petroleum Institute (API) Recommended Practice 51R - Environmental Protection for Onshore Oil and Gas Production Operations and Leases, July 2009	6.1.7	Information about the drainage pattern of the site must be collected to avoid storage system failure due to runoff due to erosion of the base
	8.1	The system and its operation must be set up so as to achieve minimum possible land footprint
	8.3.1 j	The facility must be situated away from the major transmission lines
American Petroleum Institute (API) G00004 – Guidelines for Commercial Exploration and Production Waste Management Facilities, March 2001	4.2.3	The system must be protected from overflowing using a combination of one or more of the systems like backflow protection, automatic shut-off valves, visual check and/or loud audible alarms
National Park Service (NPS) - Operators Handbook for Nonfederal Oil and Gas Development in Units of the National Park System, October 2006	Chapter 4, Pg 88	Use of closed loop system is desirable as a storage system to decrease the spill potential and the area of impact
New Mexico Energy, Minerals, and Natural Resources Department - Pollution Prevention Best Management Practices for the New Mexico Oil and Gas Industry, 2000	Table 7.2	Use of closed-loop system with hydrotest pipelines is desirable

Document	Section	Description
Railroad Commission of Texas - Surface Waste Management Manual, December 15, 2010	Chapter 4	The liner must be able to sustain impact during installation and transport. It should be tear and puncture resistant and must be able to withstand thermal stress, weather conditions unique to the site, inflow, and outflow of the waste and must be compatible with it
		High-temperature waste fluids discharged in the storage system over high pressure, accidental runover of the vehicles or equipment over the liner, burrowing animals must be considered for the compatibility of the liner
U.S. Fish and Wildlife Service (Arkansas Field Office) - Best Management Practices for Fayetteville Shale Natural Gas Activities, April 2007	4.4	The capacity of the secondary containment system must be able to contain 1.5 times the total volume of all the storage tanks
	4.19	Closed loop system is recommended near sensitive areas to decrease area of impact and avoiding environmental contamination

2.6 Summary

In this chapter, the UOG resources have been defined and types of UOG have been described. The amount of UOG resources present in Canada at national and provincial level have been recognised. Hydraulic fracturing process and flowback water quantity, quality and management have been reviewed. Risks unique to hydraulic fracturing and the evidence of possible surface water contamination were summarized. Types of storage systems and the potential failure modes have been examined. The concepts of risk assessment have been discussed and the techniques to conduct a risk assessment of uncontrolled release of flowback water due to the failure of the storage container on aquatic ecology have been explored. Risk has been defined as a product of probability and consequence. The study proposes the ecological risk assessment for assessing the environmental effect and backward integrated analysis for identifying, evaluating probability and prioritizing failure modes of the storage system. Regulations, in effect, to ensure the integrity of the storage container and avoid environmental contamination have been studied for Canada at national and provincial level and have been examined in light of the voluntary best practices in the U.S. A detailed methodology, based on the frameworks discussed in this chapter, is proposed in the next chapter.

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Overview of Methodology

A methodology is developed to calculate risk to the aquatic ecology from accidental release of flowback water due to storage system failure as shown in Figure 3.1. It consists of two frameworks, Backward Integrated Analysis (BIA) and Ecological Risk Assessment (ERA). The probability of failure of the storage system is calculated using the BIA framework. The failure modes are identified and ranked to prioritize the areas of corrective action. The impact to the aquatic ecology is measured using ERA framework. The toxicity benchmark and exposure concentration of the flowback water constituents are computed. The probability number derived from BIA is input into the exposure component of ERA to incorporate the probability of accidental release for the contamination of aquatic ecology. The proposed methodology is developed for above-ground walled storage system (AWSS) type of storage system also known as C-rings as shown in Figure 2.5. It can also be applied to another type of storage system with minor modifications.

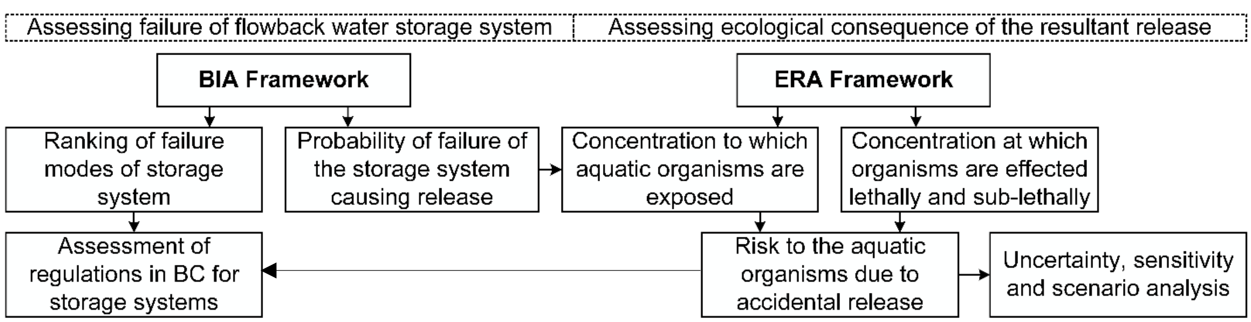


Figure 3-1 Proposed methodology for assessing risk to the aquatic ecology due to accidental release of flowback water

3.2 Backward Integrated Analysis (BIA) Framework

Backward integrated analysis (BIA) is an integration of Fault Tree Analysis (FTA) and Failure Modes Effects Analysis (FMEA) techniques as shown in Figure 3.2. BIA uses FTA as the main technique and FMEA as supplementary. The integration of these techniques is proposed to achieve a dual purpose of determining the probability of failure of the storage system using FTA and ranking the failure modes by means of FMEA. FTA and FMEA have widely used techniques in risk assessment as discussed in the previous chapter (Chiozza & Ponzetti, 2009; Duwe et al., 2005; Ericson, 2005; Lee, 1985; Mahmood et al., 2013; US NRC, 1981; Vesely, 2002).

In BIA framework, the first step is to examine the storage system, determine the scope of the analysis and identify the undesired top event. A logical fault tree is constructed in a top down manner to logically identify the basic and intermediate events, contributing factors for the system failure. Then the failure rates of the basic events are determined through historic data, literature data or expert advise. Based on the failure rates, top event failure probability is calculated using gate to gate analysis. This entire process is FTA. The details of each step are explained in Section 3.2.1. Once the basic events are identified, they can be evaluated through FMEA. Detectability and severity ranking are allocated to the basic events and risk probability number (RPN) is calculated by taking the product of occurrence (calculated from failure rate), severity and detectability. The basic events are ranked using the RPN and the areas to achieve the most effective risk reduction are assigned, however, corrective action evaluation for FMEA is not carried out. These steps partially define the FMEA technique which is further explained in Section 3.2.2. This framework is a modified version of the BIA as proposed by Hong & Binbin (2009).

The BIA framework can be most effectively applied during the design phase of the system. The overall storage system is made of sub systems like the walled system, liner, piping, drainage system, secondary system. These sub-systems are made of numerous components and the failure for each of these components is to be analyzed. The number of failure modes increases rapidly for such a complex system with a large number of components, making it impracticable to analyze them item by item when done using the traditional FMEA technique (Hong & Binbin, 2009).

When the fault tree is constructed the entire system reduces to a number of logically derived basic events. With this information, it is reasonable to identify critical areas with great concern using FMEA for mitigation and risk management. For a complex system, the analysis process can be simplified by logically determining basic events through FTA and considering them as critical areas to perform FMEA. BIA framework advocates efficiency by integrating FTA and FMEA (Hong & Binbin, 2009). FTA and FMEA techniques are discussed at length in the following sections.

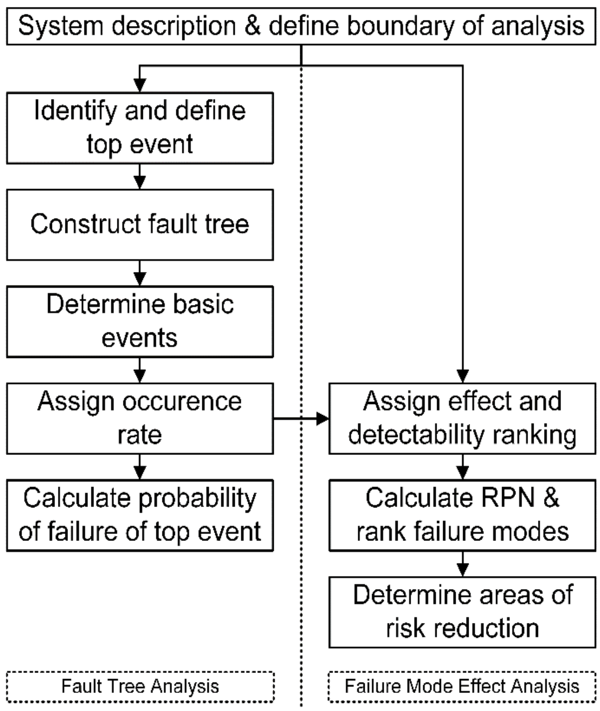


Figure 3-2 Backward Intergrated Analysis (BIA) framework

3.2.1 Fault tree analysis (FTA)

Fault tree analysis (FTA) is a hazard and root cause analysis technique where an undesired state of the system is analysed to find all the credible ways in which the undesired state can occur in the context of the operation and environment of the system (Ericson II, 2005b; US NRC, 1981). A fault tree is a graphic presentation of parallel and sequential combinations of failure events that will lead to the occurrence of the top or undesirable event. It portrays the logical interconnection of basic and intermediate events resulting in the undesired event (US NRC, 1981).

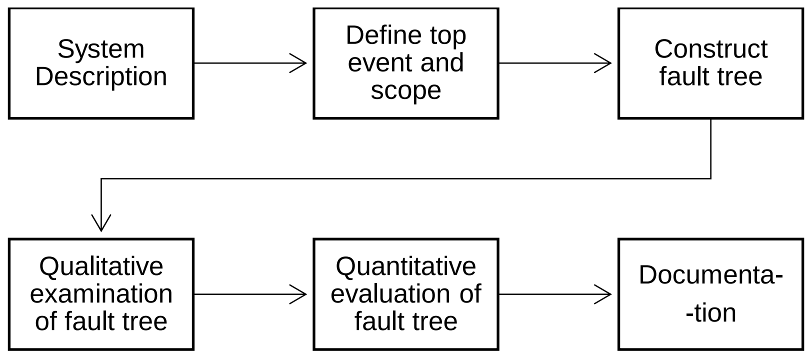


Figure 3-3 Steps required to perform fault tree analysis (CCPS, 2000b; Ericson II, 2005b)

The main functions of FTA are to:

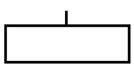
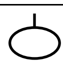
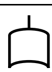
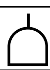
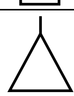
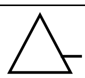
1. Determine the combinations of equipment failures, operating conditions, environmental conditions, human errors and other such root causes or hazards contributing to the top event
2. Identify the relationship between the root causes and determine their probability
3. Estimate the probability of occurrence of the top event

There are six basic steps that are required to perform a complete and accurate FTA, as shown in Figure 3.3. FTA is the primary technique in the BIA framework and all the steps are carried out. The first step of FTA is to understand the system by studying the design drawings, schematics, and operation procedures. Then the scope and the top or undesired event of the fault tree is defined. A deductive logical fault tree model of the system is constructed (Ericson, 2005). The construction of the fault tree is an iterative process. The process begins at the top and moves down through the branches until all the events are defined in terms of the basic identifiable faults or human error (Ericson II, 2005b; US NRC, 1981). Often necessary, immediate and sufficient (N-I-S) concept is used to construct the fault tree, determining if the fault is necessary, immediate and sufficient to cause the top or intermediate events (Ericson II, 2005b; US NRC, 1981). In this manner, the fault tree proceeds down and continually approaches finer resolution until ultimately, the basic component failures or basic events are identified (CCPS, 2000b).

Once the fault tree is developed, it is inspected qualitatively. This can be done by inspection or using the rules of Boolean algebra. The combinations of the events can be expressed in terms of the Boolean equation. The evaluation can also be carried out using the minimal cut sets analysis (CCPS, 2000b). The minimal cut set analysis uses the rules of Boolean algebra to determine all the possible combinations of events in terms of basic and intermediate events that cause the top event to occur. These basic event combinations are called minimum cut sets. They represent the minimum set of events that are necessary and sufficient in order for the top event to occur. The minimal cut sets are more manageable for examining the fault tree qualitatively (CCPS, 2000a).

Once the fault tree is satisfactory in terms of logical correctness, completeness, effectiveness, the probability of the failure of the top event is computed and documented (CCPS, 2000b; Ericson II, 2005b; US NRC, 1981; Vesely, 2002). The symbols commonly used in the FTA are described in Table 3.1. The quantitative evaluation is done using the concepts of probability theory.

Table 3-1 Commonly used fault tree symbols (CCPS, 2000b; Ericson II, 2005b; US NRC, 1981)

Symbol	Name	Description
	Intermediate event	It is a failure event that can happen due to one or more preceding event connected through the logic gates
	Basic Event	A basic event that does not need any additional development
	OR Gate	The resulting failure event will happen if at least one of the input events occur
	AND Gate	The resulting failure event will happen only if all the input events occur
	Transfer In	Symbolizes that the tree is further developed at the respective TRANSFER OUT
	Transfer Out	Symbolizes that the tree is to be connected to the respective TRANSFER OUT

A basic assumption in FTA is that all failures in a system are binary in nature, i.e., a component or operator either performs successfully or fails completely (CCPS, 2000b). In order to calculate the probability of failure of a system from the failure rate of its sub-system and components, principles of reliability theory and probability distribution theory have been used. The Poisson distribution has numerous applications in describing the occurrence of the system failure under steady state condition (US NRC, 1981). Assuming that the system is in steady state does not undergo any degradation, the failure is likely to occur equally over the time and the system either fails prior to time t or it does not, the reliability of a system will be defined by the probability of continuous successful operation for a time t (US NRC, 1981).

For the quantitative analysis, the probability model is selected based on the type of failure processes in the fault tree. For evaluating the probability of the storage system failure, longer exposure time period increases the probability of failure. As discussed above, the causes of failure can be due to human error, can be caused by operational, maintenance, and/or environmental factors. This model is most often used for quantification of the fault tree. The probability distributions are assumed exponential. The probability P that the component fails in time period t, assuming that the component is initially working can be represented using equation 3.1 (US NRC, 1981):-

$$P = 1 - e^{-\lambda T} \tag{3.1}$$

Where P is the probability of failure, λ is the component failure rate per time t, and T is the component exposure time. In this case, the component is exposed over its operational life time, thus, $t = T$. Equation 3.1 is an exponential distribution which has a constant failure rate. It arises out of Poisson distribution. . A ranking scale and corresponding probability of a failure is shown in Table 3.2.

The probability of the failure of a top undesired event is calculated using "gate-to-gate" analysis. If, G is probability of event, and z_1, z_2, z_3 are the probability of the events leading to G, the probability of AND gate would be:

$$G = z_1 \times z_2 \times z_3 \tag{3.2}$$

If the events are mutually exclusive or upper bound probability is considered, the equation for OR gate would be:

$$G = z_1 + z_2 + z_3 \tag{3.3}$$

For example for Figure 3.4, the overflow of the storage system would occur if the control is lost over water level, AWSS is nearly full and the system fails to shut down. All the failure events occur at once. If the control is lost over water level but the AWSS is empty, then the overflow would not occur. All the three events have to occur at once for the system to overflow. So, the use of AND gate is appropriate. The lost control of water level occurs if either the inlet/outlet valve fails or water level was not monitored. Even if one of the two events occur, the control of water level is lost. Hence, the use of OR gate is appropriate. Also, "AWSS is nearly" full is a basic event, "overflow of the system" is an intermediate event and is transferring in, while "the system shut down failure" is transferring out.

A scale is created to predict the occurrence of the basic events as shown in Table 3.2. This scale is similar to the traditional FMEA occurrence ranking. The failure rate values are relative. The corresponding probability of failure can be computed using equation 3.1 for a given ranking. A number from 1 to 10 can be allocated to each basic event. While the failure rate is not precise, for a new analysis like AWSS for which historic failure data is not available, data can be collected for the failure of basic events based on the given ranking. This occurrence rank is also used in the FMEA to calculate risk priority number (RPN).

3.2.2 Failure mode and effect analysis

FMEA is a proactive fault prevention technique designed to identify problems in a system before they occur (Duwe et al., 2005). FMEA can be used as qualitative or semi-quantitative analysis. The main goals of the FMEA are to identify failure modes, assess causes and effects of failure modes, prioritize the failure modes by evaluating them and recognize actions to decrease the chance of the potential failures from occurring (Ben-daya, 2009). The FMEA has following major steps (Pillay & Wang, 2003):

i. Understand the system and identify and enlist the components of each sub-system and assembly
ii. Determine the failure modes of the components

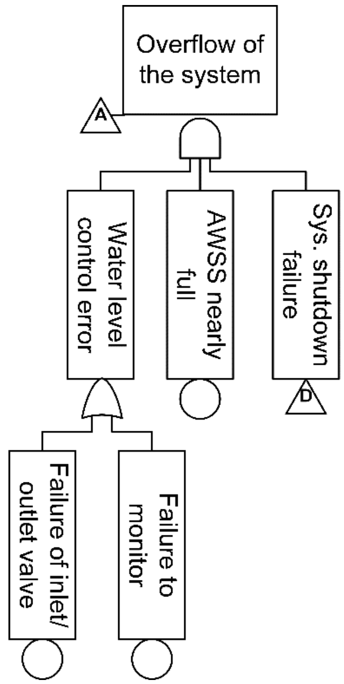


Figure 3-4 Example use of AND and OR gate

Table 3-2 Failure rate and correspoonding probability values and assigned ranking (Chang et al., 2001; Pillay & Wang, 2003)

Ranking*	Failure rate	Probability
10	1/2	4E-01
9	1/10	1E-01
8	1/20	5E-02
7	1/100	1E-02
6	1/200	5E-03
5	1/1000	1E-03
4	1/2000	5E-04
3	1/10000	1E-04
2	1/20000	5E-05
1	1/100000	1E-06

iii. Analyse each failure mode to understand the severity of its effect on the system, its detectability, and its occurrence
iv. Estimate the occurrence of failure, severity of effect and detectability qualitatively (terms defined in Table 2.6)
v. Calculate RPN, which is a ranking of the risk events and is a product of the three elements: severity (S), occurrence (O), and detectability (D) of the cause (Carlson, 2012; Ericson II, 2005a).
vi. Rank the failure modes based on the RPN values. Develop recommendation and document the information in form of a table.

The purpose of ranking the failure modes in order of their criticality is to allocate the limited resources to the most critical failure modes and achieve the most effective results. A rank scale for occurrence, severity, and detectability of the FMEA is devised as shown in Table 3.3. This is the scales suggested by the traditional FMEA (Chang et al., 2001; Pillay & Wang, 2003). The table shows that the traditional FMEA uses the rank of 1-10 to measure the occurrence, severity, and detectability. This ranking is assigned to each failure mode. A risk priority number, a product of occurrence, severity, and detectability, is computed for each failure mode. The failure modes are then arranged in a decreasing order of their RPN to prioritize failure modes needing immediate attention.

The FMEA and FTA have common occurrence scales. The FMEA is supplementary in the BIA framework. Step1 of the FMEA is common in both FTA and FMEA. Step 2, determination of failure modes is carried out using FTA. The failure modes in form of basic events are logically determined using the FTA. Steps 3 to 7 of FMEA are carried out in the BIA framework, however, the recommendations are not developed.

The BIA framework gives two outputs: the probability of failure of the system and the ranking of the failure modes. The probability of failure derived is input into the ERA framework to calculate the final risk to the ecology. The failure modes ranked above are assessed in light of the current provincial regulations and guidelines reviewed in Chapter 2. In the next sections, the risk to the aquatic ecology would be assessed using the ERA framework.

Table 3-3 Severity, Occurrence and Detectability scale assigned for FMEA

Rank	Severity (S)	Occurrence (O)	Detectability (D) (%)
10	Complete system failure without warning	1/2	0-5
9	Complete system failure with warning	1/10	6-15
8	Serious damage	1/20	16-25
7	Major damage	1/100	26-35
6	Significant damage	1/200	36-45
5	Moderate damage	1/1000	46-55
4	Performance deterioration	1/2000	56-65
3	Slight deterioration	1/10000	66-75
2	Very slight deterioration	1/20000	76-85
1	No effect	1/100000	86-100

3.3 Ecological Risk Assessment (ERA) Framework

The information about the failure of the storage system is available. The subsequent contamination of the surface water body is to be analysed. The aquatic ecological risk due to the accidental release of flowback water is estimated using the ecological risk assessment (ERA) framework. US EPA (1998) has defined ecological risk assessment as

"*a process that evaluates the likelihood that adverse ecological effects occur or are occurring as a result of exposure to more or more stressors*".

The ERA process is based on the characterization of ecological effects and characterization of the exposure of flowback water constituents to the aquatic ecology. The characterization of ecological effects evaluates the ability of a pollutant or contaminant, also known as a stressor(s), to cause adverse effects under a particular set of circumstances. While the characterization of exposure evaluates the interaction of the stressor with one or more ecological entities. These provide the focus for conducting the phases of risk assessment: problem formulation, analysis, and risk characterization (US EPA, 1998). The guidelines were proposed by the US EPA (1998) for conducting ERA. The ERA framework provides guidelines to avail consistency in carrying the risk assessment, however, they do not discuss the modeling tools to conduct the assessment (Sadiq, 2001). Figure 3.5 portrays the ecological risk assessment (ERA) framework for flowback water and the proposed techniques to conduct each of the three phases (US EPA, 1998). These phases are developed step by step in the following sections.

3.3.1 Problem formulation

Problem formulation is the first phase of ERA. This phase evaluates the primary hypothesis as to what kind of ecological effects might occur and refines the objectives of assessment. It consists of the integration of available data to produce assessment endpoints, conceptual model and analysis plan (US EPA, 1998). An accidental release of flowback water causes a release of contaminants into surface water through runoff, solute migration through groundwater or other pathways. The possible primary effect is related to the contaminants in flowback including increased mortality and behavioral, biochemical, growth, physiology, population and reproduction related adverse effect on the aquatic life (US EPA, 2016f). The problem identified in this assessment is to measure short-term acute adverse effects on the species found in an aquatic water body because of an accidental spill or release of flowback water into a surface water body. The three sub-steps of problem formulation process are discussed below.

3.3.1.1 Assessment endpoints

The basic criteria to select appropriate assessment endpoints are ecological relevance, susceptibility to stressors, and relevance to management goals. Ecologically relevant endpoints reflect important characteristics of the system and are functionally related with other endpoints (US EPA, 2003). Aquatic organisms are vulnerable to salts, metals and organic compounds when exposed to concentrations above the benchmark levels. Selecting food web as assessment endpoint seems more accurate than choosing a single or a group of species (Nazir et al., 2008; Sadiq, 2001). As it is difficult to obtain toxicity data for all organisms of the aquatic ecosystem, the organisms representing taxonomic groups are used as surrogates (Nazir et al., 2008; Sadiq, 2001). In this assessment, the endpoints are chosen depending on the availability of the acute toxicity data of the aquatic organisms in the literature.

3.3.1.2 Conceptual model

A conceptual model was developed to predict the relationships between ecological entities and the stressors to which they may be exposed, possible exposure pathways, resulting in ecological effects on the endpoints. The conceptual model can be complex, depending on the number of stressors, assessment endpoints, characteristics of effects and the receiving ecosystem. Conceptual models is an influential tool for risk assessors for a future application that also helps for adjustment as knowledge about the parameter improves (Suter II, 1996, 2007; US EPA, 1998).

The conceptual model is shown in Figure 3.6. It shows the possible contamination pathways including soil, surface water, groundwater and potable aquifer contamination by mechanisms like leaching, run off release and groundwater transport. The contamination leads to lethal and sub-lethal effects on the aquatic and terrestrial biota, which are in-turn ingested by human causing risk to human health. The scope of the assessment is limited to the contamination due to run off.

Flowback water is a mixture of organic compounds, salts, and metals. As defined in the scope of the assessment, only the inorganic constituents of the flowback water, metals and salts are considered. Toxicity of salts are often expressed as a combination of ions as their toxic effects might be more influenced by ion imbalance than the absolute concentration of the ions (Bright & Addison, 2002; Mount et al., 1997; Mount et al., 2016). However, this can lead to multiple single ion interactions among the ions in flowback, ions present in a surface water body as well as between the ions of flowback water and surface water.

In addition, the ion concentrations in flowback water, surface water background concentration values, and available benchmark toxicity guideline values are measured for individual ions. Thus, it is practicable to consider single ion toxicity for the contaminants of flowback water.

The Canadian Water Quality Guidelines for Protection of Aquatic Life (CWQG-PAL) has recommended deriving acute toxicity values for short-term high intensity event like a spill (CCME, 2012). To access the lethal and non-lethal toxic effect of the inorganic ionic

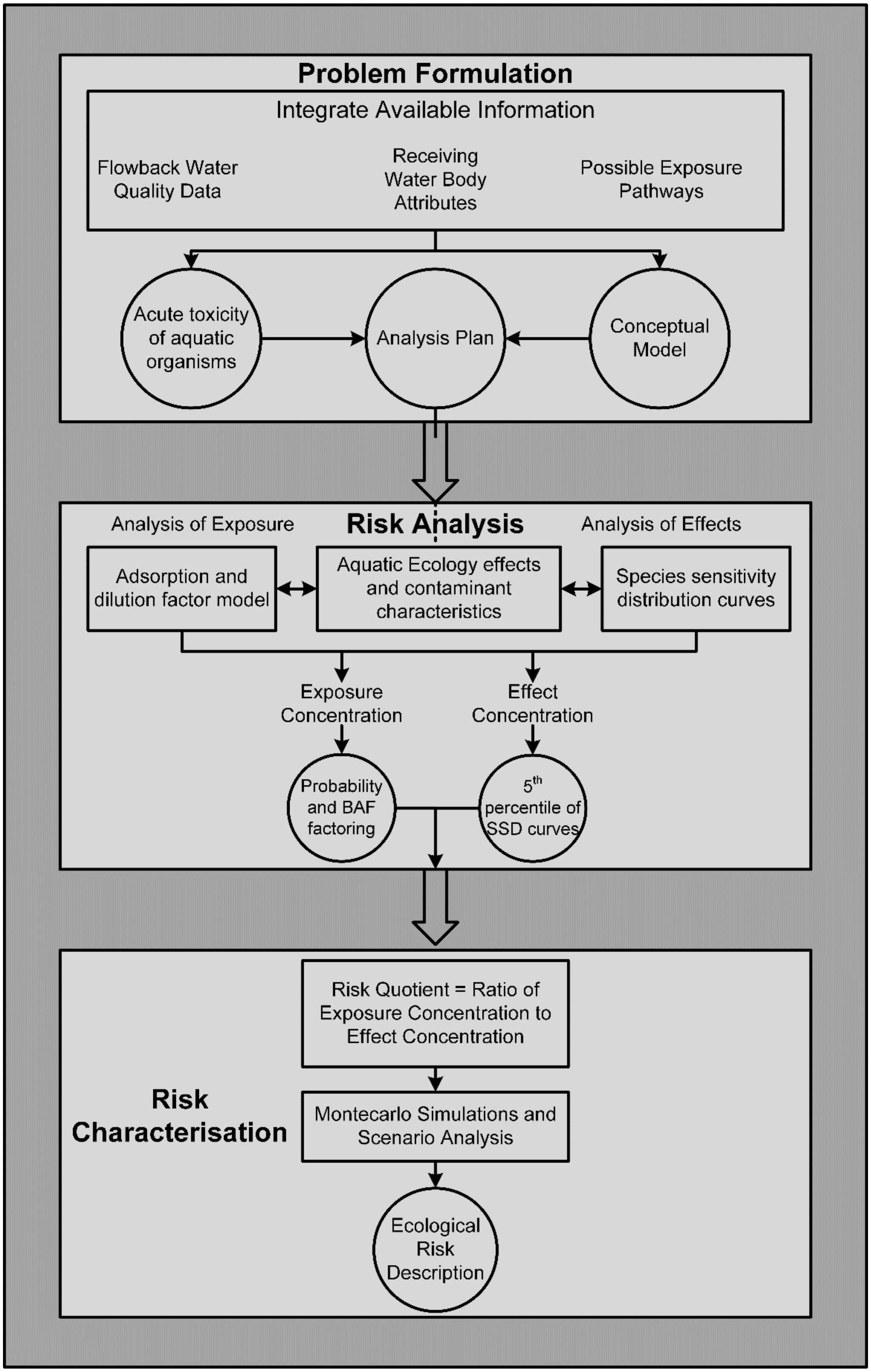


Figure 3-5 Ecological Risk Assessment framework for flowback water, adapted from (US EPA, 1998)

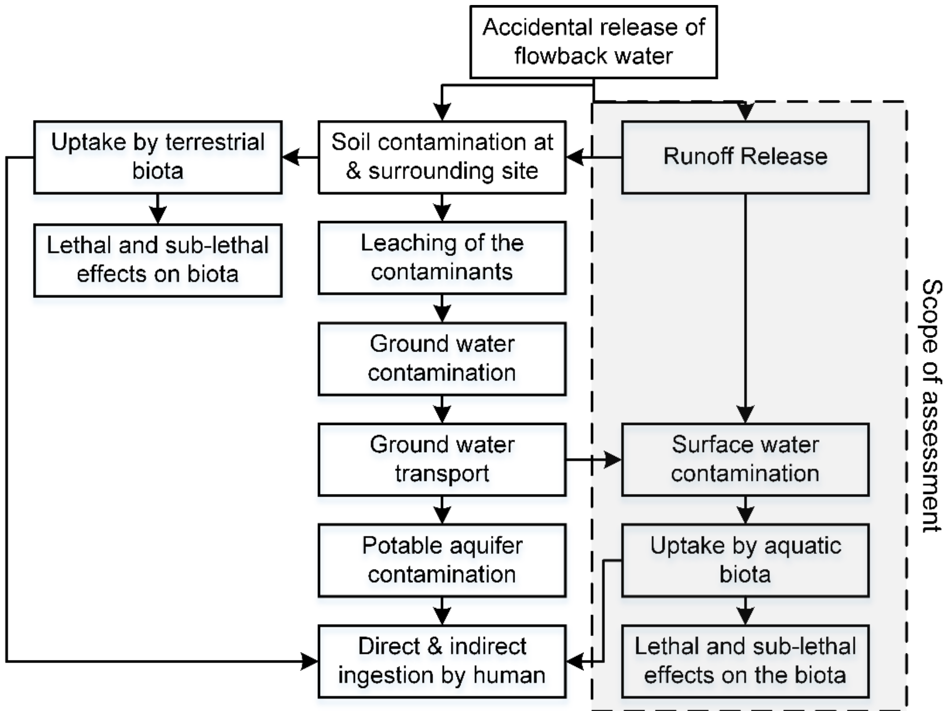


Figure 3-6 Conceptual model for flowback water release from storage and contamination pathways [4]

contaminant on the species, LC_{50} (Lethal Concentration 50%) and EC_{50} (Effect Concentration 50%) values are considered. LC_{50} is the concentration of the contaminant at which 50% of the population is killed. EC_{50} is the concentration of the contaminant at which 50% of the population is adversely effected in terms of reproduction, mobility, and other factors. The LC_{50} and EC_{50} values for each contaminant of the flowback water are collected from the literature. The endpoint acute toxicity values are collected from literature for an exposure period of 96 hours or less. The geometric mean is taken if more than one LC_{50} or EC_{50} values are available for the same exposure period for the same organism.

3.3.1.3 Analysis plan

This is the last stage of problem formulation. The stressor (flowback water) exposure to an aquatic organism could be through contaminated water and/or food. Physicochemical properties of the flowback water constituents and physical parameters of the surface water body are

[4] Contamination due to volatilization during accidental release not considered for open top storage system

required to be examined to conduct exposure assessment. The acute toxicity values of an organism for the stressor are derived in the effect analysis.

3.3.2 Analysis phase

The two primary components of the analysis phase are exposure and effects analysis (US EPA, 1998). The analysis phase is an intermediate phase between problem formulation phase and risk characterization and links them. The analysis plan developed using assessment endpoint and conceptual model in the problem formulation phase act as the basis for the risk analysis. In the following subsections, the techniques to conduct exposure and effects assessment are discussed. The risk is assessed in the form of a risk quotient which is the ratio of exposure concentration to effect concentration. Uncertainty and sensitivity analyses are then performed to quantify the errors and improve the credibility of the analysis (Sadiq, 2001; Suter II, 2007; US EPA, 1998).

3.3.2.1 Analysis of effects

An aquatic life is the assessment endpoint based on the availability of data. To assess short-term (acute) response, LC_{50} or EC_{50} values are used. Figure 3.7 represents the guidelines of CWQG-PAL to be used corresponding to the type of data available for deriving acute toxicity of the contaminant. Primary data refers to the data that are based on scientifically defensible toxicity tests whereas secondary data originate from literature studies that are of acceptable quality and documentation (CCME, 2007). In this analysis, only secondary type of data is considered.

For Type A analysis, species sensitivity distribution (SSD) curves are generated. SSDs model the variation of the sensitivity of species to the defined stressor. They are generated by fitting a statistical or empirical distribution function (EDF) to the proportion of species affected with respect to the stressor concentration (CCME, 2011; US EPA, 2016e). SSDs are created using secondary LC_{50} and EC_{50} data and they help understand the relative sensitivities of the species.

The empirical distribution of a random sample is the uniform discrete measure on the observation. For random samples, $y_1, y_2, \ldots, y_n$, an EDF can be defined as (Van der Vaart, 2000):

$$F_n(t) = \frac{1}{n}\sum_{i=1}^{n} 1(y_i \leq t) \tag{3.5}$$

The distribution curves were fitted by determining the goodness of fit of the model using Akaike Information Criterion (AIC). The AIC statistics are calculated from the log-likelihood function by the simple expressions and are generally recommended (Palisade Corporation, 2015b).

A standard safety level was set at the 5th percentile on the fitted SSD curve to save 95% of the ecological community. This measure is defined as the contaminant effect concentration (Suter ll, 2006, Shaw-Allen & Suter II, 2016). Tools like SSD generator and @Risk can be used to develop the SSD curves (Palisade Corporation, 2010; US EPA, 2016e). For deriving toxicity value for using guideline Type B2, the LC_{50} value of the most sensitive species from the available dataset is divided by a safety factor of 10 (CCME, 2011).

The derived effect concentrations are then compared with background concentrations of the contaminants naturally present in the water body. If the naturally occurring levels of the given contaminant are higher than the derived effect concentration value, then it is assumed that the aquatic life at this location has adapted to this condition. The natural background concentration is then taken as the site specific value (CCME, 2011).

3.3.2.2 Analysis of exposure

Exposure assessment is used to understand the fate, transport through various exposure pathways and the bioavailable fraction (BAF) of the contaminant. It represents the final concentration available to the receiving ecology (CCME, 1997). The surface water contamination can occur through groundwater, land contamination or runoff as shown in Figure 3.6. The exposure pathway considered for this assessment is surface water contamination through runoff. For exposure analysis of surface water body, fugacity and aquivalence based models are widely used. Fugacity models are applicable to contaminants which maintain vapour pressure, which is mostly valid for organic chemicals. Inorganics and metallic compounds do not maintain vapour pressure, hence a modified form of fugacity model, aquivalence is used for evaluating fate and transport of heavy metals (Diamond et al., 1994; Sadiq, 2001b).

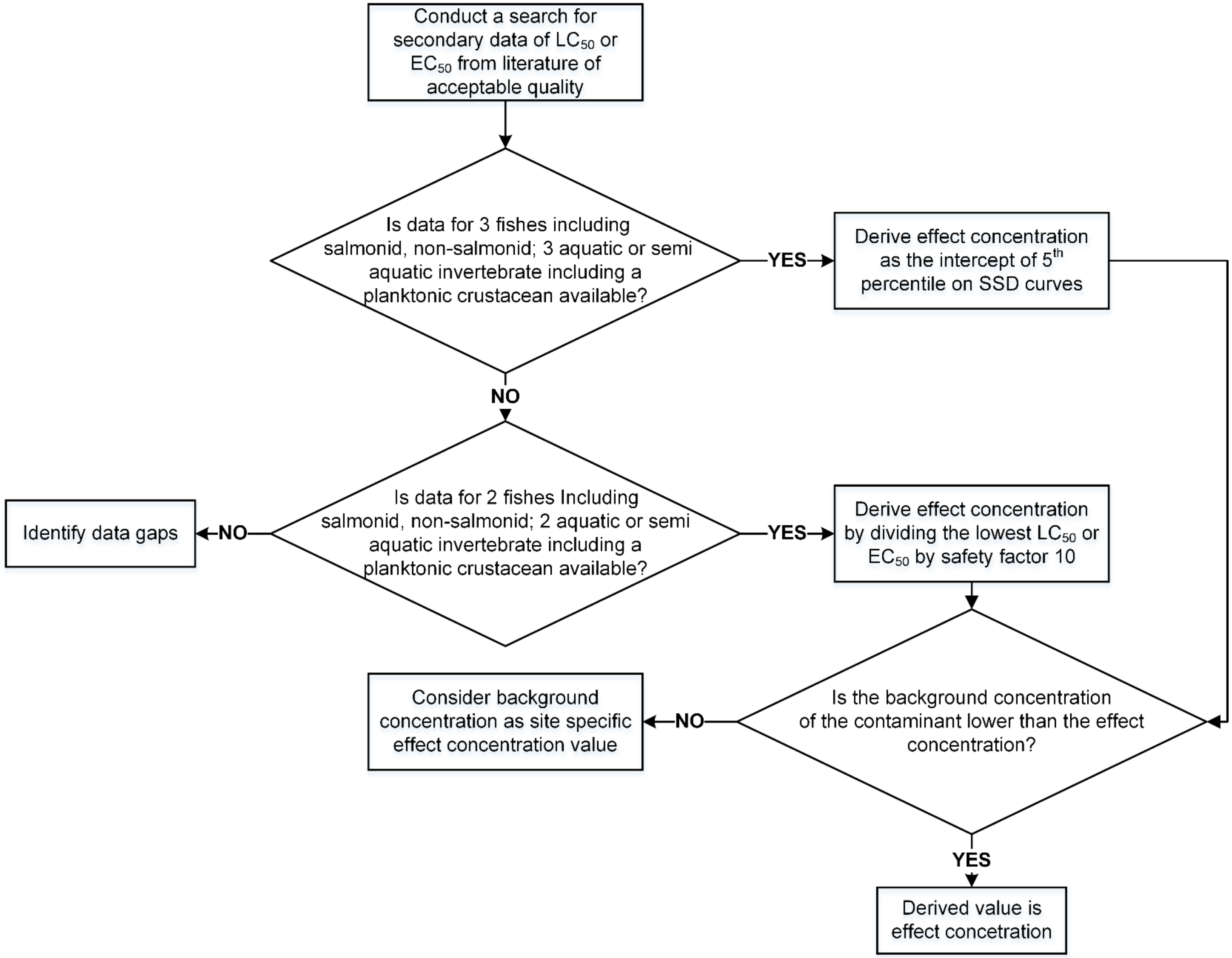


Figure 3-7 Minimum secondary data requirement for short-term exposure in freshwater and applicable guidelines (Adapted from (CCME, 2012))

Various exposure assessment models for organic contaminants are available. For surface water exposure assessment, the US EPA suggests the use of models like the AQUATOX, the GIS-based BASINS model, and the EXAMS for pesticide contamination, and the Visual PLUMES to evaluate dilution and dispersion behaviour of contaminants in surface water bodies (Suter II, 2007; US EPA, 2016g). These models have very specific application purposes requiring explicit inputs. For instance, the AQUATOX evaluates the toxic effects of biologically available chemicals through processes such as sorption, hydrolysis, volatilization, and photolysis. It requires inputs of nutrient, sediment, and toxic chemical loadings, general characteristics of site, growth characteristics and sensitivity of the population to the contaminants (Suter II, 2007).

Another such tool is EFAST or exposure and fate assessing screening tool. It calculates human potential dose rates for a variety of exposure routes and estimates the number of days per year that an aquatic eco-toxicological benchmark concentration will be exceeded for organisms in the water (Tobias & Kwon, 2016). It requires inputs like the amount of chemical released; media of release; days per year of release; chemical properties; and, detailed release location data; if applicable (Tobias & Kwon, 2016). In addition, these models are designed for organic and pesticide fate and transport.

For assessing the fate and transport of the metals, PHREEQC, MINTEQA2, Visual MINTEQ, MINEQL, WHAM models are available (Gustafsson, 2014; HydroGeoLogic Inc & Allison Geoscience Consultants Inc., 1998; US EPA, 2007). They consider the physicochemical properties unique to the inorganics like speciation, complexation, adsorption, indefinite persistence, bioavailability and bioaccumulation (US EPA, 2007). However, each of these models includes only some of the metal-specific capabilities and no single model is currently available for use, that includes all the features (US EPA, 2007). For instance, Visual MINTEQ calculates speciation, redox reactions, adsorption, and precipitation but it is difficult to calculate transport rate of the metal from contaminant source to water body (Gustafsson, 2014). Furthermore, due to the complexity and multiplicity of the processes and the interaction of multiple ions, recourse is made to the use of a single partition coefficient for this assessment.

The exposure route to be assessed is a runoff of the flowback water from land into the surface water body from the source of the spill. The excess water that does not infiltrate is a runoff

(Findeling et al., 2003). The contaminants in the flowback water have different physicochemical properties, affecting their transport and fate in the environment. Contaminants having a higher tendency for soil adsorption, have higher adsorption coefficient value. They can potentially bind to soil and can become comparatively steady. The rest of the contaminants might travel with the transporting media, and get introduced into surface waters and ultimately to the aquatic organisms through ingestion, inhalation, direct consumption and biomagnification (US EPA, 1988).

Metal ions are persistent in the environment and the rate of their movement through soils and their concentrations in groundwater are governed by the advection, dispersion, matrix diffusion, and retardation processes (US EPA, 2007). Advection and dispersion are functions of the transporting media. Matrix diffusion, which is a function of the contaminant, is relatively unimportant and is omitted in most transport models (US EPA, 2007). Retardation depends on a number of factors and may involve sorption, precipitation, colloid formation, and bio-fixation. Salt ions are highly soluble in water, and they are resistant to biodegradation, volatilization, and photolysis due to the inorganic nature (Bright & Addison, 2002).

The environmental transport of these ions is being assessed for adsorption (US EPA, 2007). The assumption underlying the exposure assessment is that during run off, the flowback water constituents are adsorbed on to the surface of a solid and are in chemical equilibrium. Adsorption can be defined as the net accumulation of matter at the interface between a solid phase and an aqueous-solution phase (US EPA, 1999). The distribution coefficient or the adsorption coefficient is a measure of adsorption and can be defined as the ratio of the amount of the substance adsorbed (known as adsorbate) on the solid to the amount of adsorbate remaining in the solution at equilibrium (US EPA, 1999).

$$K_d = \frac{A_i}{C_i} \tag{3.6}$$

Where K_d is the adsorption coefficient, A_i is the amount of adsorbate adsorbed per unit mass of solid, and C_i is the concentration of the chemical remaining in the solution per unit volume of liquid phase at equilibrium. Equation 3.6 is valid under the assumption that concentration of free or unoccupied surface adsorption site on a solid phase is in great excess to C_i. The limitation of this model is that K_d is constant for homogenous conditions and a new value of K_d would be required if there is change in groundwater and soil properties.

There are various approaches available to measure K_d values including laboratory or in-situ batch method, flow-through (or column) method, field modeling method, and K_{oc} method (US EPA, 1999). Flow through method uses mean residence time and are helpful for non equilibrium conditions, field modeling is highly field specific and K_{oc} method is used for determining organic constituent partition. For further analysis the K_d values are taken from literature and simple Batch method equations are used to establish A_i (US EPA, 1999)-

$$A_i = \frac{V_s\,(C_o - C_i)}{M_{soil}} \tag{3.7}$$

Where, V_s is the volume of spilled liquid, C_o is the concentration of contaminant in the spilled liquid, and M_{soil} is the unit mass of soil contaminated by the spill. For the analysis, we need the amount of concentration remaining in the solution after passing through the land. Thus, the value of C_i for given K_d can be calculated using:

$$C_i = \frac{V_s C_o}{K_d M_{soil} + V_s} \tag{3.8}$$

The exposure concentration of the contaminant in the surface water body is evaluated based on the volume of contaminant introduced in the stream and their dilution coefficients. Contaminants may be restricted and might remain concentrated, or might disperse and become diluted in the stream to insignificant concentrations (US EPA, 1988). A simple mass balance equation is proposed to calculate the contaminant concentration in the natural water body after the flowback water is discharged into it. The total contaminant concentration (C_∞) at equilibrium in the creek is obtained using the following equation (CCME, 1997; Leeuwen & Hermens, 2004; US EPA, 1988)-

$$C_\infty = \frac{C_W Q_W + C_i Q_s}{Q_W + Q_s} \tag{3.9}$$

Where, Q_w and Q_s are the discharge of the creek and spilled flowback water, respectively, and C_w is the concentration of the contaminant in the surface water body. The dilution factor theory assumes that the blending of the contaminants in the creek water is uniform and complete. It also assumes that decay and removal processes like sorption, volatilization, leaching are negligible and the flow rates of the water and the contaminant remain constant (US EPA, 1988). If the spilled chemicals do not have a short biodegradation half-lives and high sorption potentials, the dilution factor model can be effectively used to predict the concentrations of the contaminants in the natural water body within few kilometers of the spill site as processes other than dilution would have relatively smaller effect (Leeuwen & Hermens, 2004). Moreover, the decrease in concentration due to adsorption are incorporated into the total contaminant concentration. Hence, the integration of these techniques should give satisfactory results.

In order to take into consideration the movement of aquatic organisms about the contaminated water as well as the bioavailability of the contaminants, the estimated exposure concentration (EEC), would be estimated using equation 3.10 (Nazir et al., 2008):

$$EEC = p \times C_{\infty} \times BAF \qquad (3.10)$$

Where p is the probability of exposure. It is the ratio of the impact area to the total area under consideration. If the area considered for assessment is equal to the area under impact area, p can be equal to the probability of contamination. The value of p is derived from the BIA framework using FTA. BAF is the bioavailable fraction which is approximately 1 for chemicals having a log of octanol water partition coefficient less than 5, that is, log K_{ow}< 5 (US EPA, 1988, 2016f). The entire exposure assessment process is explained in Figure 3.8. The flowback water with initial concentration of its constituents, stored in the AWSS gets released accidently. Runoff of the flowback water occurs and some of the constituents get adsorbed by the soil. Remaining concentration enters the stream and dilutes, greatly reducing the concentration of the contaminants. After taking into consideration background concentration and BAF, the final concentration, EEC is available to the aquatic organisms.

3.3.3 Risk characterization

As the final phase of the risk analysis, risk characterization combines the results of exposure and effects analysis and the associated uncertainties. The risk quotient is used for risk characterization. A sum of the ratio of exposure and effects concentration for each contaminant is obtained from risk quotient (Sadiq, 2001; US EPA, 1998)-

$$Risk\ Quotient = \sum_n \frac{(EEC)_n}{(EC)_n} \tag{3.11}$$

Where n is the contaminant and EC is effect concentration for the contaminant to be a concern. If the risk quotient is greater than one, there is a possible adverse effect to the ecology. The quotient integrates risk due to multiple stressors. This approach assumes that the toxicities of the chemicals are additive. The synergistic or antagonistic effects between different chemicals contained in the flowback water are not considered (Suter II, 2007; US EPA, 1998). The full equation for calculating risk quotient (R) is shown as equation (8):

$$R = \sum_n \frac{p \times BAF}{EC_n}\left(\frac{C_{w_n} \times Q_w}{Q_w + Q_s} + \frac{V_s \times C_{o_n} \times Q_s}{\left((K_{d_n} \times A_{soil} \times d \times \rho) + V_s\right) \times (Q_w + Q_s)}\right) \tag{3.12}$$

Where V_s is the volume of spilled flowback water (L), EC_n is effects concentration of the n^{th} contaminant (mg/L), A_{soil} is the area of the contaminated soil (m), d is the distance of the spill site from the water body (m), C_{o_n} is the initial concentration of the n^{th} contaminant in the flowback water (mg/L), C_{w_n} is the background concentration of the n^{th} contaminant in the creek (mg/L), ρ is the soil bulk density (g/m^3) and K_{d_n} is the adsorption coefficient of the n^{th} contaminant. A critical value of R as 1, would mean that the exposure concentration has reached the effect concentration value and 95% of the ecology is at risk to the lethal and sub-lethal effects caused by the increase in exposure concentration.

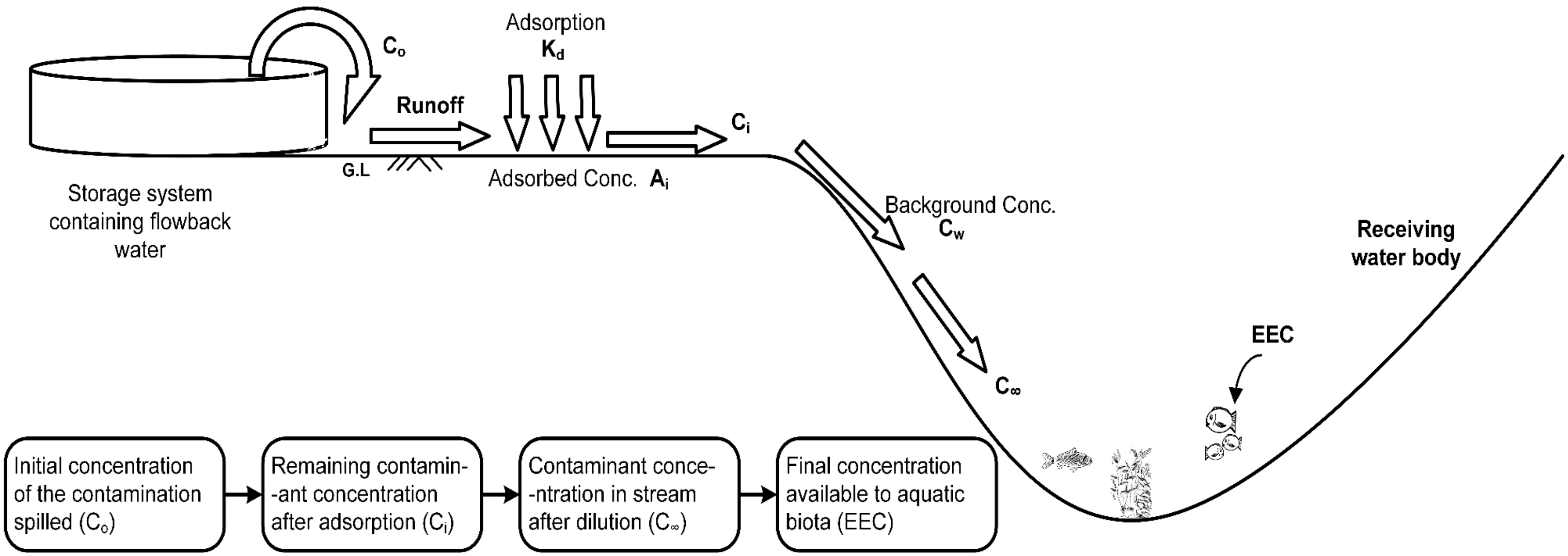


Figure 3-8 Exposure assessment model proposed for inorganic constituents of flowback water

3.3.4 Uncertainty, sensitivity and scenario analyses

The risk quotient generates single point estimate of the risk. The single values used for the calculation of risk might be conservative to decrease the possibility of underestimating the true risk to the organism. However, in this approach, the possibility of overstating the risk might be high. Uncertainty analysis is used in the ERA framework to measure the confidence in the risk estimate. It can further help to fully characterize risk to wholly assess the consequences and limitations of the risk assessment (Hammonds et al., 1994).

Uncertainty analysis can be a valuable tool for ranking the parameters contributing to the uncertainty in risk estimate of the contaminants. The rankings give guidance regarding the acquisition of additional data pertaining to the parameter to reduce uncertainty in risk estimates (US EPA, 1998). In order to assess the full range of possible values, the usual approach is developing probability distributions for the uncertain parameters included in the computation of risk quotient. Conservative estimates of EC and EEC are considered for risk assessment. Probability distributions are generated for a range of EC values for each contaminant derived from SSD generator and @Risk. The distributions for initial concentration, C_o are produced for a range of concentration values of selected contaminants in flowback water collected from literature. The true values of EC and C_o exists but are unknown. Such uncertainty is known as epistemic uncertainty (Regan et al., 2003). The distributions are fitted using the AIC test as discussed for SSD curve generation (Palisade Corporation, 2015a).

For the assessment of uncertainty, Monte Carlo analysis is proposed. It is a computer-based simulation technique that is used to obtain a probabilistic approximation to the solution of a mathematical equation or model (US EPA, 1997). The analysis uses statistical sampling techniques to sample a random value from each distribution of the uncertain parameter and the process is repeated for the desired number of samples or iterations (Hammonds et al., 1994). The analysis uses the distributions generated for the uncertain parameters and the relationship established between the risk quotient and these parameters (as shown in Equation 3.12) act as inputs for uncertainty assessment of the risk estimate.

The analysis is performed using computerized mathematical Monte Carlo simulation programs to achieve a forecast of risk quotient in form of distributions which allow assignment of confidence intervals for the risk estimate (Hammonds et al., 1994; Palisade Corporation, 2015b; Regan et al., 2003)**.** The confidence interval can be adjusted based on the required level of confidence in the risk estimate. A number of software packages can be used to conduct Monte Carlo analysis including @Risk, Crystal Ball and SimLab (Oracle, 2016; Palisade Corporation, 2015b; Refsgaard et al., 2007).

Sensitivity refers to the variation in the output parameter of the mathematical model or equation with respect to changes in the value of the input parameters. Sensitivity analysis provides an insight as to which input variables contribute most to the overall uncertainty to the output parameter (Hammonds et al., 1994; US EPA, 1997). The EC and C_o of which contaminant are contributing the most towards the uncertainty in the risk estimation is examined. A reduction in the level of uncertainty of the most sensitive parameters would contribute to reduce an overall uncertainty of the output parameter. The sensitivity analysis be can be performed using Monte Carlo analysis. From the result of simulations, analytical techniques like change in output statistic, regression analysis, and rank correlation analysis are performed. The results are displayed as a tornado graph, with longer bars at the top representing the most significant input variables contributing to the uncertainty in the output (Palisade Corporation, 2015a).

Scenario analysis is conducted to logically and internally explore alternative futures, as such, it is a tool to describe the future under different assumptions (Refsgaard et al., 2007). It is a powerful tool for asking “what if” questions to explore the consequences of uncertainty (Duinker & Greig, 2007). Scenario analysis is carried out for different flowback water spill volumes and the receiving aquatic body discharge values using the analytical technique of regression analysis. Regression analysis technique performs analysis using the least squares to fit a line through a set of observations. A change in single dependent variable affected by the values of one or more independent variables can be analyzed (Refsgaard et al., 2007). A relationship between a range of volume of the spill, seasonal discharge of aquatic body and the risk quotient is derived. The result obtained can help to derive the maximum volume of the spill for which the exposed ecology of the river, stream or creek can be considered safe.

3.3.5 Risk description

The ERA is an iterative process. The tools or techniques used in each ERA phase might need assumptions due to unavailable information or missing data. As data is updated with newly available information, the risk should be assessed and quantified in light of the new data. The results generated in the risk assessment process are evaluated and interpreted. It assesses the assumptions of the risk assessment and sees if further evidence is required. The significance of the adverse effects as stated from the risk results are interpreted. The interpretation provides valuable information for decision-making. An acceptable risk, as described by US EPA, is one in a million. For risk quotient, it is binary, if greater than 1 there is a greater chance of risk and less than 1 the ecosystem is relatively safer. The risk results are evaluated as per the risk precepted by the stakeholders. Risk perception refers to an understanding of the risk among the general public and its acceptability as it is not possible to completely eliminate the risk.

The method proposes BIA and ERA framework to quantify the risk to the ecology due to the accidental release of flowback water. BIA is used to calculate the probability of the failure of the storage system and rank the failure mode. ERA helped to assess the exposure and effect of the flowback water contaminants on the aquatic ecology. The probability is input in the ERA framework to estimate the risk. Uncertainty, sensitivity and scenario analysis is carried to obtain the full range of risk estimate, to determine the parameters contributing to the uncertainty and derive the relationship between spill volume and receiving aquatic body discharge. This method is applied to a creek in Montney unconventional play in Northern BC, Canada to assess its effectiveness. The probability of failure of the AWSS system was assessed and the modes of failure studied. The study area, data collection, results of the assessment and conclusion are discussed in the following chapters.

CHAPTER 4. CASE STUDY

4.1 Study Area

Montney unconventional play trend is the single most important unconventional gas producing horizon in Canada with over 3100 active gas wells (NRCAN, 2016a). The Montney is a massive resource play that reaches across northwest Alberta and into northeast British Columbia. Flatbed Creek located near Montney play within BC is selected for assessment. The creek orginates in the Rocky Mountains passes by 110 Heritage Highway in the Peace River regional district and flows North-West into Murray River (CEAA, 2012). The path of the creek is as traced in Figure 4.1. The creek is selected because it is located in an area of intensive unconventional gas productions and there are sufficient hydrogeological data available for the risk assessment including data for background concentration of contaminants and monthly discharge value. The selection was creek was done to determine the possible environmental effects on smaller discharge suface water body. The Flatbed Creek basin covers an area of 486 km^2 and has an average annual discharge of 4.14 m^3/s (BCOGC, 2016). An accidental spill or uncontrolled release of flowback water is assumed to have occurred from AWSS type of storage system located 200 m near the creek.

Figure 2.5 illustrates major components of the AWSS. The AWSS is an open, bottomless, insulated, short cylindrical system lined with heavy duty tarp liner clamped on the shell. It consists of structural walls system, a diked form of the secondary containment system, liner system, a pipeline system leading up to AWSS with an inlet/outlet pump and inlet/outlet valve. The flowback water is discharged into the AWSS via pipelines. There are no openings in the walled structure. The pipelines go over the shell. The AWSS, liner, pipeline, valve, and pump consist of the primary storage system. A secondary containment system in the form of a dike is constructed immediately surrounding the primary storage system.

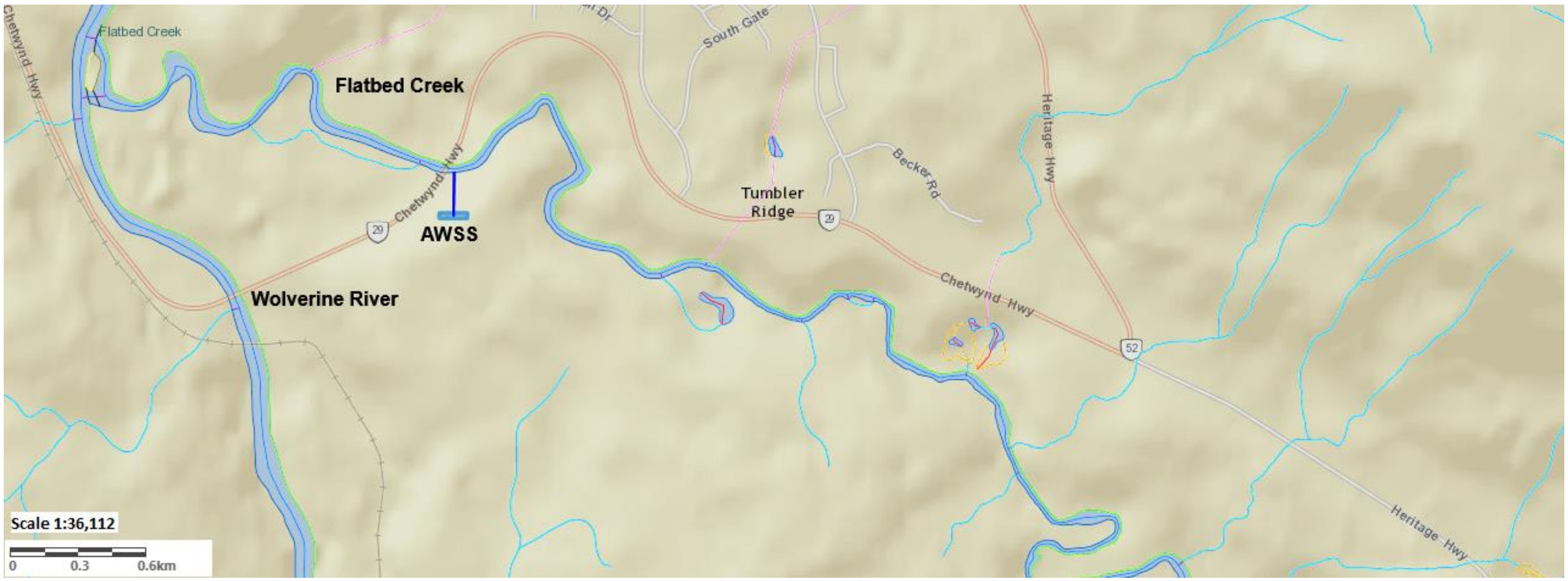


Figure 4-1 Flatbed Creek and AWSS located at 200m from the creek near Montney in BC[5]

[5] Source: iMapBC http://maps.gov.bc.ca/ess/sv/imapbc/. Copyright 2013 Province of British Columbia. All rights reserved.

4.2 Data Collection

Variety of data was collected from literature in line with the study area described above and the method proposed to conduct the hypothetical case study in order to demonstrate the application of the assessment.

4.2.1 Data for BIA framework

The most important and challenging component of BIA was understanding the failure modes of the system which is relatively new and does not seem to have been studied from the current literature review. The failure modes for the AWSS were determined by understanding the failure modes of its sub-systems and their components. The failure modes of shell like structural wall system and secondary system of AWSS were deduced by studying relevant failure modes and their mechanism of the tanks and containment ponds type of storage system from the existing literature including API (2014), Atherton et al. (2008), CCPS (2000b), Choi & Chang (2016), Cunat (2002), Kuwayama et al. (2015), Nakashima (2010), Trebuňa (2009), US EPA (2009, 1986a, 1986b, 2002). The liner failure was studied from sources like Cheng et al. (2009), Klimchuk et al. (2016), Peggs (2009), Robeson (2013), US EPA (1985, 1996). Pipeline and other components failure were investigated from Shahriar et al. (2012) and US EPA (1986b, 1986c).

Site specific information about AWSS failure modes as well as the occurrence, severity and detectability ranking was obtained from Secure Energy Services Inc. and visit their AWSS storage facilities in Grand Prairie, Alberta, Canada (C. Krauskopf and G. Dickie, personal communication, May 4, 2017).

4.2.2 Data for ERA framework

The ERA will require data of the stressor, i.e., flowback water and data of the receving water body, i.e., Flatbed creek. The flowback water generated from the wells in Montney are sampled, tested and registered at IHS AccuMap as a database implemented by the BCOGC (IHS Accumap, 2016). The data for flowback of the wells in the Montney shale gas play from 2009 to 2016 were collected and cleaned. 212 wells were shortlisted based on the sampling date and well completion date to ensure the flowback period of 28 days. The contaminants and their concentrations in the flowback water are as shown in Table 4.1. It is not a requirement to register flowback water quality during hydraulic fracturing operations; hence, it is difficult to determine if the enlisted contaminants in Table 4.1 represent all the constituents of flowback water. Circumstantial evidence shows the presence of NORMs, hydrocarbons, and grease in the flowback water; however, they were not included in the assessment due to lack of reliable data source.

The monthly average flow and the average background concentrations of serveral inorganic chemicals in the Flatbed creek are shown in Table 4.2. The monthly and average annual discharge rate of the creek is also reported. The information presented in Table 4.2 for Flatbed Creek was collected from BC Water Portal (BCOGC, 2016).

Table 4-1 Contaminants and their concentrations found in flowback water samples collected in Montney

Contaminants	Mean (mg/L)	Median (mg/L)	Maximum (mg/L)	Minimum (mg/L)
TDS	93079	90037	260000	1458
Sodium	26852	25000	69700	96
Potassium	2148	1050	18200	16
Calcium	5282	4950	17164	80
Magnesium	797	708.5	8427	13.4
Barium	212	20.85	2470	0.61
Strontium	618	551	1573	3.8
Iron	33	26	240	0.2
Manganese	3	1.75	15	0.46
Chloride	57278	54869	177100	208
Bromide	259	196.5	1150	13.4
Iodide	12	10.4	41.1	0.6
Bicarbonate	450	190.5	3363	19.2
Sulfate	247	137	3499	2.4
Carbonate	121	77.6	416	14.1
Hydroxide	203	203.4	203.4	203.4
Hydrogen Sulfide	257	255.6	511.2	8.5

The impoundment is assumed to store flowback water with the mean concentration value of each contaminant (Table 4.1). Based on the historic spill volumes, a spill of 1000 L is assumed to occur over a period of 96 hours (US EPA, 2015).The surrounding soil is assumed to be loamy clay with a bulk density of 1.5 g/cm^3 and an effective porosity of 0.39 (Clark et al., 1962; Rawls et al., 1982; US EPA, 2005). The affected soil area is assumed 100 m wide and 5 cm deep. For deriving acute toxicity guidelines, an extensive literature review was carried out and secondary toxicity data was collected for lethal and sub lethal effects on fish, crustaceans, amphibians, molluscs, worms and aquatic plant (duckweed). These organisms were tested in the lab in freshwater media for an exposure duration of 96 hours or less for the endpoints LC_{50} and EC_{50}.

Considering the road salt toxicity studies, relatively larger amount of toxicity data exists for chloride ion. However, not enough data for sodium and calcium ions. Also, experimental studies show that the toxicity of the Na^+ and Ca^+ salt ions is negligible and can be attributed to the corresponding anion (Mount et al., 1997). The sufficient data for deriving acute freshwater toxicity of barium, potassium, magnesium, iodide, bicarbonate, carbonate and hydroxide were not available as required by the guidelines defined in Figure 3.7.

Table 4-2 Background concentrations and monthly discharge rate of the Flatbed Creek (BCOGC, 2016)

Chemicals	Average Concentration (mg/L)	Month	Discharge (m^3/s)	Month	Discharge (m^3/s)	Month	Discharge (m^3/s)
Barium	0.2	Jan/Feb	0.5	Jun	11.1	Oct	2.1
Iron	0.0843	Mar	0.6	Jul	7.1	Nov	1.5
Manganese	0.00399	Apr	4.8	Aug	3.3	Dec	0.8
Strontium	0.111	May	15.1	Sep	2.8	Annual Mean	4.1

Table 4-3 Physicochemical properties of the contaminants (Bright & Addison, 2002; US EPA, 1988, 1999, 2005, 2016f)

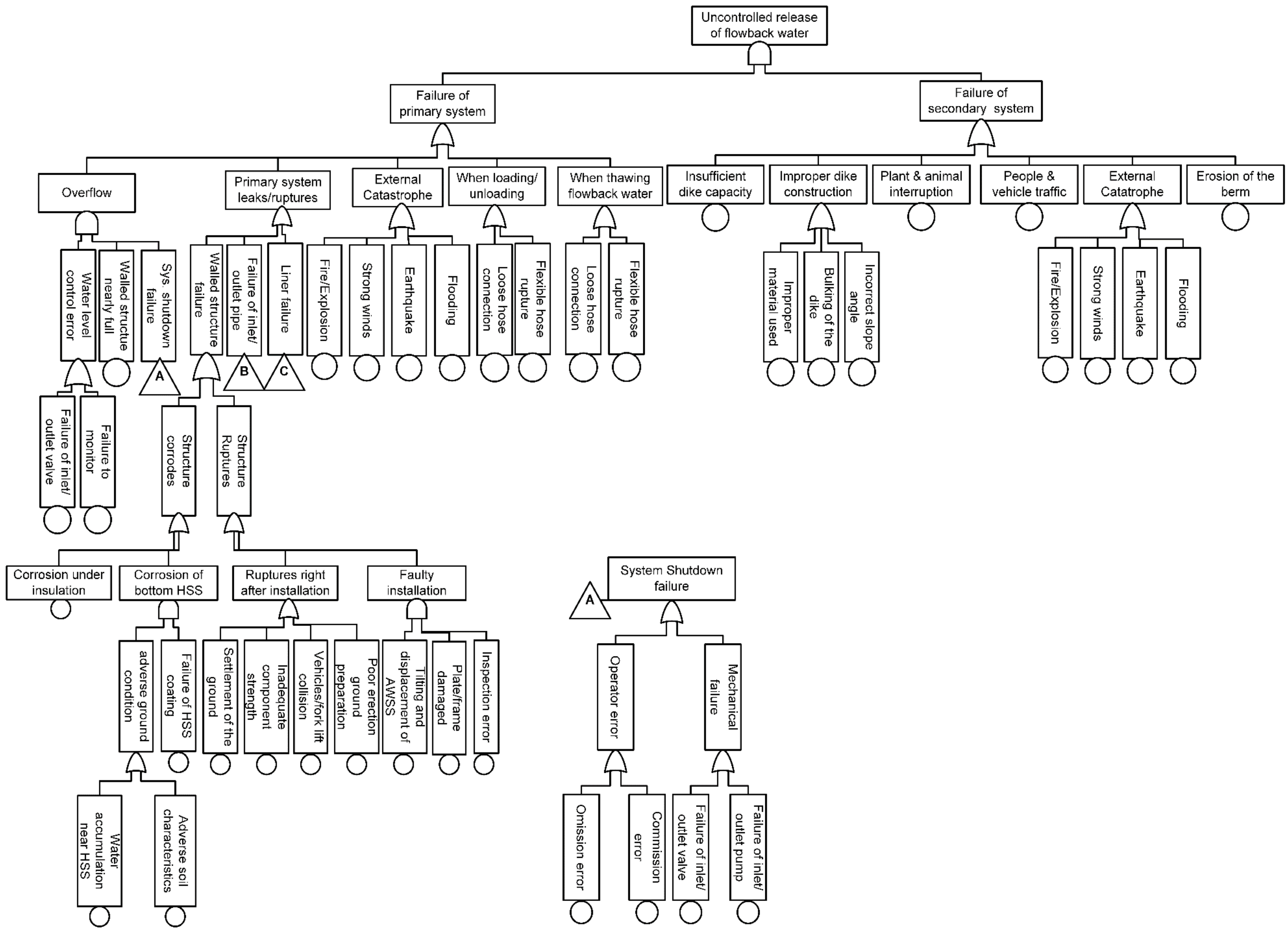
Contaminant	K_d(mL/g)	log K_{ow}	Molecular weight (g/mol)	Water Solubility
Barium	4.1E+01	2.3E-01	1.3E+02	5.8E+03
Hydrogen Sulfide	9.9E+00	2.3E-01	3.4E+01	3.7E+03
Iron	2.5E+01	-7.7E-01	5.5E+01	3.5E+05
Manganese	6.5E+01	2.3E-01	5.4E+01	6.6E+04
Strontium	1.0E+00	2.3E-01	8.7E+01	6.7E+03
Chloride	0.0E+00		3.5E+01	
Sulfate	0.0E+00		9.6E+01	
Bromide	0.0E+00		7.9E+01	

Appendix A lists the dataset used for the derivation of acute toxicity effect concentration values. These data are collected from ECOTOX (US EPA, 2016), CCREM (2008), McPherson, et al. (2014), Pacholski (2009), Hedayati, et al. (2015), Shuhaimi-Othman, et al. (2013) and other sources. The physicochemical properties of contaminants, including the values of adsorption coefficient, log octanol water partition coefficient, molecular weight and water solubility are shown in Table 4.3 (Bright & Addison, 2002; US EPA, 1988, 1999, 2005, 2016f). Chloride, sulfate, and bromide are usually reported to travel via soil columns at the same rate or faster than water in their dissolved form (US EPA, 1999). Thus, their adsorption coefficient was assumed zero (Bright & Addison, 2002).

4.3 Implementation of BIA Framework

A fault tree entails a failure analysis of sub-system and components of the AWSS. The top failure event is identified as the uncontrolled release of flowback water. The failure modes for walled structure, liner, pipe, valve, pump and secondary containment system are assessed. Each failure event of the fault tree is described in Table 4.4 with the corresponding probability of failure values. It should be noted that the analysis is can have many variations to the fault tree and can be constructed in several ways. This is an example of the fault tree to the required level of detail for the analysis.

The basic failure events of the fault tree and the failure rates are used as inputs to the FMEA in BIA. Severity, occurrence, and detectability were ranked based on the scale given in Table 3.3 (C. Krauskopf and G.Dickie, personal communication, May 4, 2017). Detectability of the failure event is only through manual monitoring. Based on this assumption, Table 4.5 shows the FMEA table for failure modes as ranked using risk priority number (RPN). The failure modes are prioritized based on the calculated RPN and are arranged in decreasing order of their RPN. The higher the RPN, the higher the rank. For example, “Penetrations through liner” is a potential failure mode having the highest RPN of 30 and is ranked 1.



Uncontrolled release of flowback water
Failure of primary system
Failure of secondary system
Overflow
Primary system leaks/ruptures
External Catastrophe
When loading/ unloading
When thawing flowback water
Insufficient dike capacity
Improper dike construction
Plant & animal interruption
People & vehicle traffic
External Catatrophe
Erosion of the berm
Water level control error
Walled structue nearly full
Sys. shutdown failure
Walled structure failure
Failure of inlet/ outlet pipe
Liner failure
Fire/Explosion
Strong winds
Earthquake
Flooding
Loose hose connection
Flexible hose rupture
Loose hose connection
Flexible hose rupture
Improper material used
Bulking of the dike
Incorrect slope angle
Fire/Explosion
Strong winds
Earthquake
Flooding
A
B
C
Failure of inlet/ outlet valve
Failure to monitor
Structure corrodes
Structure Ruptures
Corrosion under insulation
Corrosion of bottom HSS
Ruptures right after installation
Faulty installation
adverse ground condition
Failure of HSS coating
Settlement of the ground
Inadequate component strength
Vehicles/fork lift collision
Poor erection ground preparation
Tilting and displacement of AWSS
Plate/frame damaged
Inspection error
Water accumulation near HSS
Adverse soil characteristics
A
System Shutdown failure
Operator error
Mechanical failure
Omission error
Commission error
Failure of inlet/ outlet valve
Failure of inlet/ outlet pump

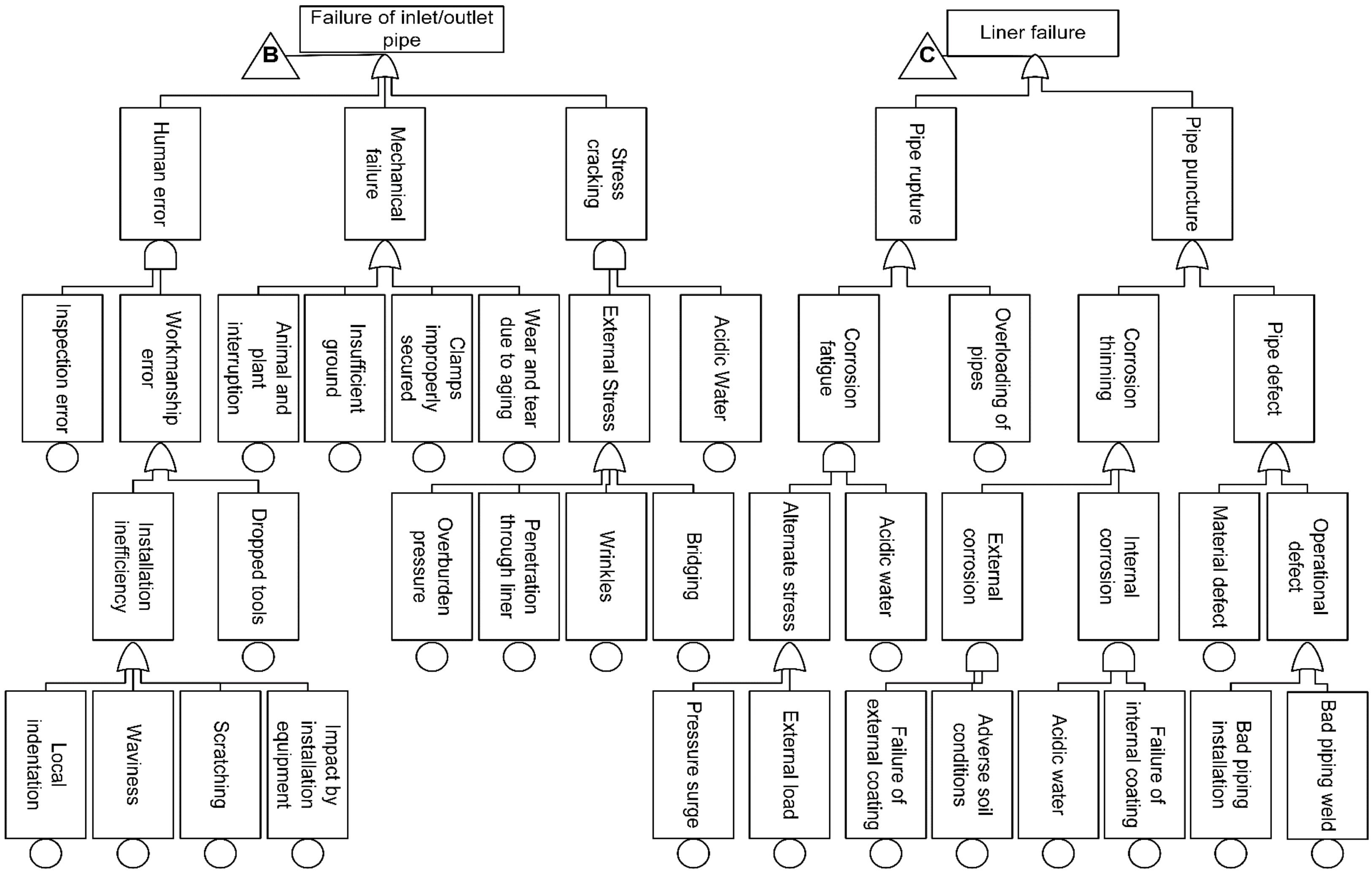


Figure 4-2 Fault tree for uncontrolled release of flowback water from AWSS failure[6]

[6] Secondary system is the berm surrounding the primary system. Primary system includes walled structure, lined system, piping system

Table 4-4 Description and probability of fault tree events

Failure Event	No.	P[7]	Description
Uncontrolled release of flowback water	G1		Undesired top event for overall risk evaluation
Failure of primary storage system	G2		Failure of the primary storage system
Failure of secondary containment system (dike)	G3		Uncontrolled release of flowback water due to secondary containment (dike) failure
Overflow of the AWSS	G4		Overflow of flowback water from the AWSS
Primary storage system develops leak or ruptures	G5		Failure of the primary storage system by developing leak or rupturing
External catastrophe	G6		Failure of the primary storage system due to external catastrophe
Spill during loading/unloading	G7		Release of flowback water due to spill during loading/unloading
Spill during thawing	G8		Release of flowback water during thawing
Improper construction	G9		Failure due to improper construction of the dike
Water level control error	G10		Failure to control the overflow of flowback water
System shutdown failure	G11		Failure of the system to shutdown the inflow of water
AWSS failure	G12		C-ring tank leaks or ruptures
Pipe failure	G13		Flowback water release due to pipe failure
Liner failure	G14		Leak or rupture of storage system due to liner failure
Operator error	G15		Error of the operator in shutting down the system
Mechanical failure	G16		Device failure to shutdown the system
AWSS corrodes	G17		Release of flowback water due to corrosion of C-ring
AWSS ruptures	G18		Release of flowback water due to rupture of C-ring
Pipe puncture	G19		Failure of pipe due to puncturing
Pipe rupture	G20		Pipe failure due to rupture of pipe
Stress Cracking on the liner	G21		Liner failure by stress cracking at the break strength of the liner
Mechanical Failure of the liner	G22		Failure of liner by cracking and breaking
Human error	G23		Liner failure due to human error
Corrosion of the bottom HSS	G24		Corrosion of the hollow steel section in contact with the ground
AWSS ruptures right after installation	G25		C-ring fails as soon as installed
Undetected faulty installation	G26		Failure of the c-ring due to undetected faulty installation
Corrosion thinning of piping	G27		Puncture of pipe due to corrosion thinning
Pipe defect	G28		Puncture of pipe due to pipe defect
Corrosion fatigue	G29		Pipe failure due to corrosion fatigue of pipe
External stress on the liner	G30		Stress cracking of the liner due to excessive external stress in presence of acidic water
Workmanship error	G31		Liner failure due to poor or erroneous workmanship

[7] Probability of failure; applies to only basic events. Basic events are numbered xn

Failure Event	No.	P[7]	Description
Adverse ground conditions	G32		Corrosive ground characteristic
Piping external corrosion	G33		Puncture of pipe due to external corrosion
Piping internal corrosion	G34		Puncture of pipe due to internal corrosion
Operational defect	G35		Puncture of pipe due to operational defect
Alternate stress	G36		Corrosion fatigue due to development of tensile stress
Installation inefficiency	G37		Inefficient installation of liners induces failure by stress cracking
Traffic from people and equipment	x1	1E-05	Secondary containment failure (dike) due to traffic from people and equipment
Animal and plant interruption	x2	1E-05	Burrows or holes created by animals and roots of plants voids in the embankment and weakening the dike
Erosion of the berm	x3	1E-04	Failure of the dike due to erosion
Insufficient dike capacity	x4	1E-05	Overflowing of flowback water due to insufficient dike capacity
AWSS nearly full	x5	5E-05	Water level in AWSS above freeboard
Strong winds	x6	5E-05	Failure of the primary storage system due to high winds
Earthquake	x7	1E-05	Failure of the primary storage system due to earthquake
Flooding	x8	1E-05	Failure of the primary storage system due to flooding
Fire/Explosion	x9	1E-05	Release of flowback water due to fire or explosion
Flexible hose rupture	x10	1E-03	Spill during filling or discharging due to rupture of flexible hose
Loose flexible hose connection	x11	1E-03	Spill during filling or discharging due to loose flexible hose connection
Flexible hose rupture	x12	1E-05	Spill during thawing due to rupture of flexible hose
Loose flexible hose connection	x13	1E-05	Spill during thawing due to loose flexible hose connection
Bulking	x14	5E-05	Dike failure due to bulking
Improper material used	x15	1E-05	Dike failure due to standing water at surface
Incorrect slope angle	x16	1E-05	Failure of dike due to construction at incorrect slope angle
Failure to monitor the water level	x17	5E-05	Failure to monitor the flowback water level in AWSS
Failure of inlet/outlet valve	x18	1E-05	Failure of the inlet/outlet valve to shutdown allowing/restricting water inflow
Commission error	x19	1E-05	Error in commissioning the system shutdown
Omission error	x20	1E-05	Error in acting correctly to shutdown the system
Failure of inlet/outlet pump	x21	5E-05	Failure of the inlet/outlet pump to shutdown allowing/restricting water flow
Corrosion under insulation of the wall	x22	1E-05	Corrosion of C-ring plates under insulation
Overloading of pipelines	x23	1E-05	Pipe failure due to overloading of pipe
Acidic water	x24	1E-05	Stress cracking of the liner due to excessive external stress in presence of acidic water
Inadequate ground preparation	x25	5E-05	Failure to remove debris and smoothen the ground adequately

Failure Event	No.	P[7]	Description
Clamps improperly secured	x26	1E-05	Tear of liner due to improperly securing clamps
Wear and tear due to aging*	x27	1E-05	
Inspection error	x28	1E-05	Failure of liner due to error or omission in inspecting/reporting/acting upon areas of poor workmanship
Failure of bottom HSS coating	x29	1E-05	Protective coating of the hollow steel section fails
Settlement of ground	x30	1E-05	Settlement of soil due to c-ring installation
Inadequate component strength	x31	1E-05	Rupture of C-ring due to inadequate component strength
Vehicle /fork lift collision	x32	1E-05	C-ring ruptures due to accidental collision with the working equipment
Tilting or displacement of AWSS*	x33	1E-05	AWSS ruptures due to tilting or displacement
C-ring plate or frame damaged during or before installation	x34	1E-05	Failure of the c-ring due to damage to c-ring plate or frame during or before installation
Piping material defect	x35	1E-05	Puncture of pipe due to defect in pipe material
Overburden Stress on the liner	x36	1E-05	Liner failure by induced stress due to high overburden pressure
Wrinkles on the liner	x37	1E-05	Wrinkles can fold over under load and can create weakened areas causing line failure
Bridging of the liner	x38	5E-05	Liner is lifted off its support at concave areas of the pond, toe, corners, etc. putting excessive stresses on liner
Penetrations through liner	x39	1E-03	Penetrations in a lined containment unit, increasing the potential for breaches
Dropped tools on liner	x40	1E-05	Accidental dropping of tools causing tear of liner due to impact, stress
Adverse soil conditions	x41	1E-05	Presence of salts of chloride in soil
Water accumulation near bottom HSS	x42	1E-05	Standing water near the HSS
Failure of exterior coating of a pipe	x43	1E-05	Corrosion of piping due to failure of external protective coating
Failure of interior pipe coating	x44	1E-05	Corrosion of piping due to failure of internal coating
Bad piping installation	x45	1E-05	Pipe failure due to bad installation of pipe
Bad piping weld	x46	1E-05	Pipe failure due to faulty welding of pipes
Pressure surge in the pipe	x47	1E-05	Development of tensile stress due to pressure surge in the pipe
Excessive External load on the pipe	x48	1E-05	Development of tensile stress due to external load on the pipe
Local indentation on the liner	x49	5E-05	Failure of liner due to local dents created while installing developing weak areas in the liner
Waviness of the liner	x50	1E-05	Liner failure due to waviness creating local stresses
Scratching on the liner	x51	1E-05	Failure of liner due to lowered tensile resistance in the areas of scratch
Impact by installation equipment	x52	1E-03	Failure of liner due to impact by installation equipment

Table 4-5 FMEA table for basic failure events determined through FTA

Potential Failure Modes	Potential Effects of failure modes	S	Potential causes of failure	O	D	RPN
Penetrations through liner	Weakened areas in the liner due to development of local stress	3	Debris and plants not cleared off site	5	2	30
Impact on the liner by installation equipment	Liner susceptible to tear, breach, puncture	3	Inappropriate handling of the liner during installation	5	2	30
Bridging of the liner	Increased stress on the liner due to absence of immediate support	4	Lifted off liner's support at concave areas of the c-ring like toe, corners, etc. putting excessive stresses on liner	2	2	16
Local indentation in the liner	Causes stress cracking of the liner	3	Dragged debris, equipment, and hoses	2	2	12
Flexible hose rupture during filling and discharging	Flowback water leakage through the ruptured hose	2	Wear and tear of the hose, Clogging of the hose	5	1	10
Corrosion under insulation	Stress corrosion cracking	10	Corrosive environment and applied/residual tensile stress	1	1	10
Inadequate component strength of the shell	AWSS rupture and deformation	10	Design error/defective material/improper use of the component	1	1	10
Vehicle /fork lift collision with the shell	AWSS deformation	10	Equipment/vehicle operator carelessness	1	1	10
Wear and tear due to aging	Tearing of liner	5	Reuse of liner	2	1	10
Earthquake	Deformation and crack in shell, Spillover of the stored flowback water	10	Natural or induced seismicity	1	1	10
Flooding	Spillover of the stored flowback water, Deformation of the shell	10	Heavy precipitation	1	1	10
Fire/Explosion	Liner failure	10	Defective liner material	1	1	10
Fire/Explosion	Pipe failure	10	Presence of H2S in the flowback water	1	1	10
Fire/Explosion	Deformation, cracks, rupture of the shell	10	Presence of H2S in the flowback water	1	1	10
High winds	Overflow of the flowback water	4	Wave action in the shell	2	1	8
Cring nearly full	Flowback water level rising above the free board level	3	Increased inflow of water	2	1	6
Cring nearly full	Flowback water level rising above the free board level	3	Operational error of inaction or incorrect action	2	1	6
Failure to monitor water level in C-ring	Rising water level in the c-ring with a potential of overflow	3	Failure of water level detection system	2	1	6
Improper erection ground preparation	Failure of liner due to excessive stress	1	Uneven ground surface	2	3	6

Potential Failure Modes	Potential Effects of failure modes	S	Potential causes of failure	O	D	RPN
Improper erection ground preparation	C-ring rupture right after installation	1	Inferior ground strength	2	3	6
Clamps loosely secured	Flowback water release to the ground	3	Falling off the liner from c-ring shell walls	1	2	6
Dropped tools on liner	Tearing of liner	3	Impact and stress caused by dropping of tools	1	2	6
Waviness of the liner	Physical failure of the liner	3	Development of local stress	1	2	6
Scratching of the liner	Lowered tensile resistance in the areas of scratch	3	Improperly installed liner	1	2	6
Loose flexible hose connection during filling and discharging	Flowback water leakage through the hose connection	1	Failure to connect properly	5	1	5
Loose flexible hose connection during filling and discharging	Flowback water leakage through the hose connection	1	Failure to inspect connection	5	1	5
Loose flexible hose connection during filling and discharging	Flowback water leakage through the hose connection	1	Faulty hose fitting/adaptor	5	1	5
Traffic from people and equipment	Disturbance to the dike structure	1	Insufficient compaction of the dike	1	3	3
Traffic from people and equipment	Erosion of slope	1	Use of Low-density, saturated, cohesion-less soils	1	3	3
Animal and plant interruption	Weakening of the structure	1	Formation of holes or dents	1	3	3
Erosion of the dike	Reduced capacity of the dike	1	Wind and water action	3	1	3
Commission error	Failure to stop inflow of flowback water	3	Failure to detect cause of overflow	1	1	3
Omission error	Failure to stop inflow of flowback water	3	Failure to monitor water level	1	1	3
Bulking of dike	Failure/weakening of the dike	1	Improper construction of the dike	2	1	2
Incorrect slope angle of the dike	Instability of the dike	2	Construction/design error	1	1	2
Failure of inlet valve	Lost control over inflow of flowback water	2	Wear and tear of the valve/fatigue	1	1	2
Failure of inlet valve	Lost control over inflow of flowback water	2	Impact load	1	1	2
Failure of inlet valve	Lost control over inflow of flowback water	2	Corrosion of the valve	1	1	2
Failure of inlet pump	Leaky pumps	1	Failure of mechanical seal of the pump	2	1	2

Potential Failure Modes	Potential Effects of failure modes	S	Potential causes of failure	O	D	RPN
Settlement	C-ring rupture and deformation right after installation	2	Inferior ground strength/liquefaction	1	1	2
AWSS plate or frame damaged during or before installation	Formation of a dent in the plate/frame	2	Impact during loading, unloading or installation	1	1	2
Adverse soil conditions	Soil corrosion	2	Presence of chloride, adverse pH levels of the soils	1	1	2
Failure of exterior coating of a pipe	Outer surface of the pipe susceptible to corrosion	2	Acidic water/corrosive soil attack	1	1	2
Failure of interior pipe coating	Inner surface of the pipe susceptible to corrosion	2	Acidic water/corrosive soil attack	1	1	2
Insufficient dike capacity	Overflow of the flowback water	1	Construction/design error	1	1	1
Flexible hose rupture during thawing	Flowback water leakage through the ruptured hose	1	High temperature	1	1	1
Flexible hose rupture during thawing	Flowback water leakage through the ruptured hose	1	High vapor pressure	1	1	1
Flexible hose rupture during thawing	Flowback water leakage through the ruptured hose	1	Clogging of the hose	1	1	1
Loose flexible hose connection during thawing	Flowback water leakage through the hose connection	1	Failure to connect properly	1	1	1
Loose flexible hose connection during thawing	Flowback water leakage through the hose connection	1	Failure to inspect connection	1	1	1
Loose flexible hose connection during thawing	Flowback water leakage through the hose connection	1	Faulty hose fitting/adaptor	1	1	1
Standing water on the top of dike	Failure/weakening of the dike due to water seepage	1	Precipitation/melting of snow	1	1	1
Overloading of pipelines	Rupture of pipe	1	Clogging of the pipelines	1	1	1
Acidic water	Corrosion of the storage system components	1	Failure to take corrective action upon escape of acidic flowback water	1	1	1
Inspection error	Faulty C-ring installation	1	Failure to conduct corrective actions before initiating operations	1	1	1
Failure of bottom HSS coating	C-ring collapse or cracking	1	Failure of the c-ring shell support system	1	1	1
Piping material defect	Puncture of pipe	1	Inappropriate material selection for the given quality of flowback water	1	1	1
Overburden Stress on the liner	Increase in external stress on the liner	1	High overburden pressure	1	1	1

Potential Failure Modes	Potential Effects of failure modes	S	Potential causes of failure	O	D	RPN
Wrinkles on the liner	Weakened areas in the liner due to development of local stress	1	Liner installation inefficiency	1	1	1
Acidic water accumulation near bottom HSS	Corrosion of the bottom HSS	1	Breakdown of the protective coating	1	1	1
Bad piping installation	Erroneous operation of the pipe	1	Inexperienced piping installation personnel	1	1	1
Bad piping weld	Weakened piping connection at the faulty weld leading to pipe puncture	1	Inexperienced piping welding personnel/Adverse welding conditions	1	1	1
Pressure surge in the pipe	Increased pressure on the surface of the pipe	1	Change in flow velocity of the flowback water	1	1	1
Excessive External load on the pipe	Rupture of pipe	1	Heavy equipment cut across pipeline	1	1	1

Table 4-6 Probability of failure calculation

Gate	Calculation	Value	Gate	Calculation	Value
G37	x49+x50+x51+x52	0.001	G24	x29*G32	2E-10
G36	x47+x48	2E-05	G23	x28*G31	1.1E-08
G35	x45+x46	2E-05	G22	x2+x26+x26+x27	8E-05
G34	x24*x42	1E-10	G21	x24+G30	0.001
G33	x44*x41	1E-10	G20	x23+G29	8E-05
G32	x42+x43	2E-05	G19	G27+G28	3E-05
G31	x41+G37	0.001	G18	G25+G26	9E-05
G30	x37+x38+x39+x40	0.001	G17	x22+G24	1E-05
G29	x36+G36	7E-05	G16	x18+x21	6E-05
G28	x35+G35	3E-05	G15	x19+x20	2E-05
G27	G33+G34	2E-10	G14	G21+G22+G23	0.001
G26	x34*x28	1E-10	G13	G19+G20	1E-04
G25	x30+x31+x32+x26+x33	9E-05	G12	G17+G18	1E-04
G11	G15+G16	8E-05	G5	G12+G13+G14	0.001
G10	x17*x18	5E-10	G4	G10*x5*G11	2E-18
G9	x14+x15+x16	7E-05	G3	x1+x2+x3+G9+x4+G6	0.0002
G8	x12+x13	2E-05	G2	G4+G5+G6+G7+G8	0.003
G7	x10+x11	0.002	G1	G2*G3	**1E-06**
G6	x6+x7+x8+x9	8E-05			

The probability of the uncontrolled release of flowback water is calculated using the gate to gate analysis. The detail calculation for each gate is shown in Table 4.6. It is to be noted that the p value derived here is the upper bound value and that the probability cannot be higher than this. The value of p for the identified top event is computed to be 1E-6. The present numbers represent the upper bound of the probability of failure.

The BIA prioritizes failure of liner due to penetrations, impact by installation equipment, liner bridging and local indentations as top failure events having high severity but low detection rank. The failure of the liner is followed by flexible hose rupture during filling discharging. Next in ranking are corrosion of the shell under insulation, inadequate component strength, and collision with vehicles on site. The failure due to natural disaster follows right after. Even though the probability of a natural event is low, their effects are extremely severe.

The corrective actions, like providing two liners, providing rig-mats, monthly inspection of liners, providing extensions on AWSS shells to avoid bridging, taking extra measures to avoid splashing flowback water over insulated shell should be taken. These can provide cost benefit in long term by avoiding failure of the system. Regulations pertaining to the AWSS or above ground walled storage system, discussed in chapter 2, provide an insight to some of the issues related to the storage of flowback water. The failure modes are discussed in line with those regulations in Section 4.6. Although the corrective actions are not discussed here, the analysis gives valuable information to reduce risk.

4.4 Implementation of ERA Framework

Based on the data availability as assessed in Appendix A, the toxicity of ferric ion, sulfate, manganese ion, bromide, chloride, and hydrogen sulfide was derived using Type A guidelines. Strontium toxicity was derived using Type B2 guidelines. Significant data gaps were identified for magnesium, potassium, sodium, and iodide. For Type A analysis, acute toxicity curves for each ion was derived using @Risk and US EPA's species sensitivity distributions (SSD) generator and overlaid to compare the derived effect concentration values (Palisade Corporation, 2015b; US EPA, 2016e). SSD generator is an excel template to calculate and plot the proportion of species affected (US EPA, 2016e). The 5th percentile from the best fit distribution and lognormal distribution are derived from @Risk to compare with the SSD plots.

Table 4.7 and Figure 4.3 shows the results from the @Risk and SSD generator. The tables and curves in the graph represent the central tendency, the upper and lower 95% prediction interval, and the best-fit and lognormal distribution from @Risk. These values are compared with the established standard acute, chronic or drinking water concentrations in Canada, US, New Zealand and Australia. Based on the availability, guidelines for acute toxicity, chronic toxicity for aquatic or marine life or drinking water quality, are used.

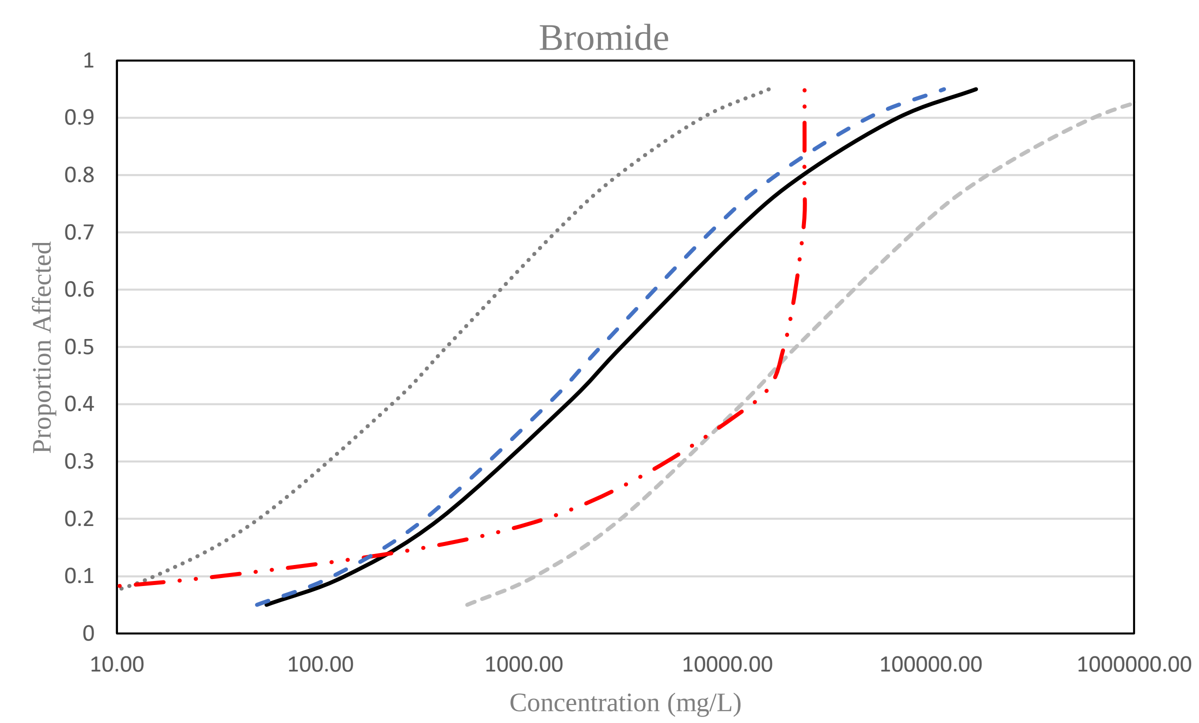
The effects concentration of chloride is very close to the US Standard but much higher than the Canadian standard. This is because Northern riffle shell mussel, the most sensitive species, was not used in this analysis as this species is resident to Ontario (GC, 2016b). The background concentration of the contaminant in the creek are safely below the derived effect concentration values, hence they do not affect the derived values. The effect concentration of strontium is found to be 7.5 mg/L. The chronic toxicity threshold value of strontium in fresh water is 21 mg/L (McPherson et al., 2014; Pacholski, 2009). Lower prediction interval effect concentration values are used in risk quotient except for hydrogen sulfide. The lower PI value for hydrogen sulfide is too low as compared to the estimated concentration using the best-fit and lognormal values of @Risk and the toxicity threshold values in Canada, US, Australia and New Zealand. The threshold chronic toxicity value in Australia-New Zealand is the lowest (0.001), followed by the US (0.002) and they are comparable with the lognormal estimate of @Risk and a central estimate of the SSD generator. For this reason, the central estimate is considered for the analysis.

SSD curves of bromide, chloride, hydrogen sulfide, iron, manganese, and sulfate, show a similar trend for central curve developed from SSD generator and log normal curve generated from @Risk. The best-fit distribution for chloride, iron, manganese, bromide, sulfate and hydrogen sulfide are gamma, kumaraswamy, pearson5, kumaraswamy, kumaraswamy, and levy, respectively. The central, best fit and log normal (@Risk curve) for chloride perfectly coincide. The highest number of data points are available for chloride, better curves can be generated for the larger data set.

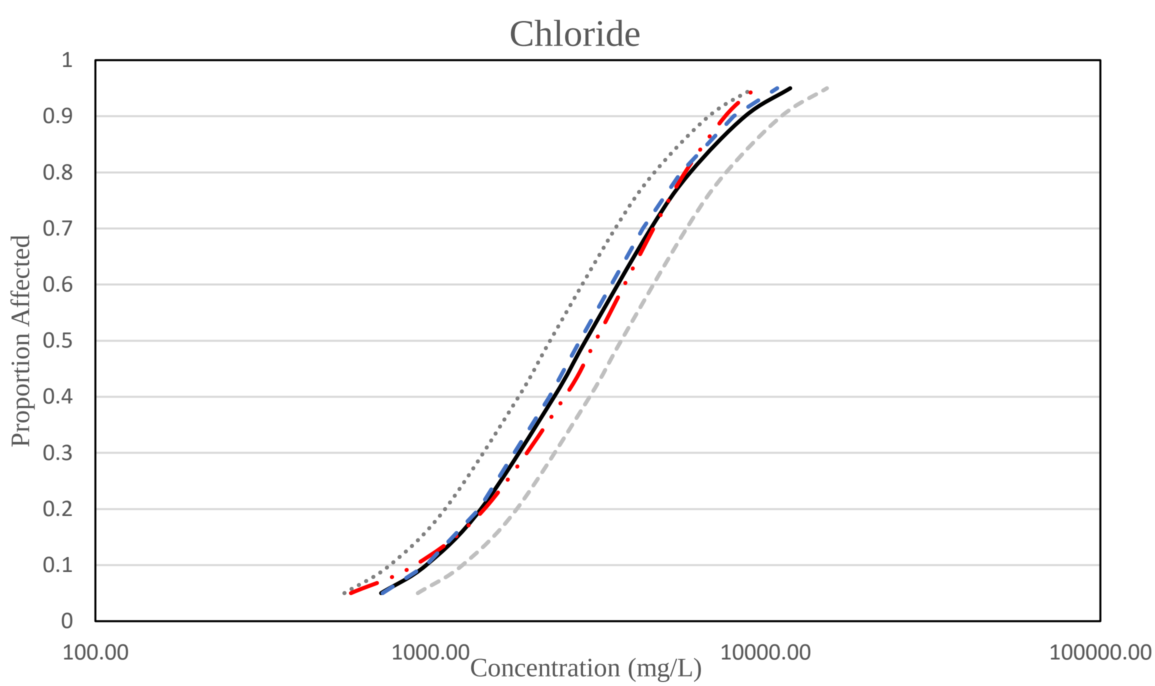
Table 4-7 Effect concentrations of contaminants

Contaminant (mg/L)	SSD Generator 11			Result @Risk®		Toxicity Threshold Values				
	Upper PI	Lower PI	Central	Best Fit	Log Normal	Canada	Reference	US	Reference	Aus-NZ[1]
Bromide	527.1	**5.61**	54.37	0.39	48.82	6 mg/L** (WHO, 2009)				
Chloride	916.1	**553.5**	712.42	579.1	720.2	640	(CCME, 2011)	860	(US EPA, 2016d)	400*
Hydrogen Sulfide	0.02	0.0001	**0.001**	0.01	0.001	0.05**	(CCREM, 2008)	0.002*	(US EPA, 2016d)	0.001*
Iron	3.74	**0.56**	1.45	0.02	2.25	1***	(Phippen, et al., 2008)	1*	(US EPA, 2016d)	0.3*
Manganese	8.88	**1.46**	3.60	6.42	4.95	1.6	(BC MOE, 2001)	NA	-	1.9
Sulfate	830.28	**240.86**	447.19	22.47	540.68	309*	(BC MOE, 2013)	250*	(US EPA, 1986c)	400*

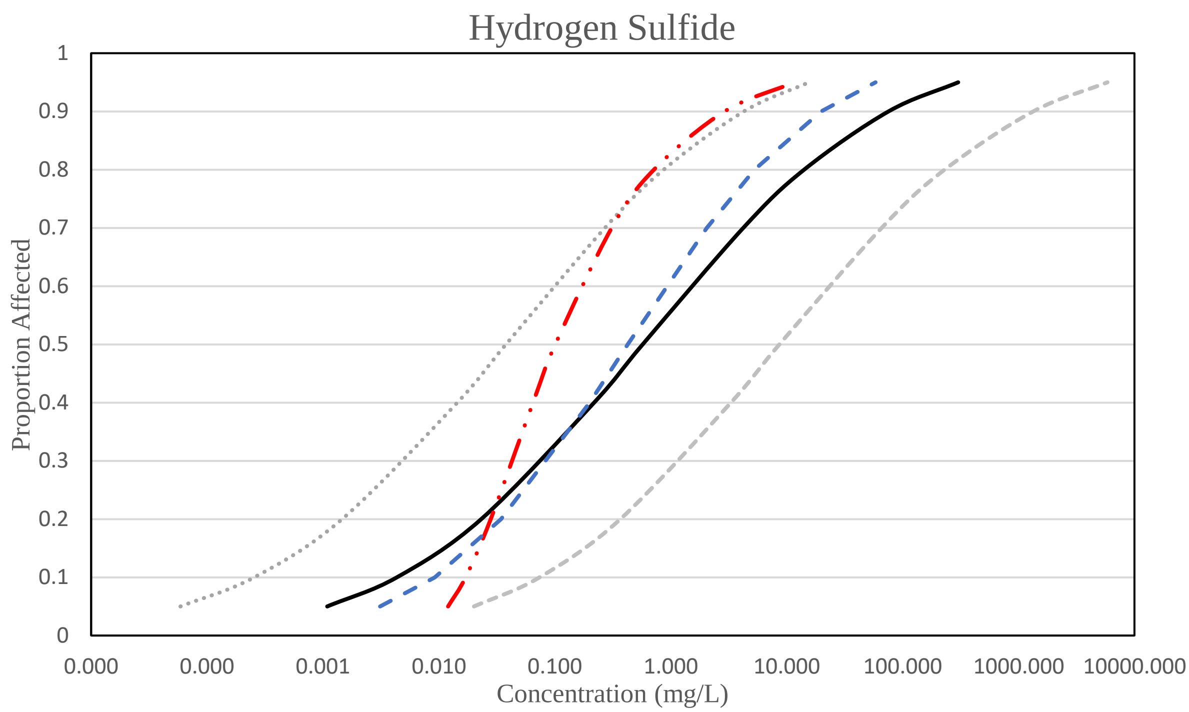
*Notes:*Chronic toxicity value; **Drinking water threshold value; ***Province or State-level chronic toxicity values;* [1](ANZECC & ARMCANZ, 2000) a.


Bromide
Proportion Affected
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10.00
100.00
1000.00
10000.00
100000.00
1000000.00
Concentration (mg/L)

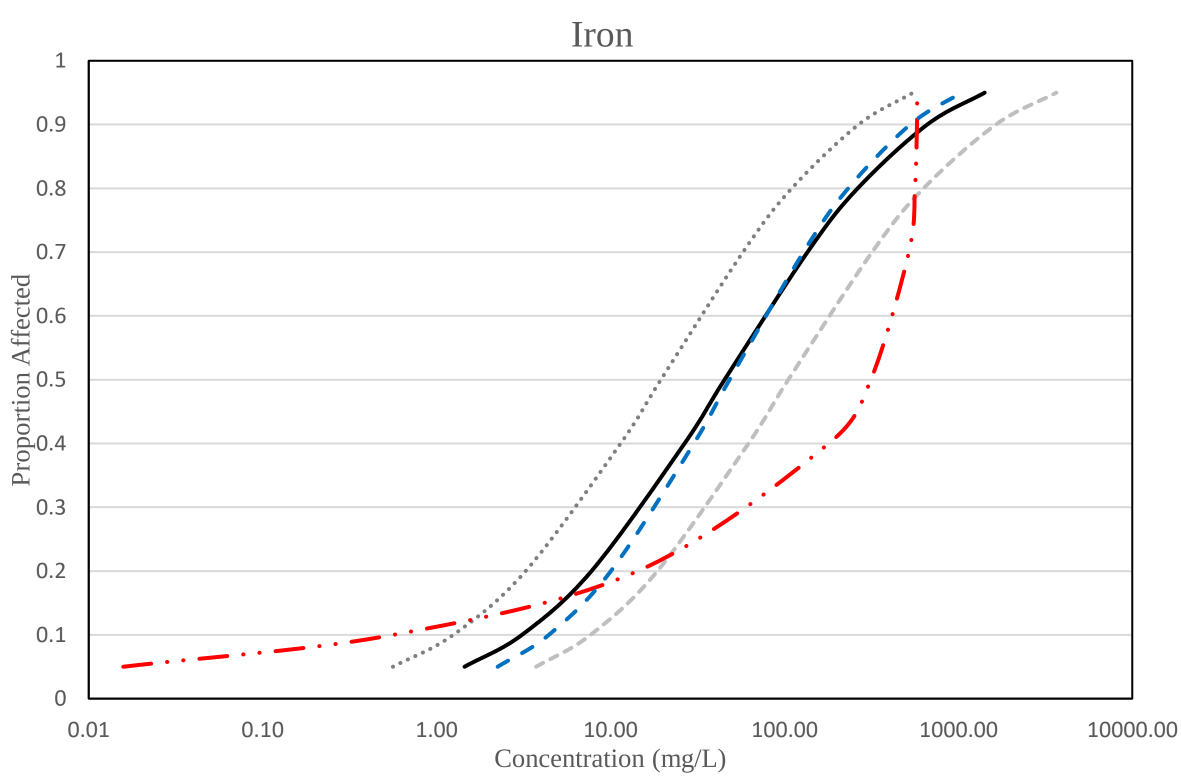
b.


Chloride
Proportion Affected
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100.00
1000.00
10000.00
100000.00
Concentration (mg/L)

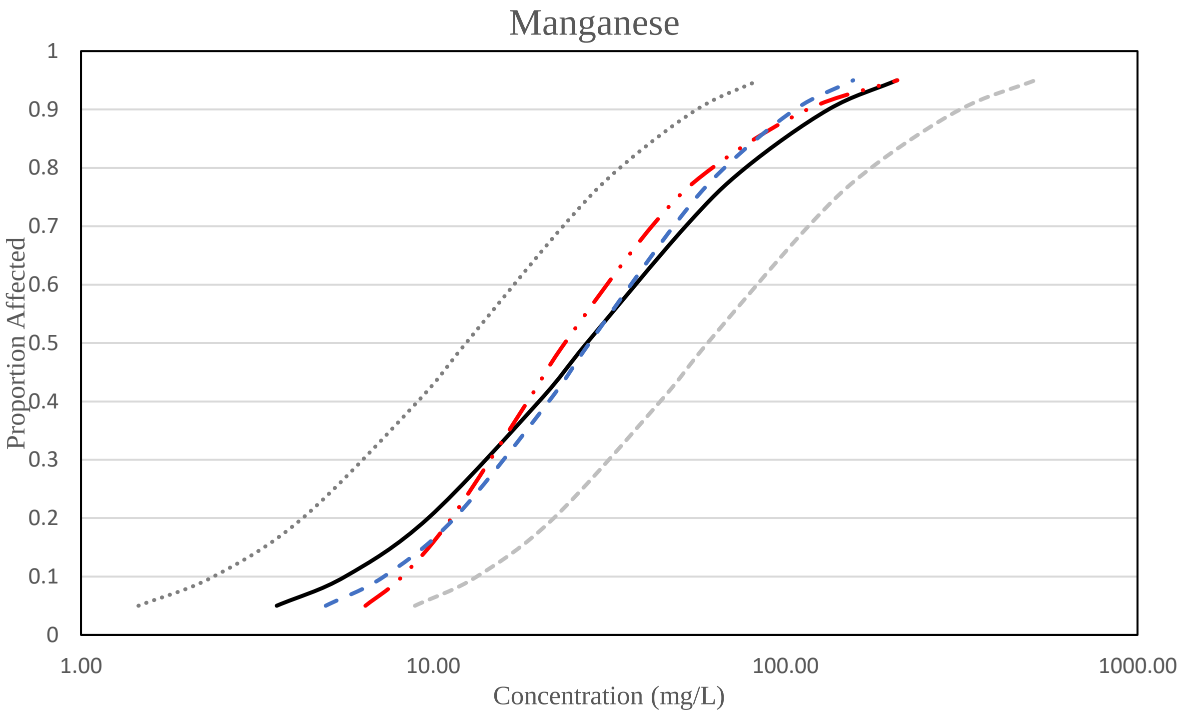
c.


Hydrogen Sulfide
Proportion Affected
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.000
0.000
0.001
0.010
0.100
1.000
10.000
100.000
1000.000
10000.000
Concentration (mg/L)

d.


Iron
Proportion Affected
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Concentration (mg/L)

e.



f.

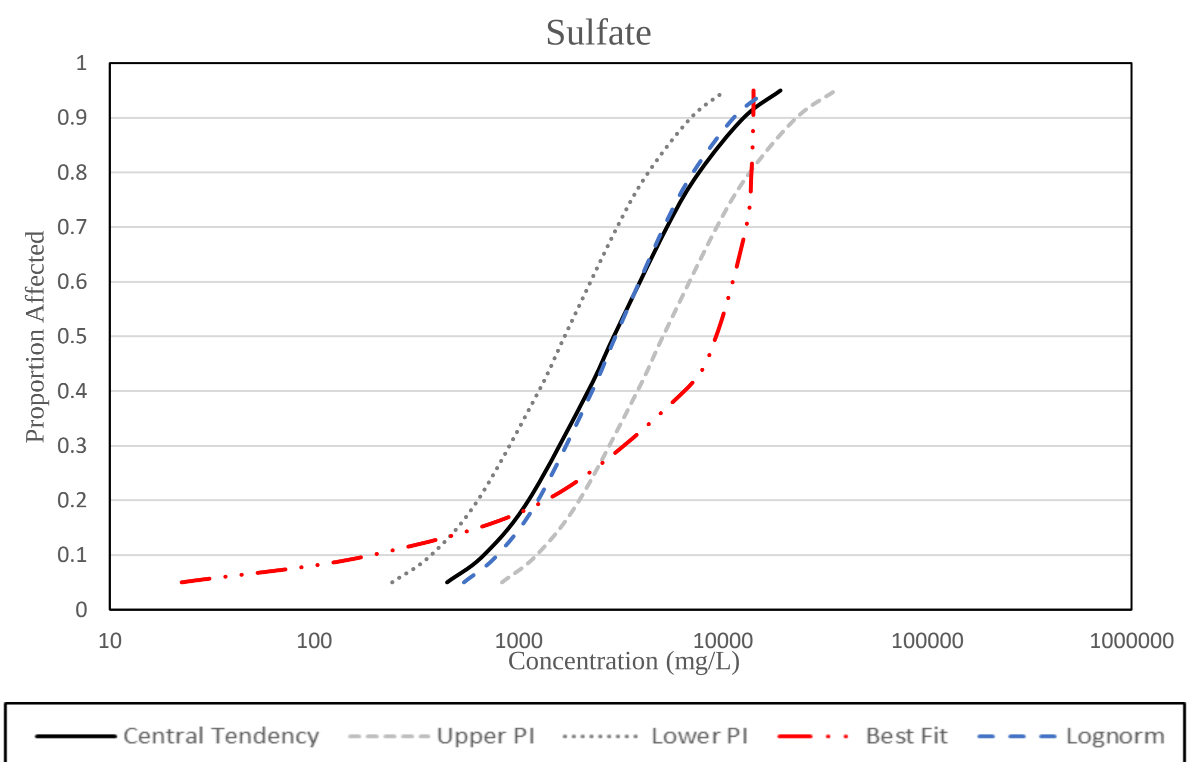


Figure 4-3 a-f Cumulative distribution curves for flowback water constituents

Table 4-8 Effect of K_d and dilution coefficient on exposure concentration

Contaminants	K_d (L/mg)	K_d*M_{soil}	Initial Conc. (mg/L) (C_o)	Remaining Conc. (mg/L) (C_i)	Final Conc. (mg/L) (C_∞)
Bromide	0E+00	0E+00	259	259	0.00018
Chloride	0E+00	0E+00	57278	57278	0.040
Hydrogen Sulfide	1E-05	1E+07	257	103.42	0.0000012
Iron	3E-05	4E+07	33	6.94	0.08
Manganese	7E-05	1E+08	3	0.28	0.004
Sulfate	0E+00	0E+00	247	247	0.00017
Strontium	1E-06	2E+06	618	537.39	0.11

For a spill of 1000 L, the effect of adsorption coefficient on the initial concentration of the contaminant is shown in Table 4.8. The concentration of the contaminants will further decrease on dilution. As per Table 4.3, the log K_{ow} values are less than 5, hence, BAF would be equivalent to 1. The reduction in the concentration of the contaminants is much higher due to dilution than due to adsorption.

Table 4-9 Estimated exposure concentration and risk quotient of contaminants

Contaminants	Exposure Conc. (mg/L) (EEC)	Background Conc. (mg/L) (C_w)	Effect (mg/L) (EC)	Risk Quotient R
Bromide	0.00018	0	5.61	3.3E-05
Chloride	0.040	0	553.49	7.3E-05
Hydrogen Sulfide	0.0000012	0	0.001	1.1E-03
Iron	0.08	0.08	0.56	1.4E-01
Manganese	0.004	0.004	1.46	2.7E-03
Sulfate	0.00017	0	240.86	7.2E-07
Strontium	0.11	0.11	7.5	1.5E-02

For the spill of 1000 L over a period of 96 hours, the final exposure concentration of the contaminant in the stream for the mean annual discharge (4400 L/s) and the corresponding risk quotient for each contaminant would be as shown in Table 4.9. The final risk quotient can be calculated by multiplying the cumulative risk quotient with the probability of failure calculated in section 4.3. For the risk equation 3.12, the probability of failure of the system was found to be 1E-6, the cumulative risk quotient is 0.16 and overall risk of the system would be 1.6E-7. This value is less than one; hence, there is no significant risk to the system for the given set of assumptions.

The risk estimate value is computed using conservative lower PI effect concentration value and typical average initial exposure concentration data to yield a point estimate of exposure and risk that is different from a true but unknown value. Hence, uncertainty analysis for the estimated exposure concentration and effects concentration was carried out for the given volume of flowback water spill and creek discharge.

Using Monte Carlo simulations, ten thousand iterations were performed to investigate the possible risk quotient values. Probability distributions were defined for the uncertain input parameters. The effect concentration values obtained from SSD (upper prediction, lower prediction, central) and from @Risk (best fit, lognormal) were used to create distributions for effect concentration. Similarly, the distribution curves for an initial concentration of each contaminant was created from the Montney well dataset downloaded from IHS AccuMap using @Risk (IHS Accumap, 2016; Palisade Corporation, 2015b).

Monte Carlo simulation was carried out for risk assessment assuming probability as 1, that the uncontrolled release of flowback water has occurred. The uncertainty analysis for the range of initial concentrations of the flowback water constituents and the effect concentration values derived would yield a probability distribution for the risk quotient. Figure 4.4 shows the result for the risk after 10,000 iterations.

From this Monte Carlo simulation, a 90% confidence interval of [3.1E-2, 7.7E-1] is attained and is shown by the marks as shown on the graph provided in Figure 4.4. This indicates that after considering the uncertainty caused due to the EC and C_o parameters, at a very confident subjective level of 90%, it can be said that the true value of RQ should lie between 3.1E-2 and 7.7E-1. The upper confidence limit, at 95%, is an RQ of 1, it can be said with high confidence that the most of the exposed aquatic organisms for this scenario would be exposed to a low level of risk.

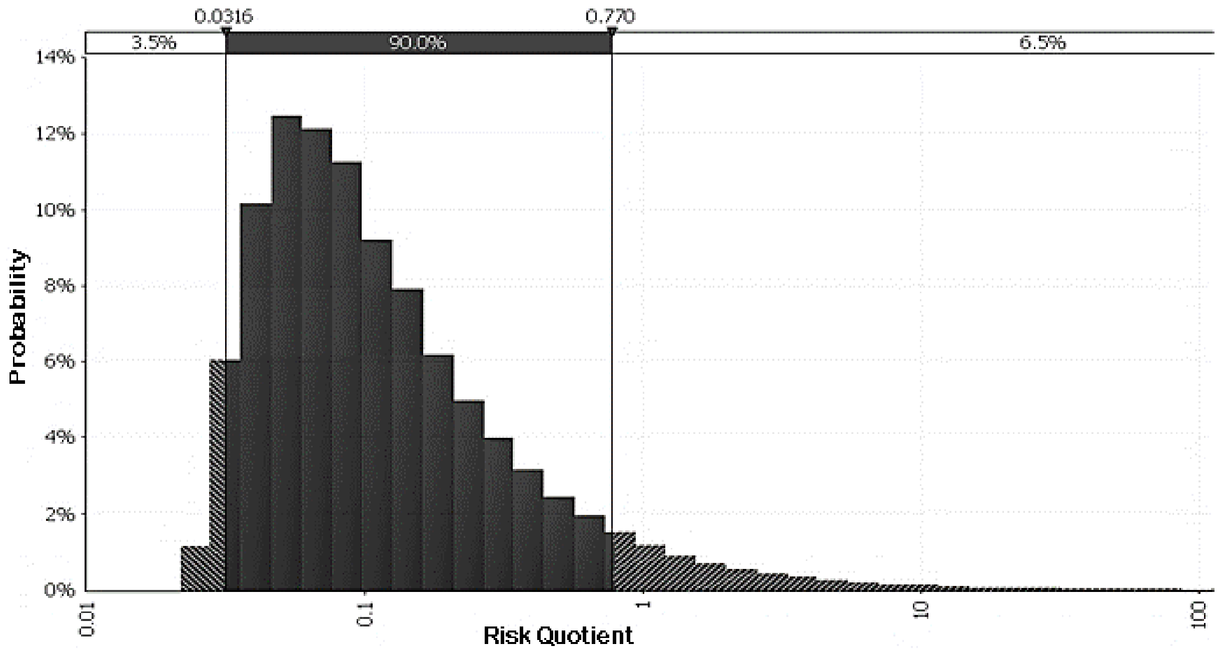


Figure 4-4 Results of uncertainty analysis for risk quotient

Sensitivity analysis results are displayed in Figure 4.5 using Tornado graphs. These results show the sensitivity of each output variable to the input distributions in the model. Since enough data points were not available for the effect concentration of strontium and initial concentration of hydrogen sulfide, they do not qualify for sensitivity analysis. The effect concentration of iron is the most sensitive (i.e., 0.04-3.9) followed by manganese, chloride, sulfate and hydrogen sulfide are cluttered near the risk values of (0.31-1.1). Moreover, the sensitivity of the initial concentration of manganese in flowback water is the highest (i.e., 0.31-1.1) and the rest are cluttered near the risk values of (0.27-1). The range of uncertainty in risk is not very high.

Scenario analysis for the risk quotient is carried out for the monthly discharge of the creek scenarios assuming probability to be 1, for a range of spill volume. A ratio of the volume of the spill (100 to 50000 L) and monthly creek discharge (500 to 15100 L/s) was plotted against risk quotient as shown in Figure 4.6. The polynomial trendline had R^2 approaching 1, hence it is the best fit for the given scenario. It can be deduced that the relationship between the ratio volume of spill and creek discharge and risk quotient is non-linear. The highest (V_s/Q_w) ratio achieved for risk quotient to be less than 1 is 4.5.

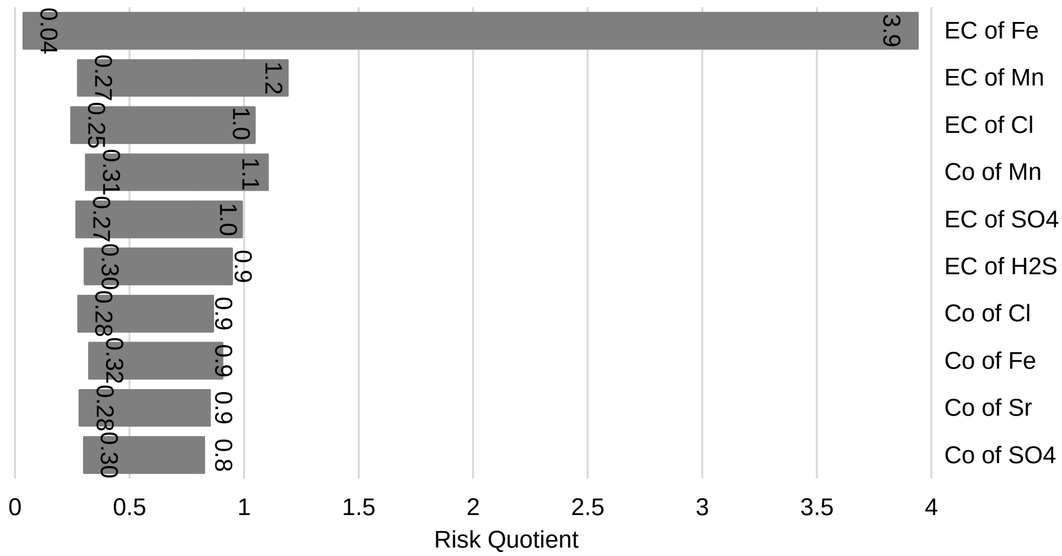


Figure 4-5 Sensitivity analysis of risk quotient for effect concentration and initial exposure concentration

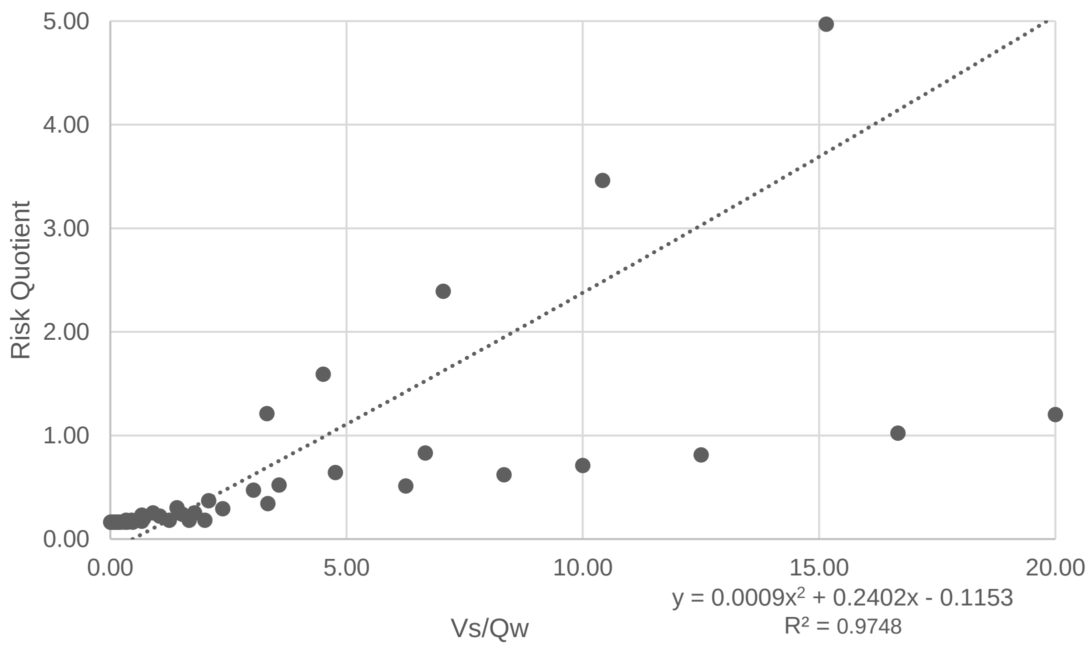


Figure 4-6 Variation in cumulative risk quotient as a function of the ratio of spill volume to creek discharge

4.5 Risk Description and Discussion

The values of the effect concentration obtained from the central of the SSD curve and the lognormal @Risk curve were comparable with the available acute toxicity values of chloride and hydrogen sulfide. This analysis also brings out the data gaps in the available acute fresh water toxicity values of barium, potassium, calcium, magnesium, iodide, bicarbonates and hydroxide.

As per Table 4.8, the adsorption coefficient greatly reduces the exposure concentration of manganese and iron. The single point risk estimate for spill volume of 1000L and stream discharge of 4400 L/s suggested that the ecology would be potentially safe in an event of a spill. However, when a range of effect concentration and initial concentration values of the flowback water constituents is considered, the extreme values of risk suggest the adverse effect to the ecology in an event of spill cannot be completely overlooked.

Also, according to scenario analysis, a spill volume larger than 7000 L from a storage system at 200 m from the surface water body can possibly cause adverse effects to the ecology. A maximum ratio of 4.5 between spill volume and stream discharge is to be maintained to ensure the safety of the aquatic ecology. The flowback water systems are often temporary storage system and can be used anywhere from 2 months to 2 years. Risk analysis using monthly average creek flow is recommended as compared to annual mean average as the risk estimate value is very sensitive to spill and stream discharge value.

Through BIA, the probability of failure of the system was found to be 1E-6. The AWSS with a secondary containment system was found to be safe. The critical failure modes of the AWSS were ranked and liner failure, spill during loading and unloading, corrosion under insulation of the wall of AWSS were ranked the highest. A study conducted by Ziemkiewicz et al. (2014) for containment ponds found liner tear as a low likelihood event carrying a high severity as the tear can cause direct exposure pathway to the environment. FMEA within BIA also states the higher likelihood of the failure for this failure mode. The storage system was also assessed for failure due to a catastrophe like an earthquake, flooding, fire/explosion, and high winds. These failure modes are ranked 10,11 and 12 respectively out of 89 potential failure modes identified due to a combination of lowest occurrence value and highest severity and detectability value.

The overall risk of the system was assessed to be 1.6E-7. Assuming the probability of failure as 1, the ecological risk was found to be 0.16 with 90% confidence interval of [3.1E-2, 7.7E-1]. The inclusion of the probability number in the risk quotient made the analysis more practicable. The risk of the analysis is measured in terms of the risk quotient. The risk quotient acts as a binary function, if it is less than 1, then there is no potential risk to the system and for greater than 1, there is a potential risk to the system. For a risk quotient, 1.6E-7, the risk to the system is almost negligible, however, it depends on a lot of factors as depicted by the analysis, including, the type and components of the storage system and the failure rates as perceived.

It should be noted that the hypothetical case study results were generated for spill volume of 1000L, for the assumed quality of flowback water, for a distance of 200m between AWSS and creek, given bulk density of the soil, assumed area of soil affected and creek discharge. The risk quotient rapidly changes with the change in the value of these parameters.

4.6 Regulations

Regulatory review was carried out on for storage systems on a national level and for the province of BC in Chapter 2. The results of the assessment provide a scientific basis for proposing regulations specific to the storage systems for waste water generated from the hydraulic fracturing process. The US is the most experienced in hydraulic fracturing and has a large-scale industry, hence, best voluntary practices followed in the US were reviewed. As per the results of FMEA, the failure modes having rank 1,4,7 and 5 are related to liner failure and are regulated under Drilling and Production regulation (DPR) and Hazardous waste regulations. Proper control of these regulations would help to prevent the failure of most storage systems. The presence of the secondary containment system brought down the probability of failure from 3E-3 to 1E-06. However, according to the DPR, the secondary containment system is needed only if the structure is in use for more than one year. A stricter regulation for making the secondary storage systems mandatory would help if the primary storage structure integrity is compromised.

The best practices suggest the inclusion of the precipitation factor in the design of open tanks and to consider storm run off for erosion safety of the storage containers. The failure mode due to flooding has high severity but low failure rate. However, for open top storage system regulating the inclusion of precipitation factor in the design of the AWSS would be beneficial. In BC, the quality of the waste water stored is not regulated. ERA proves the importance of type and concentration of chemicals in the flowback water and how they affect the risk quotient. Hence, the concentration and/or the quality of flowback water stored must be regulated.

Regulations also provide a restriction on the citing of the storage structure. DPR prohibits construction of pit or AWSS within 100m of the natural boundary of a water body. Environmental Protection and Management Regulation prohibit the citing of the storage system on top of the water supply well or the groundwater capture zone identified, groundwater recharge area, watershed, or identified aquifer. ERA results prove that the there is an indirect relation between the risk and distance between receiving water body and storage system. From the analysis, a distance of 200 m can cause risk to the aquatic ecology for spills greater than 10 m^3 under considered conditions and assumptions. Also, the allowable volume of water stored is 6600 m^3. In an event of catastrophic occurrence, from the above assessment, the potential adverse effects to the aquatic ecology could be huge. Hence, the volume and quality of water stored should be regulated with respect to the distance of AWSS from the surface water body.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Through the proposed method, the consequence of the failure of the flowback water storage system on the aquatic ecology was assessed. The probability of failure of above ground walled storage system (AWSS) was calculated. The critical failure modes of AWSS were identified and ranked. The overall risk to the ecosystem was estimated and the results of the study were assessed in light of the current regulations.

A new risk assessment method for flowback water integrating BIA and ERA frameworks was developed. BIA framework combined FMEA and FTA techniques. The probability of the failure of storage system was assessed using FTA of BIA. Basic controllable events leading to the system failure were identified logically identified though fault tree. These basic events were considered inputs as failure modes in FMEA. FMEA, as used in BIA, ranked the failure modes to help prioritize corrective actions. The prioritization achieved through FMEA help in decision making for improving the over-all integrity of the storage system.

To access ecological consequence of the failure of AWSS, exposure assessment, and effect assessment was carried out. A new technique to assess contaminant exposure for flowback water constituents was proposed. A combination of dilution factor and adsorption coefficient were used to assess exposure concentration. A simple equation reduced the complexity and multiplicity of the system. The probability and bioaccumulation were factored in to exposure concentration.

Toxicity values were derived for bromide, chloride, hydrogen sulfide, iron, manganese, and strontium using Canadian Water Quality Guidelines for Protection of Aquatic Life (CWQG-PAL). Estimating toxicity through SSD is very flexible and can be adjusted with ease to any desired safety level based on the management goals and requirements, toxicity modifying factors, background concentration levels of the water body and available data sets. The 5th

percentile of the cumulative empirical distribution curves was considered as the effect concentration benchmark to save 95% of the ecology.

Risk quotient was calculated by taking a ratio of exposure concentration and effect concentration. Uncertainty and sensitivity analysis was assessed assuming the probability value to be one, for the range of derived effect concentration and available initial exposure concentration from data set of 212 wells using Monte Carlo simulation. Scenario analysis for monthly creek discharges and historical spill volume ranges was carried out and a ratio of the volume of the spill to creek discharge was calculated to 4.5 for the safety of the ecology from flowback water and an equation dictating the relationship between them was derived.

The proposed method will be helpful in assessing the ecological risk posed by the spill of flowback water collected from hydraulic fracturing using well-established and site-specific models. The framework is flexible to be modified for a given quality of flowback or produced water. Depending upon the physicochemical properties of the flowback water constituents, more interactions like vaporization or sedimentation can be added to the exposure assessment.

The proposed risk assessment method can be effectively applied for assessing the ecological risk on the surface water body posed by the hydraulic fracturing flowback water contamination when limited information is available about the transport behaviour and fate of the contaminants in the flowback water. A single equation reduces the complexity and multiplicity of the number of contaminants and their interaction.

The results obtained by the application of framework provided valuable information, such as the safe distance between flowback water storage and surface water body, the effect of soil quality in retarding the flow of contaminants, and the effect of seasonal water discharge and the spill severity on the risk potential. Such information will facilitate decision-making for the construction of hydraulic fracturing flowback water storage facilities.

A review of the regulations, carried out in the previous chapter suggests stricter regulations pertaining to the citing of the storage system, the distance of the storage system versus the volume and quality of flowback water stored, secondary containment system for temporary storage and application of more than one liner or more frequent monitoring of the liner system.

5.2 Limitations and assumptions

This analysis is flexible and incorporates parameters important for decision making process related to the flowback water storage systems. However, the analysis has limitations. The scope of the study was limited to the aquatic ecology and only the inorganic constituents of the flowback water were assessed. The BIA and ERA framework are both limited by the data available. Only single input values from one source are used to evaluate the probability of failure of the storage system, there is a high input data uncertainty. The exposure model is true only for a system in equilibrium and does not consider all the behavioral aspects of metals and salts like speciation, precipitation, colloid matter, interaction with organic matter, bioaccumulation, bioavailability and sediment deposition. Salt ions and their interactions with the background water chemicals are not assessed. Homogenous and continues mixing is assumed for dilution and distribution coefficient. The analysis assumes the additive risk for the contaminant and does not take into consideration synergistic or antagonistic effects of the combined mixture.

5.3 Research Contributions

This is the first study that applies Ecological Risk Assessment framework for flowback water storage system. A comprehensive assessment of the failure system and its consequence on the aquatic ecology is done. It is a unique study investigating AWSS or C-ring type of storage system failure. Flowback water quality for Montney unconventional play is studied and an exposure model was proposed for the inorganic constituents like salts and metals of the flowback water. The threshold values for freshwater toxicity are derived for chloride, bromide, hydrogen sulfide, iron, manganese, sulfate, and strontium. The acute toxicity values of aquatic organisms do not exist at a provincial or national level for most of these contaminants. The framework and its applications also highlight the existing data gaps. With the rise in the unconventional oil and gas industry, the developed methodology would prove to be useful in evaluating the risk of the accidental releases of flowback water and making informed decisions regarding storage systems. The review of acts, regulations, and guidelines for storage systems in British Columbia is undertaken and recommendation for regulations and guidelines specific to the flowback water storage systems are provided. The risk assessment study provided a scientific basis for proposing regulations specific to AWSS and paved a way for risk based regulations.

5.4 Recommended future work

Recommendations are valuable for establishing the directions for future research. The recommendations are described based on the limitations of this assessment. A more comprehensive multi-media exposure model is desired that includes soil, groundwater, air and sediment media. The exposure model that could incorporate the characteristics of organic and inorganic constituents of the flowback water should be devised. Lack of reliable data for inorganic constituents like potassium, barium, sodium was being a hindrance in assessing the overall flowback water toxicity. Primary data should be generated through field study to determine the site-specific effect concentration of the native aquatic ecology infested with flowback water. Also, lack of understanding of interactions of these ions among themselves and with the media stalled a holistic risk assessment. A field based exposure concentration values must be collected for the assessment. A reliable method for obtaining failure rates of the system is desirable to acquire more dependable results for obtaining the probability of storage system failure. The framework is limited to the ranking of the failure modes and does not focus on proposing the corrective actions and measuring their effectiveness when implemented. A comprehensive assessment of the storage system that investigates the failure modes, proposes corrective actions and assesses the impact and cost effectiveness of the corrective action is recommended.

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APPENDIX A: Dataset for deriving SSDs of the contaminants

Table A-1 Data points for deriving toxicity profiles of the contaminants

Chemical Name	Species Scientific Name	Species Common Name	Species Group	Time (Days)	End point	Conc (ug/L)	Geo Mean (mg/l)	References
Iron	Ictalurus punctatus	Channel Catfish	Fish	3	LC50	500000	500.00	(Clemens & Sneed, 1959; US EPA, 2016b)
Iron	Cyprinus carpio	Common Carp	Fish	4	LC50	1220	1.20	(Alam & Maughan, 1995; US EPA, 2016b)
Iron	Cyclops Viridis	Water Flea	Crustacean	4	LC50	11800	26.54	(Mukhopadhyay & Konar, 1984; Burke et al., 2008)
Iron	Oreochromis niloticus	Mozambique tilapia	Fish	4	LC50	83200	83.20	(Mukhopadhyay & Konar, 1984; Burke et al., 2008)
Iron	Oreochromis mossambicus	Mozambique tilapia	Fish	4	LC50	118000	118.80	(Mukhopadhyay & Konar, 1984; Burke et al., 2008)
Iron	Crangonyx pseudogracilis	Northern River Crangonyctid	Crustacean	2	LC50	143000	143.00	(Mukhopadhyay & Konar, 1984; Burke et al., 2008)
Iron	Asellus aquaticus	Waterlouse	Crustacean	2.08	LC50	255900	348.20	(Burke et al., 2008)
Iron	Branchiura Soerbyi	Tubificid Worm	Worm	4	LC50	580000	580.00	(Mukhopadhyay & Konar, 1984; Burke et al., 2008)
Iron	Poecilia reticulata	Rainbow fish	Fish	1	LC50	13940	4.89	(Shuhaimi-Othman et al., 2013)
Iron	Gambusia affinis	Mosquitofish	Fish	4	LC50	26000	26.00	(Shuhaimi-Othman et al., 2013; Wallen et al., 2017)
Iron	Morone saxatilis	Striped Bass	Fish	4	LC50	6000	6.00	(Hughes, 1973; Shuhaimi-Othman et al., 2013)
Iron	Salmo trutta	Brown Trout	Fish	4	LC50	47000	47.00	(Dalzell & Macfarlane, 1999; Shuhaimi-Othman et al., 2013)

Chemical Name	Species Scientific Name	Species Common Name	Species Group	Time (Days)	End point	Conc (ug/L)	Geo Mean (mg/l)	References
Magnesium	Gammarus lacustris	Scud	Crustaceans	4	LC50	64700	64.70	(De March, 1988; US EPA, 2016b)
Magnesium	Mogurnda mogurnda	Northern Trout Gudgeon	Fish	4	LC50	40000	40.00	(Van Dam et al., 2010)
Magnesium	Daphnia magna	Water Flea	Crustaceans	2	LC50	140000	204.60	(Biesinger & Christensen, 1972)
Manganese	Craterocephalus marjoriae	Black Banded Rainbow fish	Fish	4	LC50	10200	10.20	(Shuhaimi-Othman et al., 2013)
Manganese	Poecilia reticulata	Rainbow fish	Fish	4	LC50	354000	83.83	(Slabbert & Venter, 1999; US EPA, 2016b)
Manganese	Oncorhynchus kisutch	Coho Salmon		4	LC50	26900	26.90	(Hedayati et al., 2014; US EPA, 2016b)
Manganese	Daphnia magna	Water Flea	Crustaceans	2	LC50	29000	34.06	(Stephan, 1978a; US EPA, 2016b)
Manganese	Daphnia magna	Water Flea	Crustaceans	2	EC50	40000		(C.T., Hooftman et al., 1998; US EPA, 2016b)
Manganese	Daphnia pulex	Water Flea	Crustaceans	2	LC50	32050	32.05	(Slabbert & Venter, 1999; US EPA, 2016b)
Manganese	Pimephales promelas	Fathead Minnow	Fish	4	LC50	28000	28.00	(Stephan, 1978b; US EPA, 2016b)
Manganese	Lemna minor	Duckweed	Flowers, Trees, Shrubs, Ferns	4	EC50 (Growth)	31000	31.00	(US EPA, 2016b; W. Wang, 1986)
Manganese	Chironomus plumosus	Midge	Insects/Spiders	4	LC50	9500	6.77	(US EPA, 2016b; Vedamanikam & Shazilli, 2008)
Manganese	Culicoides furens	Little Gray Punkie	Insects/Spiders	4	LC50	6100	6.44	(US EPA, 2016b; Vedamanikam & Shazilli, 2008)
Manganese	Caspian Roach	Rutilus Caspicus	Fish	4	LC50	300000	300.00	(Hedayati et al., 2014; US EPA, 2016b)
Manganese	Rasbora sumatrana	Cyprinidae	Fish	1	LC50	120800	26.72	(Shuhaimi-Othman et al., 2013; US EPA, 2016b)
Potassium	Daphnia magna	Waterflea	Crustaceans	2	LC50	93000	114.41	(Biesinger & Christensen, 1972; US EPA, 2016b)

Chemical Name	Species Scientific Name	Species Common Name	Species Group	Time (Days)	End point	Conc (ug/L)	Geo Mean (mg/l)	References
Potassium	Gammarus lacustris	Scud	Crustaceans	4	LC50	53200	53.20	(De March, 1988; US EPA, 2016b)
Sodium	Daphnia magna	Water Flea	Crustaceans	2	EC50	1820000	1675.01	(Biesinger & Christensen, 1972; US EPA, 2016b)
Strontium	Cyclops abyssorum	Freshwater Copepods	Crustaceans	2	LC50	300000	300.00	(Baudouin & Scoppa, 1974; Pacholski, 2009)
Strontium	Eudiaptomus padanus		Worm	2	LC50	180000	180.00	(Baudouin & Scoppa, 1974; Pacholski, 2009)
Strontium	Daphnia hyalina	Water Flea	Crustaceans	2	LC50	75000	75.00	(Baudouin & Scoppa, 1974; Pacholski, 2009)
Strontium	Daphnia magna	Water Flea	Crustaceans	2	LC50	125000	91.11	(Biesinger & Christensen, 1972; Pacholski, 2009)
Strontium	Daphnia magna	Water Flea	Crustaceans	2	EC50	94000		(Khangarot BS & PK, 1989; Pacholski, 2009)
Strontium	Daphnia magna	Water Flea	Crustaceans	1	EC50	162930		
Strontium	Austropotamobius pallipes pallipes	White-clawed crayfish	Crustaceans	4	LC50	440000	440.00	(Boutet & Chaisemartin, 1973; Pacholski, 2009)
Strontium	Oncorhynchus mykiss	Rainbow Trout	Fish (salmonid)	21	LC50	286000	286.00	(Pacholski, 2009)
Strontium	Morone saxatilis	Striped Bass	Fish (Non Salmonid)	4	LC50	92800	92.80	(Pacholski, 2009)
Strontium	Orconectes limosus	Spinycheek crayfish	Crustaceans	4	LC50	110000	110.00	(Boutet & Chaisemartin, 1973; Pacholski, 2009)
Strontium	Tubifex tubifex	Tubificid worm	Worm	1	EC50	540000	346.52	(Khangarot BS & PK, 1989; Pacholski, 2009)
Strontium			Worm	1	LC50	10806000	1409.61	(Pacholski, 2009; P. L. Williams & Dusenbery, 1990)
Barium	Pseudokirchneriella subcapitata	Green Algae	Algae, Moss, Fungi	4	EC50	28000	28.00	(US EPA, 2016b)
Barium	Daphnia magna	Water Flea	Crustaceans	1	LC50	530000	315.85	(LeBlanc, 1980; US EPA, 2016b)
Barium			Crustaceans	2	LC50	145000		(Biesinger & Christensen, 1972)

Chemical Name	Species Scientific Name	Species Common Name	Species Group	Time (Days)	End point	Conc (ug/L)	Geo Mean (mg/l)	References
Barium	Caenorhabditis elegans	Round worm	Worm	1	LC50	2.8	383.60	(Tatara et al., 1998; US EPA, 2016b)
Barium	Lepomis macrochirus	Bluegill	Fish	4	LC50	198000	198.00	(US EPA, 2016b)
Barium	Lemna minor	Duckweed	Flowers, Trees, Shrubs, Ferns	4	EC50	26000	26.00	(US EPA, 2016b; W. Wang, 1986)
Iodide	Daphnia magna	Water Flea	Crustaceans	2	LC50	830	0.39	(Laverock et al., 1995; US EPA, 2016b)
Iodide	Oncorhynchus mykiss	Rainbow Trout	Fish	4	LC50	17000	39.28	(Laverock et al., 1995; US EPA, 2016b)
Bromide	Oryzias latipes	Japanese Rice Fish	Fish	4	LC50	24000000	24000.	(Flury & Papritz, 1993)
Bromide	Gammarufsa sciatus		Crustaceans	4	LC50	67000	67.00	(Flury & Papritz, 1993)
Bromide	Salmo gairdneri		Fish (salmonid)	5	LC50	2200000	2200.00	(Flury & Papritz, 1993)
Bromide	Dugesia tigrina		Invertebrate	4	LC50	67000	67.00	(Flury & Papritz, 1993)
Bromide	Poecilia reticulata	Guppy	Fish	4	LC50	16000000	16000.00	(Flury & Papritz, 1993)
Bromide	Daphnia magna	Waterflea	Crustaceans	1	LC50	7200000	8510.64	(Flury & Papritz, 1993)
Bromide	Pimephales promelas	Fathead Minnow	Fish	1	LC50	14300000	13529.23	(Flury & Papritz, 1993)
Hydrogen Sulphite	Asellus militaris	Aquatic Sowbug	Crustaceans	4	EC50	1700	1.35	(Oseid Jr., 1974; US EPA, 2016b)
Hydrogen Sulphite	Carassius auratus	Goldfish	Fish	4	LC50	53	0.06	(Adelman Jr., 1972; US EPA, 2016b)
Hydrogen Sulphite	Carassius auratus	Goldfish	Fish	4	LC50	22		(L. L. Smith & Oseid, 1972; US EPA, 2016b)
Hydrogen Sulphite	Catostomus commersoni	White Sucker	Fish	4	LC50	23	0.02	(L. L. Smith & Oseid, 1972; US EPA, 2016b)
Hydrogen Sulphite	Chironomus riparius	Midge	Insects/Spiders	4	EC50	10000	22.36	(Stammer, 1953; US EPA, 2016b)

Chemical Name	Species Scientific Name	Species Common Name	Species Group	Time (Days)	End point	Conc (ug/L)	Geo Mean (mg/l)	References
Hydrogen Sulphite	Crangonyx richmondensis ssp. Laurentianus	Amphipod	Crustaceans	2	EC50	770	0.50	(Oseid Jr., 1974; US EPA, 2016b)
Hydrogen Sulphite	Dendrocoelum lacteum	Turbellarian, Planarian	Worms	4	LC50	50000	50.00	(Stammer, 1953; US EPA, 2016b)
Hydrogen Sulphite	Ecdyonurus venosus	Mayfly	Insects/Spiders	4	EC50	50000	22.36	(Stammer, 1953; US EPA, 2016b)
Hydrogen Sulphite	Erpobdella octoculata	Leech	Worms	4	EC50	10000	22.36	(Stammer, 1953; US EPA, 2016b)
Hydrogen Sulphite	Esox lucius	Northern Pike	Fish	3	LC50*	36	0.04	(Adelman Jr., 1970; US EPA, 2016b)
Hydrogen Sulphite			Fish	3	LC50*	40		(L. L. Smith & Oseid, 1972; US EPA, 2016b)
Hydrogen Sulphite	Gammarus pseudolimnaeus	Scud	Crustaceans	2	EC50	71	0.04	(Oseid Jr., 1974; US EPA, 2016b)
Hydrogen Sulphite	Hexagenia limbata	Mayfly	Insects/Spiders	3	EC50	240	0.24	(Oseid Jr., 1974; US EPA, 2016b)
Hydrogen Sulphite	Ictalurus punctatus	Channel Catfish	Fish	0.0069	LC50	620	0.80	(Bonn & Follis, 1967; US EPA, 2016b)
Hydrogen Sulphite	Lepomis macrochirus	Bluegill	Fish	4	LC50	14	0.03	(L. L. Smith & Oseid, 1972; US EPA, 2016b)
Hydrogen Sulphite	Micropterus salmoides	Largemouth Bass	Fish	4	LC50	63	0.05	(Fung & Bewick, 1980; US EPA, 2016b)
Hydrogen Sulphite	Oncorhynchus mykiss	Rainbow Trout	Fish	4	LC50*	49	0.04	(L. L. Smith & Oseid, 1972; US EPA, 2016b)
Hydrogen Sulphite	Osteichthyes	Bony Fishes	Fish	0.3889	EC50	920.7	0.92	(Ishio, 1965; US EPA, 2016b)
Hydrogen Sulphite	Perca flavescens	Yellow Perch	Fish	4	LC50	8	0.03	(Fung & Bewick, 1980; US EPA, 2016b)
Hydrogen Sulphite	Perla sp.	Stonefly	Insects/Spiders	4	EC50	10000	22.36	(Stammer, 1953; US EPA, 2016b)
Hydrogen Sulphite	Pimephales promelas	Fathead Minnow	Fish	4	LC50	806	0.07	(Broderius et al., 1977; US EPA, 2016b)

Chemical Name	Species Scientific Name	Species Common Name	Species Group	Time (Days)	End point	Conc (ug/L)	Geo Mean (mg/l)	References
Hydrogen Sulphite	Planaria gonocephala	Planarian	Worms	4	LC50	10000	22.36	(Stammer, 1953; US EPA, 2016b)
Hydrogen Sulphite	Salmo trutta	Brown Trout	Fish	4	LC50	7	0.01	(Reynolds & Haines, 1980; US EPA, 2016b)
Hydrogen Sulphite	Salvelinus fontinalis	Brook Trout	Fish	4	LC50	54	0.03	(L. L. J. Smith & Oseid, 1974; US EPA, 2016b)
Hydrogen Sulphite	Sander vitreus	Walleye	Fish	3	LC50*	60	0.03	(L. L. Smith & Oseid, 1972; US EPA, 2016b)
Hydrogen Sulphite	Stylaria lacustris	Oligochaete	Worms	4	EC50	10000	22.36	(Stammer, 1953; US EPA, 2016b)
Hydrogen Sulphite	Tubifex tubifex	Tubificid Worm	Worms	4	EC50	50000	22.36	(Stammer, 1953; US EPA, 2016b)
Chloride	Scenedesmus subspicatus	Green Algae	Algae, Moss, Fungi	5	LC50	4200000	4200.00	(US EPA, 2016b; Vinot & Larpent, 1984)
Chloride	Daphnia magna	Water Flea	Crustaceans	1	LC50	2600000	2600.00	(US EPA, 2016b; Vinot & Larpent, 1984)
Chloride	Danio rerio	Zebra Danio	Fish	1	LC50	6700000	6700.00	(US EPA, 2016b; Vinot & Larpent, 1984)
Chloride	Pimephales promelas	Fathead minnow	Fish	4	LC50	4223000	4223.00	(D.R. Mount et al., 1997; US EPA, 2016b)
Chloride	Lepomis macrochirus	Bluegill sunfish	Fish	4	LC50	5272000	5272.00	(Birge et al., 1985; CCME, 2011)
Chloride					LC50			(CCME, 2011)
Chloride	Cyprinella leedsi	Bannerfin shiner	Fish	4	LC50	6070000	6070.00	(CCME, 2011)
Chloride	Oncorhynchus mykiss	Rainbow trout	Fish	4	LC50	8634000	8634.00	(CCME, 2011; J.R.F., Bergh, & Bailey, 2011; Vosyliene et al., 2006)
Chloride					LC50			
Chloride	Gambusia affinis	Mosquito fish	Fish	4	LC50	9099000	9099.00	(Al-Daham & Bhatti, 1977; CCME, 2011)
Chloride	Gasterosteus aculeatus	Threespine stickleback	Fish	4	LC50	10200000	10200.0	(CCME, 2011; Garibay & Hall, 2004)
Chloride	Anguilla rostrata	American eel	Fish	4	LC50	13012000	13012.0	(CCME, 2011; Hinton & Eversole, 1979)

Chemical Name	Species Scientific Name	Species Common Name	Species Group	Time (Days)	End point	Conc (ug/L)	Geo Mean (mg/l)	References
Chloride	Ambystoma maculatum	Spotted salamander	Amphibians	4	LC50	1178000	1178.00	(CCME, 2011; Collins & Russell, 2009)
Chloride	Pseudacris triseriata feriarum	Chorus frog	Amphibians	4	LC50	2320000	2320.00	(CCME, 2011; Garibay & Hall, 2004)
Chloride	Lithibates sylvatica	Wood frog	Amphibians	4	LC50	2716000	2716	(CCME, 2011; Collins & Russell, 2009; Jackman, 2010; Sanzo & Hecnar, 2006)
Chloride					LC50			
Chloride					LC50			
Chloride	Pseudacris crucifer	Spring peeper	Amphibians	4	LC50	2830000	2830.00	(CCME, 2011; Collins & Russell, 2009)
Chloride	Rana clamitans	Green frog	Amphibians	4	LC50	3109000	3109.00	(CCME, 2011; Collins & Russell, 2009)
Chloride	Rana temporaria	Common frog	Amphibians	4	LC50	3140000	3140.00	(CCME, 2011; Viertel, 1999)
Chloride	Lithibates pipiens	Leopard frog	Amphibians	4	LC50	3385000	3385.00	(CCME, 2011; Jackman, 2010)
Chloride	Bufo americanus	American toad	Amphibians	4	LC50	3926000	3926.00	(CCME, 2011; Collins & Russell, 2009)
Chloride	Rana catesbeiana	Bullfrog	Amphibians	4	LC50	5846000	5846.00	(CCME, 2011)
Chloride	Sphaerium simile	Fingernail clam	Invertebrate	4	LC50	902000	902.00	(CCME, 2011)
Chloride	Ceriodaphnia dubia	Water flea	Invertebrate	2	LC50	1080000	1080	(CCME, 2011; Cowgill & Milazzo, 1990; Hoke et al., 1992; J.R.F. et al., 2011; D.R. Mount et al., 1997; Valenti et al., 2007)
Chloride				2	LC50			
Chloride				2	LC50			
Chloride				2	LC50			
Chloride				2	LC50			
Chloride				2	LC50			
Chloride	Daphnia pulex	Water flea	Invertebrate	2	LC50	1248000	1248.00	(Birge et al., 1985; CCME, 2011; Palmer, 2004)
Chloride				2	LC50			
Chloride	Elliptio lanceolata	Yellow lance mussel	Invertebrate	4	LC50	1274000	1274.00	(CCME, 2011)
Chloride	Brachionus patulus	Rotifer	Invertebrate	1	LC50	1298000	1298.00	(CCME, 2011; Peredo-Alvarez et al., 2003)
Chloride	Hyalella azteca	Amphipod	Invertebrate	4	LC50	1382000	1382.00	(CCME, 2011; Elphick et al., 2011)

Chemical Name	Species Scientific Name	Species Common Name	Species Group	Time (Days)	End point	Conc (ug/L)	Geo Mean (mg/l)	References
Chloride	Musculium transversum	Fingernail clam	Invertebrate	4	LC50	1930000	1930.00	(CCME, 2011)
Chloride	Brachionus calyciflorus	Rotifer	Invertebrate	1	LC50 LC50 LC50	2026000	2026.00	(Calleja et al., 1994; CCME, 2011; J.R.F. et al., 2011; Peredo-Alvarez et al., 2003)
Chloride	Physa gyrina	Snail	Invertebrate	4	LC50	2540000	2540.00	(Birge et al., 1985; CCME, 2011)
Chloride	Lirceus fontinalis	Isopod	Invertebrate	4	LC50	2950000	2950.00	(Birge et al., 1985; CCME, 2011)
Chloride	Gyraulus parvus	Snail	Invertebrate	4	LC50	3043000	3043.00	(CCME, 2011)
Chloride	Chironomus dilutus / tentans	Midge	Invertebrate	4	LC50	3761000	3761.00	(CCME, 2011; N. Wang & Ingersoll, 2010)
Chloride Chloride	Lumbriculus variegates	Oligochaete	Invertebrate	4	LC50 LC50	4094000	4094.00	(CCME, 2011; Elphick et al., 2011)
Chloride	Nephelopsis obscura	Leech	Invertebrate	4	LC50	4310000	4310.00	(CCME, 2011)
Chloride	Hexagenia sp.	Mayfly	Invertebrate	2	LC50	4671000	4671.00	(CCME, 2011; N. Wang & Ingersoll, 2010)
Chloride	Chironomus attenatus	Midge	Invertebrate	2	LC50	4850000	4850.00	(Thornton & Sauer., 1972; US EPA, 2016b)
Chloride	Daphnia hyalina	Water flea	Invertebrate	2	LC50	5308000	5308.00	(Baudouin & Scoppa, 1974; CCME, 2011)
Chloride	Lepidostoma sp	Caddisfly	Invertebrate	4	LC50	6000000	6000.00	(CCME, 2011; D. D. Williams et al., 1999)
Chloride Chloride Chloride	Tubifex tubifex	Oligochaete	Invertebrate	4 4 4	LC50 LC50 LC50	6119000	6119.00	(CCME, 2011; Elphick et al., 2011; N. Wang & Ingersoll, 2010)
Chloride	Chironomus riparius	Midge	Invertebrate	2	LC50	6912000	6912.00	(CCME, 2011)
Chloride	Eudiaptomus padanus padanus	Copepod	Invertebrate	2	LC50	7077000	7077.00	(Baudouin & Scoppa, 1974; CCME, 2011)
Chloride	Cyclops abyssorum prealpinus	Copepod	Invertebrate	2	LC50	12385000	12385.00	(Baudouin & Scoppa, 1974; CCME, 2011)
Chloride	Epioblasma torulosa rangiana	Northern riffleshell mussel	Invertebrates	1	EC50	244000	244.00	(CCME, 2011; Gillis, 2011)
Chloride	Lampsilis siliquoidea	Freshwater mussel	Invertebrates	1	EC50	709000	709.00	(Bringolf et al., 2007; CCME, 2011)

Chemical Name	Species Scientific Name	Species Common Name	Species Group	Time (Days)	End point	Conc (ug/L)	Geo Mean (mg/l)	References
Chloride	Lampsilis fasciola	Wavy-rayed lampmussel	Invertebrates	1 1 1	EC50 EC50 EC50	746000.0	746.00	(Bringolf et al., 2007; CCME, 2011; Gillis, 2011; Valenti et al., 2007)
Chloride	Lampsilis cardium	Plain pocketbook	Invertebrates	1	EC50	817000	817.00	(CCME, 2011; Gillis, 2011)
Chloride	Daphnia ambigua	Water flea	Invertebrates	2	EC50	1213000	1213.00	(CCME, 2011)
Chloride	Elliptio complanata	Freshwater mussel	Invertebrates	1	EC50	1620000	1620.00	(Bringolf et al., 2007; CCME, 2011)
Chloride	Epioblasma brevidens	Cumberlandian combshell	Invertebrates	1	EC50	1626000	1626.00	(CCME, 2011; Valenti et al., 2007)
Chloride	Epioblasma capsaeformis	Oyster mussel	Invertebrates	1	EC50	1644000	1644.00	(CCME, 2011; Valenti et al., 2007)
Chloride	Villosa constricta	Freshwater mussel	Invertebrates	1	EC50	1674000	1674.00	(Bringolf et al., 2007; CCME, 2011)
Chloride	Villosa iris	Rainbow mussel	Invertebrates	4	EC50	1815000	1815.00	(CCME, 2011)
Chloride	Villosa delumbis	Freshwater mussel	Invertebrates	1	EC50	2008000	2008.00	(Bringolf et al., 2007; CCME, 2011)
Sulfate	Scenedesmus subspicatus	Green Algae	Algae, Moss, Fungi	5	LC50	5600000	5600.00	(CCME, 2011; Vinot & Larpent, 1984)
Sulfate	Daphnia magna	Water Flea	Crustaceans	1	LC50	7000000	7000.00	(CCME, 2011; Vinot & Larpent, 1984)
Sulfate	Danio rerio	Zebra Danio	Fish	1	LC50	9600000	9600.00	(CCME, 2011; Vinot & Larpent, 1984)
Sulfate	Ceriodaphnia dubia	Water Flea	Invertebrate	2	LC50	2050000	2050.00	(Meays, C. & Nordin, 2013)
Sulfate	Chironomus tentans	Midge	Invertebrate	2	LC50	14134000	14134.0	(Meays, C. & Nordin, 2013)
Sulfate	Hyalella azteca	Scud	Crustaceans	4	LC50	512000	512.00	(Meays, C. & Nordin, 2013)
Sulfate	S. simile			4	LC50	2078000	2078.00	(Meays, C. & Nordin, 2013)
Sulfate	Lepomis macrochirus	Blue gill	Non-salmonid	4	LC50	13500000	13500.0	(Meays, C. & Nordin, 2013)
Sulfate	Pimephales promelas	Fathead Minnow	Non-salmonid	4	LC50	7960000	7960.00	(Meays, C. & Nordin, 2013)

Chemical Name	Species Scientific Name	Species Common Name	Species Group	Time (Days)	End point	Conc (ug/L)	Geo Mean (mg/l)	References
Sulfate	Brachionus calyciflorus	Rotifer		4	LC50	1701000	1701.00	(Meays, C. & Nordin, 2013)
Sulfate	Pseudacris regilla	Pacific Tree Frog		4	LC50	1784500	1784.50	(Meays, C. & Nordin, 2013)
Sulfate	Raphidocelis subcapitata	Microalga		4	LC50	1939000	1939.00	(Meays, C. & Nordin, 2013)
Sulfate	Oncorhynchus mykiss	Rainbow Trout	Fish (Salmonid)	4(assumed)	LC50	889000	1137.39	(Meays, C. & Nordin, 2013)
Sulfate	Lemna minor	Duckweed	Flowers, Trees, Shrubs, Ferns	4	EC50	1000000	1000.00	(Meays, C. & Nordin, 2013)