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Low Probability Receptor Analysis for Selected BC Oil and Gas Sites

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Executive Summary

Millennium EMS Solutions Ltd. (MEMS) received funding from the BC Oil and Gas Research and Innovation Society (BC OGRIS) to undertake a Low Probability Receptor Analysis (LPR Analysis) of selected oil and gas sites in BC. The objectives of this LPR analysis were to identify potential human and ecological receptors driving the remediation of oil and gas sites in BC under current regulatory requirements, and to assess the costs and benefits of remediating the sites to an endpoint that considers the current absence of certain receptors as well as their low probability of occurrence in the future.

Three British Columbia case studies were identified for LPR assessment including two sites located approximately 85 km northeast of Fort Nelson and another site located approximately 200 km north of Fort St. John. All sites used in the assessment are located in remote forested Crown land of northeast British Columbia and range in complexity from a former wellsite that included a remote drilling waste disposal area (DWDA) to a wellsite that included a production/dehydrator building, flare pit/shack, risers, and produced water catchment pits. Results of the LPR analysis indicated that the removal of the drinking water pathway and the ecological soil contact pathway, on average, reduced the total remedial volume from approximately 15,300 m^3 using conventional remedial objectives to 7,300 m^3 using the LPR approach. The 52% reduction in remedial volume accounted for an average savings of approximately $1,439,300 and a 61% reduction in greenhouse gas (GHG) emissions and fuel consumption.

MEMS is also currently assessing the applicability of LPR assessment for contaminated sites in Alberta. Results of the Alberta LPR research indicated on average a 54% reduction in remedial volume and fuel consumption and a 48% reduction in remedial costs. The application of LPR assessment methods developed by MEMS to three BC case studies, as well as parallel work conducted in Alberta, has demonstrated the potential for the costs and environmental impacts of remediation to be reduced without increasing the potential risk of adverse effects associated with the residual contamination.

Methods developed through the Alberta research also have potential benefits in BC when considering DW and ecological direct contact as LPR. In particular, development of water well mapping methods and statistical analysis methods based on BC data sources is identified as having potential benefits in BC site management, especially when extended to sites occurring in more populated areas of the Province.

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1.0 INTRODUCTION

1.1 General

Millennium EMS Solutions Ltd. (MEMS) has received funding from the BC Oil and Gas Research and Innovation Society (BC OGRIS) to undertake a Low Probability Receptor Analysis (LPR Analysis) of selected oil and gas sites in BC. The analysis is part of a broader research project aimed at evaluating the applicability and benefits of the LPR approach to the management of environmental liabilities associated with the closure of oil and gas facilities in Western Canada. The work reported herein was conducted under BC OGRIS Recipient Agreement EI-2017-02, in accordance with a proposal submitted by MEMS dated September 28, 2016.

1.2 Objectives and scope of work

The overall objectives of this LPR analysis were to identify potential human and ecological receptors driving the remediation of oil and gas sites in BC under current regulatory requirements, and to assess the costs and benefits of remediating the sites to an endpoint that considers the current absence of certain receptors as well as their low probability of occurrence in the future.

The project comprised the following general scope of work:

- a review of available files for selected oil and gas sites in BC with a view to selecting two or three representative sites for the purpose of evaluating the LPR approach; and
- determination of low probability receptors, validation of LPR benefits and estimation of costs to bring the selected sites to regulatory closure under the following scenarios:
  - application of the current process to achieve a Certificate of Restoration (CoR), including remediation to meet either the numerical or risk-based standards of the Contaminated Sites Regulation (CSR); and
  - application of a modified approach that considers LPRs in determining remediation requirements.

The work was conducted in consultation with the Canadian Association of Petroleum Producers (CAPP) and the BC Oil and Gas Commission (OGC) and was carried out in parallel with a related initiative in Alberta, funded by MEMS, the Petroleum Technology Alliance Canada, and individual industry operators. Relevant information from the Alberta work that is considered applicable to BC has also been incorporated into this report.

2.0 BACKGROUND

2.1 Overview of concept

Due to the current downturn in the oil and gas industry, governments of British Columbia, Alberta and Saskatchewan, industry, and the general public have recognized liability management as a high priority issue. It has been identified that, as a result of existing levels of risk tolerance, costs associated with managing liability in Western Canada are too high, and a broader application of risk-based closure is needed. At the same time, a broader understanding of environmental protection has evolved with a clear intent to reduce impacts and emissions to the environment.

Liability management, through contaminated site remediation, is currently based on protecting human and ecological receptors and exposure pathways that are associated, by definition, with a given land and/or water use. Most provincial regulatory systems aim to be protective by addressing all such receptors, regardless of whether or not they are present, or might occur in the future, at a given site. Some risk-based options exist within each of the regulatory systems to exclude receptors under certain conditions; nevertheless, remediation endpoints for many sites continue to be based on the assumed presence, and exposure, of potentially non-existent current and future receptors. Examples of these receptors might include occupants of a potential future residence, changes in groundwater use, future agricultural activities or non-present ecological species.

The potential for such receptors to be exposed to unacceptable levels of a contaminant of concern originating from a site depends on three factors:

- the likelihood that the receptor will occur in the vicinity of the site at some point in the future;
- the likelihood that a complete exposure pathway will exist in the future by which the receptor could be exposed; and
- the likelihood that the chemical will reach the receptor location at concentrations sufficient to cause adverse effect, taking into account the potential for the chemical to attenuate with time and distance.

There are a number of non-beneficial impacts associated with remediating sites to levels required for the protection of non-existent receptors. Firstly, the mobilization of remediation resources has a quantifiable environmental impact in the form of consumption of diesel fuel and production of greenhouse gases (GHGs) as well as other more qualitative impacts (*e.g.*, destruction of habitat and wildlife corridors, health and safety risks from remedial activities). Secondly, there is a considerable direct financial cost to industry, and in some cases the public, associated with the remediation of such sites, especially when considered on an aggregate basis across a province. Avoiding financial expenditures that do not result in any reduction in current risk levels would allow the redirection of funds towards the remediation of higher priority sites.

The three factors listed above, if considered in establishing remediation requirements for a site, have the potential to reduce the costs and impacts otherwise associated with remediation to current regulatory standards or guidelines. All these factors can be considered in a site-specific risk-based remediation strategy. However, one of the goals of the present research initiative is to "systematize" the consideration of such factors within routine regulatory applications. With this in mind, the present study focuses on the first factor, the low probability receptor (LPR); probability of exposure and probability of sufficiently high concentrations reaching the point of exposure, are expected to be the subject of further research.

A goal of the broader LPR research initiative, subject to validation of the benefits of the approach, is to move towards a relaxation in the regulatory remediation requirements for sites at which LPRs can be demonstrated. It is recognized that "low probability" still implies a finite, but small, possibility that a receptor could arise in the future. As part of a revised liability management framework that incorporates LPR considerations, it is anticipated that an industry-led financial backstop, such as a remediation fund or financial security mechanism, will be required to respond to future land and water use changes that might result in an LPR becoming operative.

2.2 BC regulatory context

2.2.1 General

The BC framework for remediation and reclamation of upstream oil and gas sites dictates that the requirements of the *Environmental Management Act* (EMA) and the CSR be met for a site to qualify for a CoR. With the exception of high risk sites, OGC is delegated with the responsibility of ensuring that these requirements are met, under the 2008 Memorandum of Understanding between OGC, the Ministry of Environment (MoE) and the (then) Ministry of Agriculture and Lands and Ministry of Energy, Mines and Petroleum Resources. OGC's requirements with respect to remediation in the context of a CoR application are outlined in the Certificate of Restoration Application Manual (OGG, 2016), which refers to the CSR and a number of related MoE documents and requirements.

Under the CSR, a contaminated site may be remediated either to numerical standards or to risk-based standards. Numerical standards include the generic soil and groundwater standards presented in Schedules 4, 6 and 10 of the CSR, as well as the matrix soil standards of Schedule 5. Additional generic standards are provided for sediment and vapour (Schedules 9 and 11, respectively), but are not considered further herein. Limited site-specific modification of the matrix soil standards is permitted in certain circumstances with sufficient site-specific information; such modified standards are referred to as site-specific numerical standards.

The numerical standards are listed, and applicable standards are selected, according to land use and water use. Land uses are defined in the CSR and include agricultural (AL), urban park (PL), residential (RL), commercial (CL), industrial (IL) and wildlands (WL). Water uses include drinking water (DW), aquatic life (AW), irrigation (IW) and livestock watering (LW). MoE Protocol 21 prescribes the method of determining applicable water use at a given site. In the case of matrix soil standards (Schedule 5), standards are also listed based on key "site-specific factors", *i.e.* key human and environmental exposure pathways to be protected. The site-specific factors of human intake of contaminated soil and toxicity to soil invertebrates and plants are considered to be applicable at all sites; standards protective of drinking water, aquatic life, livestock watering and irrigation are applied based on the determined water use.

Risk-based standards are determined on the basis of a site-specific human health and/or ecological risk assessment, which may be a screening level risk assessment (SLRA) as prescribed by MoE Protocol 13, or a detailed risk assessment (DRA). Sites remediated to risk-based standards may require ongoing risk management measures (intrinsic, engineering or institutional risk controls) to ensure that the conditions and assumptions of the risk assessment remain valid. Where a site is issued an instrument by MoE such as a risk-based Certificate of Compliance, these controls would be listed on the certificate. Note that, with the exception of high risk sites, sites for which a CoR is being sought are not required to be reviewed by MoE, or issued MoE instruments.

The above requirements apply when regulatory "closure" is being sought for a site, *i.e.* the issuance of a regulatory instrument such as a Certificate of Compliance (MoE) or a CoR (OGC). Proponents not seeking an instrument have greater flexibility, including an ability to implement long term risk management without active remediation, provided that requirements of the *Environmental Management Act* with respect to substance releases are met.

2.2.2 Options for the consideration of site-specific receptors and exposure pathways

2.2.2.1 Numerical standards

The LPR concept relies on an ability, within the regulatory framework, to remediate to standards which are protective of receptors that are either present or likely to be present at a site, and to exclude from consideration those that have a low probability of occurring. The generic numerical soil standards of the CSR are determined based on land use and are considered to be protective of all potential receptors, but are not quantitatively derived on the basis of protection of any specific receptor(s) or exposure pathway(s). Thus, for a given specified land use, there is no present opportunity to adjust the generic standards based on the presence or absence of receptors.

The matrix soil standards are derived using documented protocols on a pathway-specific and receptor-specific basis. As such, the standards could, in theory, be selected based on the pathways and receptors that are operative at a given site. From a regulatory standpoint, however, a site that is being managed to numerical standards must meet all standards for the "mandatory" site-specific factors, as well as those corresponding to the water use determined in accordance with Protocol 21.

Generic numerical water standards must also be met for the applicable water use as per Protocol 21. Protocol 21 provides an opportunity to exclude water use receptors under certain prescribed conditions. Other than water use, however, within the CSR there is limited opportunity under the numerical standards to exclude any receptors that would normally be associated with the designated land use.

Under the numerical standards of the CSR, there are two situations in which receptors or exposure pathways are implicitly modified at depth. First, regardless of the land use, soil below a depth of 3 m is considered remediated if it meets the standards for commercial land use. Secondly, and similarly, the numerical standards applicable to wildlands are urban park standards at depths of less than 3 m and commercial standards at depths greater than 3 m.

It is noted that, under the numerical standards of the CSR, soil vapour must also meet the generic vapour standards (Schedule 10 of the CSR). The generic vapour standards are designed to protect human receptors who may be exposed to vapours in the breathing zone. Vapour standards are applicable under all land uses; however, in the CoR process OGC allows professional judgement to be used in the investigation of vapours at remote oil and gas sites with little potential for human exposure.

2.2.2.2 Risk-based standards

Risk-based standards provide proponents with the opportunity to consider site-specific conditions, including the presence or absence of receptors and exposure pathways, in determining remediation requirements. Two regulatory options are available for sites proposed for closure under risk-based standards: screening level risk assessment and detailed risk assessment.

Screening level risk assessment (SLRA)

MoE's Protocol 13 prescribes the methodology for screening level risk assessment (SLRA). SLRA is a systematic process of screening the applicability of certain receptors and/or exposure pathways on the basis of site-specific conditions. Human exposure to contaminated soil/dust, vapours (at wildlands sites), and drinking water, as well as ecological exposure to contaminated soil and exposure of aquatic life, crops and livestock to groundwater, may be excluded based on factors such as depth to contamination and potential for groundwater or soil leachate to reach a receptor. SLRA follows defined methods and is subject to precluding conditions; sites that "fail" SLRA, or are ineligible, require detailed risk assessment. Some of the receptors and/or exposure pathways considered in

SLRA (*e.g.* drinking water users, or persons potentially exposed to vapours in wildlands settings) could be considered LPRs under certain circumstances. It is, therefore, anticipated that the LPR approach could be used in conjunction with, or as an extension of, SLRA to screen certain receptors and exposure pathways.

Detailed risk assessment (DRA)

While the SLRA approach is somewhat restrictive, a detailed risk assessment (DRA) is more flexible in terms of its ability to consider site-specific receptors and exposure conditions. However, a DRA conducted in support of closure to risk-based standards must still meet ministry requirements such as protection of receptors known, or reasonably inferred, to be present (Technical Guidance 7) and consideration of current and future water uses (Protocol 21). In addition, as noted previously, risk controls may be required to maintain the assumptions of the risk assessment and ensure ongoing risk management where applicable.

2.3 Identification of potential LPRs in BC

A pre-requisite to determining the applicability of the LPR approach in BC is the identification of receptors and exposure pathways that govern remediation under current regulatory requirements. The governing receptor is that for which the pathway-specific soil matrix standard, and/or the water use-related standard, is the lowest for a given contaminant of concern and therefore drives remediation requirements. Exclusion of a governing receptor, if justified on the basis of current absence from a site and a low probability of future occurrence, would in most cases result in a relaxation of the applicable standard. A review of the generic and matrix soil and water standards was conducted in order to identify governing receptors for common contaminants at upstream oil and gas sites.

As noted previously, generic soil standards are not pathway-specific, and typically cannot be associated with receptors that may be present or absent. Generic soil standards are therefore generally not amenable to relaxation based on the LPR approach, although exceedances of such standards may still, in some cases, be managed using a risk-based approach. Matrix soil standards and generic water standards, as well as generic vapour standards, are receptor or water use-specific, and receptors associated with these have the potential to be LPRs. Potential LPRs are discussed in the following paragraphs.

2.3.1 Drinking water (DW) use

Drinking water (DW) use frequently drives the soil matrix standards for typical oil and gas contaminants, and is the dominant driver of generic groundwater standards. Furthermore, it appears that DW will be the driver of soil standards for several additional potential contaminants of concern under the Stage 10 CSR updates to be implemented in November 2017.

Under Protocol 21, both current DW use and future DW use must be considered. Future use applies to all geological units that meet prescribed yield criteria and are not protected by an adequate confining layer as defined in the Protocol. Bedrock must be considered a potential DW aquifer if mapped in the BC Water Resources Atlas.

While not explicitly allowed to be excluded under Protocol 21, it appears that future DW users in remote areas with no current use may be considered potential LPRs. Mapping of aquifers in conjunction with population growth and/or development trends may provide support for this on an area-specific basis.

2.3.2 Aquatic life water (AW) use

Aquatic life water (AW) use drives soil matrix standards for a few typical oil and gas related contaminants, and could also become a driving factor when DW does not apply. AW would drive groundwater standards in most cases in the absence of DW.

Aquatic life water (AW) is based on fixed surface water features and hence is considered to be either present or not within a specified distance from a site; it would not therefore be considered a potential LPR.

2.3.3 Irrigation (IW) and livestock watering (LW) water use

Irrigation (IW) and LW water use govern soil standards in few instances, even in the absence of DW or AW use. One exception, however, is chloride. The same is true of groundwater standards.

Under Protocol 21, it is not required that future IW and LW use be considered. Therefore, considering these receptors as LPRs does not offer any additional advantage, since they may already be excluded if they are not currently present. While in Alberta dugouts are considered to be candidate receptors for LPR analysis (see Section 5.0), this would not be the case in BC.

2.3.4 Toxicity to soil invertebrates and plants

Toxicity to soil invertebrates and plants (also known as ecological soil contact) is the governing pathway for soil standards for several oil and gas related contaminants. The pathway will govern in fewer instances under the Stage 10 CSR updates, but may still drive remediation in the absence of DW and/or AW use. Ecological soil contact is not considered in applying groundwater standards (other than implicitly in the standards for IW).

Toxicity to soil invertebrates and plants is a mandatory matrix standard, although it can be excluded under SLRA (Protocol 13) for soils below 1 m depth in the absence of deep rooting vegetation and with certain risk controls (such as preservation of a 1 m layer of "clean" soil). Ecological soil contact also defaults to the CL standard below 3 m.

Ecological soil contact may be amenable to LPR analysis, based on rooting depth of different types of vegetation in conjunction with a depth criterion such as that used in SLRA (or a modified criterion).

2.3.5 Other human exposure pathways

Human intake of contaminated soil is a mandatory matrix standard but rarely governs (an exception would be benzo[a]pyrene after the Stage 10 updates are in effect). Human intake of contaminated soil can currently be excluded for soil at depths greater than 1 m or where the ground surface is covered under Protocol 13 (with appropriate risk controls).

Other human pathways could include vapour inhalation. This pathway is addressed through generic vapour standards under the CSR. Vapour exposure can be excluded for wildlands sites under Protocol 13 if humans are rarely present (less than 2 hours per week). In addition, OGC allows the use of professional judgement in determining the need for vapour assessment at other remote sites if humans are not expected to be present, unless there are nearby buildings or the land is zoned for PL, RL or CL. Based on this, human receptors potentially exposed to soil vapour contamination may be considered potential LPRs, although defining them as such may not offer significant advantages given the flexibility that exists to exclude the vapour pathway within Protocol 13 and the CoR process.

2.3.6 Summary

Drinking water (DW) use is considered a candidate for LPR analysis at oil and gas sites in BC. Toxicity to soil invertebrates and plants (ecological soil contact) was also considered as a potential candidate for LPR analysis; however, the results presented are preliminary as research into that pathway is still ongoing. Other human exposure considerations (*e.g.* direct intake or vapour exposure) would not offer significant benefit under the LPR approach, and IR and LW receptors also are considered to have minimal potential as LPRs.

3.0 SITE SELECTION

3.1 Identification of BC candidate sites

A number of candidate oil and gas sites in BC were identified for the purpose of an initial file review with a view to selecting two or three sites for a detailed LPR analysis, in accordance with the scope of work. Potential sites were initially identified from our in-house files as well as from the OGC's

Orphan Site Reclamation Fund (OSRF). Criteria for initial site identification included region of the province, land use, water use, site size and complexity, nature of contamination (*e.g.* classes of contaminants present), extent of impacts (*e.g.* volume of contaminated soil), completeness of site characterization, and potential for evaluation of the LPR approach based on receptors and exposure pathways anticipated to be operative at the sites.

Six sites were identified at the outset for initial file review and analysis: three industry sites from our in-house files and three OSRF sites proposed by OGC. Files for the industry sites were reviewed with the agreement of our clients on the understanding that detailed identifying information and client identities would not be reported. A brief summary of the six sites selected for initial review is presented in Table 1.

3.2 Final site selection

One of the industry sites was subsequently removed from the short list at the request of the client, and therefore the initial analysis was conducted on five of the sites. The following information was reviewed and compiled for each of the sites:

- regional site setting, land use and designation (*e.g.* Crown, Agricultural Land Reserve);
- water use(s), distance to surface water bodies, presence of registered water wells and/or mapped aquifer(s);
- applicable soil standards;
- potential contaminants of concern (PCOC);
- summary of site investigation activities;
- measured contaminant concentrations in comparison to applicable standards;
- approximate volume of soil exceeding applicable soil standards;
- key receptors/pathways governing applicable soil standards for each identified PCOC; and
- potential for receptor exclusion based on LPR approach.

An initial, semi-quantitative analysis was conducted for each site to identify revised standards based on the exclusion of potential LPRs and to estimate preliminary soil volumes exceeding revised standards. On the basis of the summarized information, three BC sites were selected that were representative of the range of site settings, sizes and contaminants and were considered suitable to evaluate the feasibility of the LPR approach.

The final sites selected for detailed LPR analysis are identified as *Good Candidates* in Table 1.

Table 1 List of Candidate Sites for LPR Analysis

Site/location	Facility type	Setting / land use	Brief description	Contaminants of concern	Impacted soil volume (estimated)	Governing pathways/water uses	Potential LPR(s)	Suitability for study
Rigel Doig River area (confidential location)	Former well site and line heater	Agricultural land use	Well drilled in 1960s, flarepit and UST excavated between 2002 and 2008	Hydrocarbons	12,000 m^3	Drinking water use, ecological soil contact, aquatic life	Drinking water use, ecological soil contact	N/A - removed from consideration at client request
Jedney B-019-A/94-G-08	Acid gas injection well site	Forested Crown land in remote area	Well drilled in 1950s, flare pit backfilled. Large offsite plume	Hydrocarbons including BTEX, minor chloride, barium	2,500 m^3	Drinking water use, ecological soil contact, aquatic life	Drinking water use, ecological soil contact	Moderate candidate
Kahntah B-066-D/94-I-02	Remote drilling waste disposal area	Forested Crown land in remote area	Well drilled 2005, 9 m^3 drilling cutting and 388 m^3 of total waste	Benzene, arsenic, chloride, and EC	225 m^3	Drinking water use, ecological soil contact, aquatic life	Drinking water use, ecological soil contact	Good candidate*
Orphan Louise D-071-I/94-P-04	Former dehydrator/fluid storage site	Forested Crown land in remote area	Drilled 1979, evidence of historical spills. Site decommissioned in 2016	Hydrocarbons**, chloride and sodium	3,700 m^3	Drinking water use, ecological soil contact, aquatic life	Drinking water use, possibly ecological soil contact	Good candidate*

Table 1 List of Candidate Sites for LPR Analysis

Site/location	Facility type	Setting / land use	Brief description	Contaminants of concern	Impacted soil volume (estimated)	Governing pathways/water uses	Potential LPR(s)	Suitability for study
Orphan Buick D-054-F/94-A-14	Well site	Forested, but in Agricultural Land Reserve	Drilled 1977, abandoned in 1996. Landfarm on site	Hydrocarbons including BTEX, PAHs, barium	1,300 m^3 but not fully delineated	Drinking water use, ecological soil contact, aquatic life, livestock ingestion	Potential ecological soil contact, livestock ingestion	Poor candidate
Orphan Louise B-070-L/94-P-03	Wellsite including drilling waste disposal area, production/ dehydrator building, flare pit/shack, risers, produced water catchment pits	Forested Crown land in remote area	Drilled 1979	Benzene, barium, cadmium, selenium, uranium, sodium and chloride	42,000 m^3	Drinking water use, ecological soil contact, generic standards	Drinking water use, possibly ecological soil contact	Good candidate*

* Sites selected for detailed analysis

** Petroleum hydrocarbons including benzene, ethylbenzene, xylene, naphthalene, volatile petroleum hydrocarbons (VPH), light extractable petroleum hydrocarbons (LEPH), and heavy extractable petroleum hydrocarbons (HEPH).

4.0 SITE ANALYSIS

4.1 BC Case Studies

The British Columbia case studies identified for LPR assessment included a site located approximately 200 km north of Fort St. John and another two sites located approximately 85 km northeast of Fort Nelson. All sites used in the assessment are located in remote forested Crown land of northeast British Columbia. For each site, Phase 2/Stage 2 environmental assessments, site investigation, and/or remediation reports were reviewed to identify concentrations of contaminants and receptor pathways affected. An overview of the three BC Case Studies is provided in Table 2. Receptor pathways associated with drinking water use and toxicity to soil invertebrates and plants (ecological soil contact) were identified for further analysis using an LPR approach. Potential impacts from GHGs and differences in the consumption of diesel fuel and financial costs between conventional remediation and LPR approaches were also evaluated.

Table 2 British Columbia Case Study Overview

					CSR* Soil and Groundwater Remediation Standards Exceeded for Pathway?		
British Columbia (BC) Case Study	**Land Use**	**Contaminants**	**Remediation Volume (m^3)**	**Estimated Cost of Conventional Remediation**	**Ecological Soil Contact**	**Drinking Water (DW)**	**Aquatic Life Water (AW)**
BC 1	Forested Crown Land	Benzene, arsenic, chloride, EC	225	$62,200	Yes	Yes	Yes
BC 2	Forested Crown Land	Benzene, barium, cadmium, selenium, uranium, sodium and chloride	42,000	$7,535,800	Yes	Yes	Yes
BC 3	Forested Crown Land	benzene, ethylbenzene, xylene, VPH, LEPH, HEPH, naphthalene, sodium and chloride	3,700	$661,500	Yes	Yes	Yes

* Contaminated Sites Regulation (Province of British Columbia, 1996).

4.1.1 BC Case Study #1 Summary

The BC Case Study #1 (Kahntah B-066-D/94-I-02) is located approximately 200 km north of Fort St. John, British Columbia, on forested Crown land. The site is associated with a former wellsite and includes a remote drilling waste disposal area (DWDA). The site is not located within the BC Agricultural Land Reserve (ALR). There were no registered water wells or residence identified within 1,000 m of the site. The nearest surface water body is the Kahntah River located approximately 450 m east of the site.

Historical site assessments identified the following potential contaminants of concern (PCOC) elevated compared to the applied standards:

- elevated benzene concentrations were detected in four samples with values ranging from 0.086 to 0.315 mg/kg collected from 2.2 to 3.8 m below ground surface (bgs) within the DWDA;
- elevated arsenic concentration was identified at 2.2 m bgs within the DWDA; and
- elevated salinity parameters, including electrical conductivity (EC) and chloride concentrations were identified from 0.2 to 4.4 m bgs in the DWDA.

Of the approximately 225 m^3 of affected soil, approximately 80 m^3 of salt impacted soil above the limit for the protection of aquatic life water are expected to be excavated and disposed of at an approved landfill. The remaining affected area, consisting primarily of elevated salt concentrations, benzene and arsenic, was assessed in subsequent sections of this report. Exceedances for EC, chloride, benzene and arsenic have been noted for the drinking water, aquatic life water and/or ecological soil contact pathways.

Current impacts to drinking water have not been identified at the site. According to the BC Water Well Database and the BC Water Resource Atlas there are no water wells identified within 10 km of the site. Furthermore, no geological unit meeting the criteria of the aquifer as outlined in Protocol 21 was identified on site *via* borehole logs to the maximum depth of investigation (*i.e.* 10 m bgs).

Current and future impacts to the ecological soil contact pathway are not expected as the majority of the chloride mass is located between 2.2 and 4.4 m bgs. Previous works (Azimuth 2013; PTAC 2013) confirmed that the vast majority of soil invertebrates are present in the top 2 m of the soil profile and would not be affected by deeper salt concentrations. Furthermore, plant species present on site including black spruce, white spruce and aspen have rooting depths ranging between 2 and 3 m bgs (Azimuth 2013); therefore, are only marginally in contact with PCOC. In addition, there was no accumulation of sulphate in surficial soils at background boreholes locations which indicates long-term net downward water movement.

Based on the evidence presented, both the ecological soil contact and the drinking water pathways could be excluded using the LPR approach. Groundwater used for irrigation and/or livestock water is excluded as the site is not located within BC ALR. The aquatic life pathway is active as the Kahntah River is located within 500 m of the site.

4.1.2 BC Case Study #2 Summary

The BC Case Study #2 (Orphan Louise B-070-L/94-P-03) is located approximately 85 km northeast of Fort Nelson, British Columbia, on forested Crown land. The site is a former wellsite that included a production/dehydrator building, flare pit/shack, risers, produced water catchment pits and potentially a DWDA. The area is described as having muskeg vegetation with black spruce present the low lying bog areas and white spruce and aspen vegetation present in the higher relief areas. The site is not located within the BC Agricultural Land Reserve (ALR). There were no registered water wells or residence identified within 1,000 m of the site. The nearest surface water body is the unnamed creek located approximately 600 m east of the site.

Historical site assessments identified the following PCOC elevated compared to the applied standards:

- elevated benzene concentration (0.09 mg/kg) was detected in one sample collected from 2 m bgs within the vicinity of the former dehydrator buildings;
- elevated concentrations of trace metals, including barium, cadmium, selenium, and uranium were identified between 0.2 and 1.0 m bgs in the vicinity of the former dehydrator building and the produced water catchment pits area; and
- elevated sodium and chloride concentrations were identified from 0.25 to 6 m bgs at multiple locations throughout the site. Elevated sodium concentrations ranged between 205 and 2,610 mg/kg and elevated chloride concentrations ranged between 96 and 5,100 mg/kg.

Of the approximately 42,000 m^3 of affected soil, approximately 20,500 m^3 of salt and trace metal impacted soil above the limit for the protection of aquatic life water and/or the generic standards are expected to be excavated and disposed at an approved landfill. The remaining affected area, consisting primarily of elevated salinity and hydrocarbons were assessed in subsequent sections of this report. Exceedances for chloride, sodium, barium, cadmium and benzene have been noted for the drinking water, aquatic life water, and/or ecological soil contact pathways.

Current impacts to drinking water have not been identified at the site. According to the BC Water Well Database and the BC Water Resource Atlas, nine water wells were identified within 10 km of the site, of which the nearest water well is located 5.3 km from the site. Previous assessment program included the installation of groundwater monitoring wells; however, no assessment was carried out thereafter to demonstrate that the shallow geological unit qualifies as a drinking water aquifer. Furthermore, no geological unit meeting the criteria of the aquifer, as outlined in Protocol 21, was identified on site as the dominant lithology present at the site was silts and clays with no presence of sands or gravels as per the borehole logs.

Current impacts to the ecological soil contact pathway are present; however, their persistence in the environment may not result in future impacts as the majority of the chloride mass is located between 1.5 and 6 m bgs. Previous works (Azimuth 2013; PTAC 2013) confirmed that the vast majority of soil invertebrates are present in the top 2 m of the soil profile and would not be affected by deeper salt concentrations. In addition, there was no accumulation of sulphate in surficial soils at background boreholes locations which indicates long-term net downward water movement.

Based on the evidence presented, both the ecological soil contact and the drinking water pathways could be excluded using the LPR approach. Groundwater used for irrigation and/or livestock water is excluded as the site is not located within BC ALR. The nearest water body is approximately 600 m from the site; however, lateral and vertical delineation was only partially complete, therefore, for conservative reasons the aquatic life pathway is active.

4.1.3 BC Case Study #3 Summary

The BC Case Study #3 (Orphan Louise D-071-I/94-P-04) is located approximately 85 km northeast of Fort Nelson, British Columbia, on forested Crown land. The site is a former wellsite that includes a DWDA. The area is described as having muskeg vegetation with black spruce present the low lying bog areas and white spruce and aspen vegetation present in the higher relief areas. The site is not located within the BC ALR. There was no registered water wells or residence identified within 1,000 m of the site. The nearest surface water body is the unnamed tributary located approximately 600 m north of the site.

Historical site assessments identified the following PCOC elevated compared to the applied standards:

- elevated petroleum hydrocarbons (PHC), including benzene, ethylbenzene, xylene, volatile petroleum hydrocarbons (VPH), light extractable petroleum hydrocarbons (LEPH), and heavy extractable petroleum hydrocarbons (HEPH), concentrations were detected in six boreholes collected from 2.0 to 3.0 m bgs within the DWDA;
- elevated polycyclic aromatic hydrocarbon (PAH), naphthalene, was detected in a single borehole at 1 to 1.5 m bgs within the DWDA; and
- elevated salinity, including chloride and sodium, concentrations were identified in twelve boreholes collected from 1.0 to 4.5 m bgs within the DWDA.

Of the approximately 3,700 m^3 of affected soil, approximately 1,200 m^3 of salt impacted soil above the limit for the protection of aquatic life water, and/or generic standards are expected to be excavated and disposed of at an approved landfill. The remaining affected areas, consisting primarily of elevated salts, benzene, ethylbenzene, and xylene concentrations, were assessed in subsequent sections of this report. Exceedances for salinity associated parameters (*i.e.* sodium and chloride), benzene, ethylbenzene and xylene have been noted for the drinking water, aquatic life water and ecological soil contact pathways.

Current impacts to drinking water have not been identified at the site. According to the BC Water Well Database and the BC Water Resource Atlas, nine water wells were identified within 10 km of the site, of which the nearest water well is located 5.4 km from the site. Previous assessment program included the installation of groundwater monitoring wells; however, no assessment was carried out thereafter to demonstrate that the shallow geological unit qualifies as a drinking water aquifer. Furthermore, no geological unit meeting the criteria of the aquifer, as outlined in Protocol 21, was identified on site as the dominant lithology present at the site was silts and clays with no presence of sands or gravels as per the borehole logs.

Current and future impacts to the ecological soil contact pathway are not expected as the majority of the chloride mass is located between 2.0 and 4.5 m bgs. Previous works (Azimuth 2013; PTAC 2013) confirmed that the vast majority of soil invertebrates are present in the top 2 m of the soil profile and would not be affected by deeper salt concentrations. Furthermore, plant species present on site including black spruce, white spruce and aspen have rooting depths ranging between 2 and 3 m bgs (Azimuth 2013); therefore, are only marginally in contact with PCOC. In addition, there was no accumulation of sulphate in surficial soils at background boreholes locations which indicates long-term net downward water movement.

Based on the evidence presented, both the ecological soil contact and the drinking water pathways could be excluded using the LPR approach. Groundwater used for irrigation and/or livestock water is excluded as the site is not located within BC ALR. The aquatic life pathway is not active as the nearest water body is >500 m from the site; however, for conservative reason, it may be included as verification of surface water bodies has not been completed.

4.2 Remediation Impact and Economic Costs Methodology

The economic and environmental costs associated with remediation of the site based on conventional site assessment methods were compared to those estimated using the MEMS LPR assessment methods. The overall cost estimates were based on site-specific data as well as assumed logistical parameters and emission estimates. Site-specific data included the volume of impacted material requiring removal, distance from the site to the nearest Class II landfill and distance to a backfill source. Assumed parameters, including average number of hours worked per day, number of available trucking units for transport and average amount of material hauled per trucking unit were based on MEMS experience with remediation cost estimates. Fuel consumption and air emissions were estimated based on industry standards and reported consumption estimates.

4.2.1 Economic Costs

Economic costs associated with conventional versus MEMS LPR remedial objectives were assessed for each case study. Standardized remediation cost projections have been established using over eight sites specific to northwest Alberta & northeast British Columbia which range from $65 to $440 per tonne (Figure 1). The remedial rates take into account consulting fees, contractor costs, landfill fees and general expenses and laboratory costs. The general relationship defines the remedial rate as a function of tonnage, whereby the per tonne rate decreases as the remedial volume increases (Figure 1). For the purposes of this assessment, the remediation costs were projected using the expression outlined above, assuming the average bulk density of the impacted soil is 1,800 kg/m^3. In addition, the potential reduction in costs due to increased volume was cut off at $100/tonne when volumes exceeded 1,000 tonnes or approximately 550 m^3.

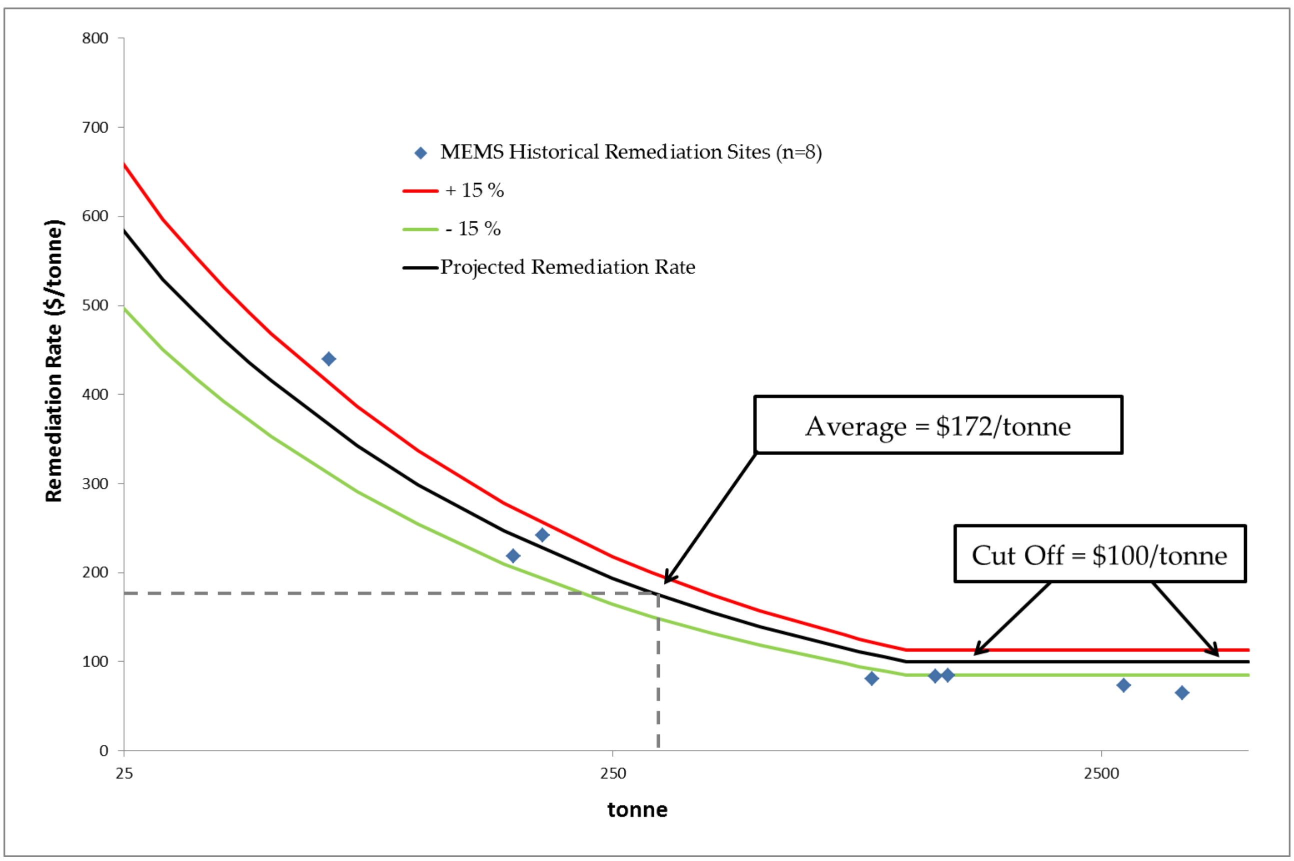

Figure 1 Remediation costs as predicted using historical MEMS remediation Sites (n=8).

4.2.2 Fuel Consumption and Emissions

The mobilization of remediation resources has a quantifiable environmental impact in the form of consumption of diesel fuel and production of GHGs as well as other more qualitative impacts (*e.g.* destruction of habitat and wildlife corridors). Fuel that would be consumed during remediation was separated into two categories:

1. Fuel requirements for the excavation/loading equipment; and
2. Fuel requirements for trucks hauling impacted material from the site to the landfill and for trucks hauling backfill material from the backfill source to the site.

For simplification, the fuel requirement for the excavation/loading equipment was assessed using a 324D excavator operating at 8 hour per day at an assumed medium load capacity and the fuel requirements for dump trucks was assessed using a Mack Granite axle-forward GU713 (Class 8 model) dump truck. The 324D excavators are reported to consume 16 to 24 L/hr of diesel (CAT 2011) while the Mack Granite axle-forward GU713 (Class 8 model) dump trucks have a fuel consumption rate on average of 6.2 mpg or 37 L/100 km for highway (Equipment World 2010).

Emission parameters for GHGs included volatile organic carbon (VOC), total hydrocarbon (THC), carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), oxides of nitrogen (NO_x) and particulate matter ≤10 μm (PM). Truck emissions were estimated using the US EPA estimates for class 8 vehicles (gross vehicle weight [GVW] 15 to 27 tonnes) (US EPA 2008). Excavator emissions were estimated using predicted emission factors based on discrete-event simulation (DES) modelling which account for variability in utilization rates (*i.e.* idle time *vs.* active construction) (Anh *et al.* 2010). Emission factors for the excavating equipment and hauling vehicles are presented in Table 3 below. Table 4 lists the parameters used in the GHG emission calculations.

Table 3 Emission Factors for Excavator and Dump Trucks

Equipment Type	Units	Emission Factors						
		VOC	THC	CO	CO_2	SO_2	NO_x	PM
Class 8 (GVW 15 – 27 tonne)	g/L	0.745[a]	0.755[a]	3.923[a]	2,680[b]	0.017[c]	15.054[a]	0.734[a]
Excavator (324 D)	g/hr	4.95[c]	126.94[d]	341.57[d]	98,050[d]	0.025[c]	1,122.5[d]	10.22[d]

a - (US EPA 2008) b - (US EIA 2016) c - (Australian Government 2008) d - (Anh *et al.* 2010)

Table 4 Site Specific Parameters and Assumptions

Parameter	Units	Value	Comments
Distance to Landfill [a]	km	150	Tervita – North Rockies
Bulk Density	kg/m³	1,800	Default Value
Truck Capacity [b]	m³/truck	16	Assumed (Truck + Pup)
# of Truck on Site	-	3	Assumed Site Restriction
Turnaround Time	hrs	4	300 km Round Trip

a - Nearest Class II landfill to all case studies assessed.

b - Assumed dump truck plus pup trailer (27 tonne/truck).

4.3 Remedial Cost Analysis

4.3.1 Case Study #1 (B-066-D/094-I-02)

Case Study #1 is a remote sump located in the mixed forest transitional area of northeastern British Columbia at B-066-D/094-I-02. The Stage 2 Preliminary Site Investigation (PSI) indicated benzene, arsenic, electrical conductivity (EC) and chloride concentrations in soil were elevated compared to applied standards. Remediation costs for the conventional and LPR approaches for the site are summarized in Figure 2 below. The estimated remedial volume for the site, based on conventional remediation objectives, was approximately 225 m^3, which equates to a total estimated remediation cost of $62,200 from Figure 2.

Remedial objectives for BC Case Study #1 were primarily driven by the drinking water standards for benzene, arsenic and chloride. Removal of the drinking water pathway resulted in the aquatic life pathway driving the remedial objectives for benzene and arsenic, and the ecological soil contact pathway for chloride. Removal of the drinking water pathway resulted in a 66% reduction in the total remedial volume required from 225 m^3 to 77 m^3.

Removal of the ecological pathway did not reduce the overall remedial volume any more than what was achieved by removing the drinking water pathway as chloride concentrations that were elevated to ecological soil contact were also elevated to the aquatic life pathway (*i.e.* > 550 mg/kg).

Overall, the reduction in the projected remedial volume that could be achieved by applying the LPR approach at this site is 148 m^3, which equates to a 66% reduction in greenhouse gas emissions and a 43% reduction in financial costs.

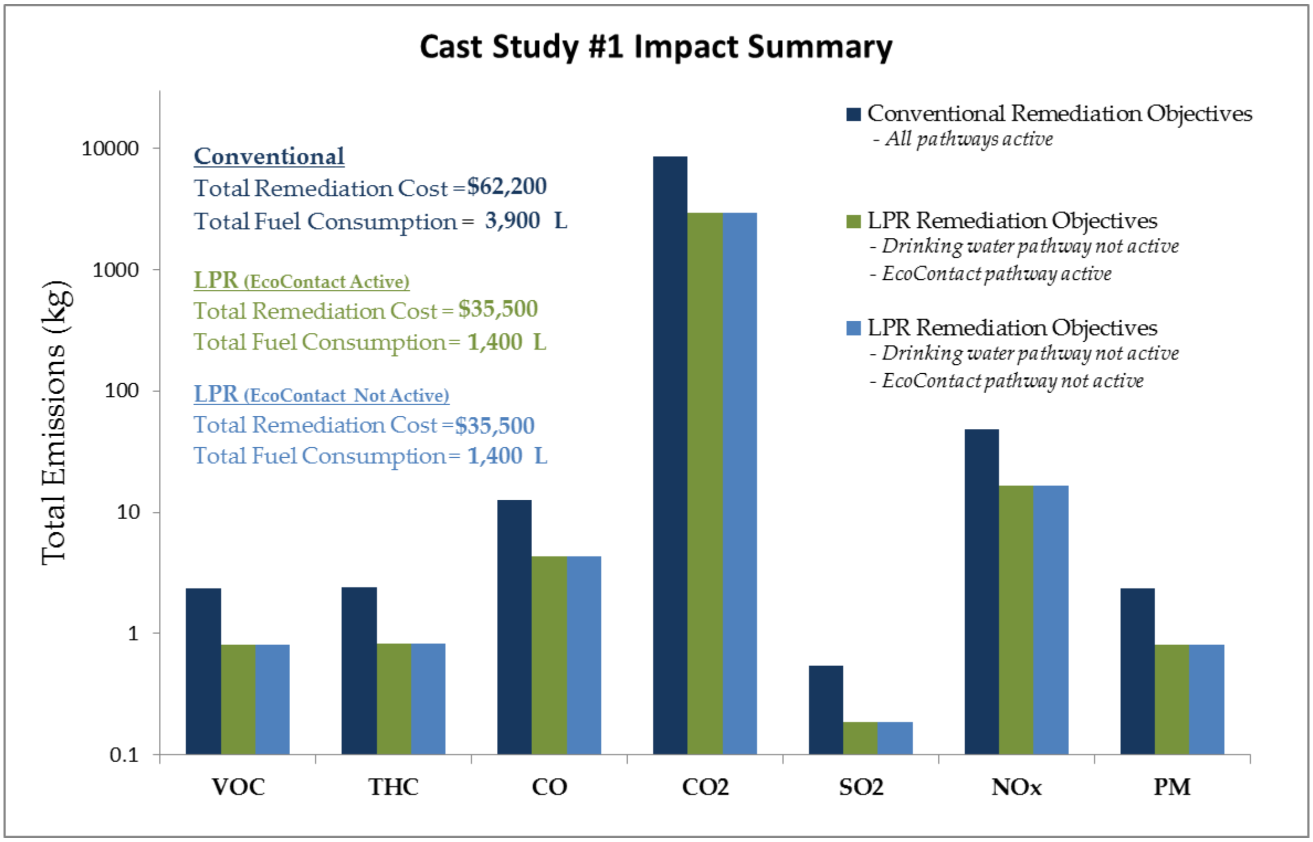

Figure 2 **Comparative fuel consumption and total GHG emissions for conventional remediation versus MEMS LPR approach.**

4.3.2 Case Study #2 (B-070-L/094-P-03)

Case Study #2 is a wellsite located in the mixed forest transitional area of northeastern British Columbia at B-070-L/094-P-03. The Stage 2 PSI indicated benzene, barium, cadmium, selenium, uranium, sodium and chloride concentrations in soil that were elevated compared to applied standards. Remediation costs for the conventional and LPR approaches for the site are summarized in Figure 3 below. The estimated remedial volume for the site, based on conventional remediation objectives, was approximately 42,000 m^3, which equates to a total estimated remediation cost of $7,535,800 from Figure 3.

Remedial objectives for BC Case Study #2 were driven by the drinking water standards for benzene, barium and chloride, aquatic life for cadmium, ecological soil contact for sodium, and generic standards for selenium and uranium. Removal of the drinking water pathway resulted in the aquatic life pathway driving the remedial objectives for benzene and chloride (soil > 3 m bgs), and the ecological soil contact pathway for barium, chloride (soil ≤ 3 m bgs) and sodium. The removal of the drinking water pathway reduced the overall projected remedial volume by 39%, from 42,000 m^3 to 25,600 m^3.

Removal of the ecological pathway resulted in the aquatic life pathway driving the remedial objectives for barium and chloride, and human ingestion of soil for sodium. The removal of the ecological contact pathway reduced the overall projected remedial volume by an additional 12%, from 25,600 m^3, as projected previously, to 20,500 m^3.

Overall, the reduction in the projected remedial volume that could be achieved by applying the LPR approach at this site is 21,500 m^3, which equates to a 51% reduction in greenhouse gas emissions and a 51% reduction in financial costs.

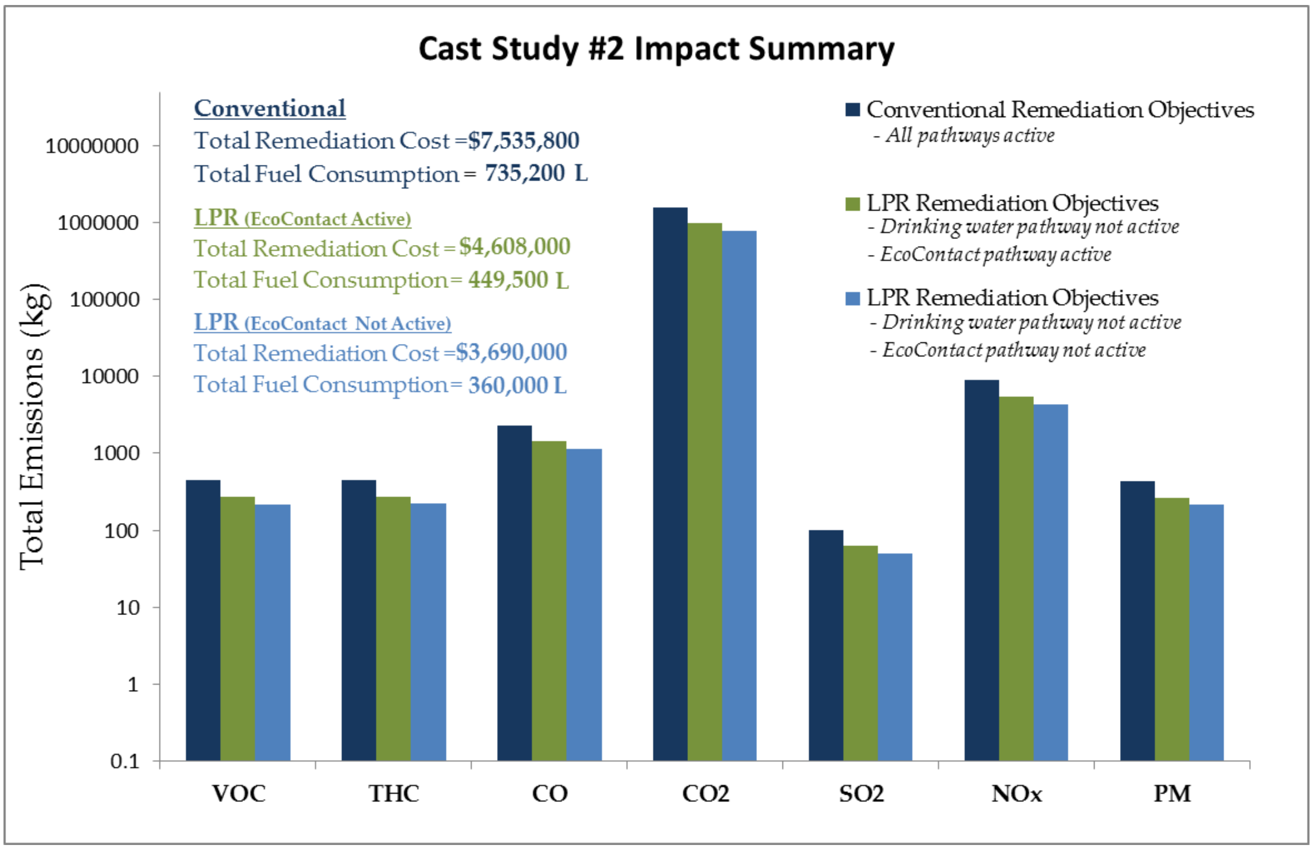

Figure 3 **Comparative fuel consumption and total GHG emissions for conventional remediation versus MEMS LPR approach.**

4.3.3 Case Study #3 (D-071-I/094-P-04)

Case Study #3 is a wellsite located in the mixed forest transitional area of northeastern British Columbia at D-071-I/094-P-04. The Stage 2 PSI indicated benzene, ethylbenzene, xylene, VPH, LEPH, HEPH, naphthalene, sodium and chloride concentrations in soil that were elevated compared to applied standards. Remediation costs for the conventional and LPR approaches for the site are summarized in Figure 4 below. The estimated remedial volume for the site, based on conventional remediation objectives, was approximately 3,700 m^3, which equates to a total estimated remediation cost of $661,500 from Figure 4.

Remedial objectives for BC Case Study #3 were driven by the drinking water standards for benzene and chloride, ecological soil contact for ethylbenzene, xylene and sodium, and generic standards for VPH, LEPH, HEPH and naphthalene. Removal of the drinking water pathway resulted in the aquatic life pathway driving the remedial objectives for benzene and chloride (soil > 3 m bgs), and the ecological soil contact pathway for ethylbenzene, xylene, chloride (soil ≤ 3 m bgs) and sodium. The removal of the drinking water pathway reduced the overall projected remedial volume by 67%, from 3,700 m^3 to 1,200 m^3.

Removal of the ecological pathway did not reduce the overall remedial volume any more than what was achieved by removing the drinking water pathway as the majority of the chloride impacts identified at this site were spatially distributed at depths greater than 3 m bgs where the aquatic life pathway is driving remedial objectives. Furthermore, ethylbenzene and xylene, which were both driven by the ecological contact pathway, were spatially correlated with other PCOC that could not be eliminated due to the inclusion of generic standards or concentrations that were elevated to other active pathways.

Overall, the reduction in the projected remedial volume that could be achieved by applying the LPR approach at this site is 2,500 m^3, which equates to a 67% reduction in greenhouse gas emissions and a 67% reduction in financial costs.

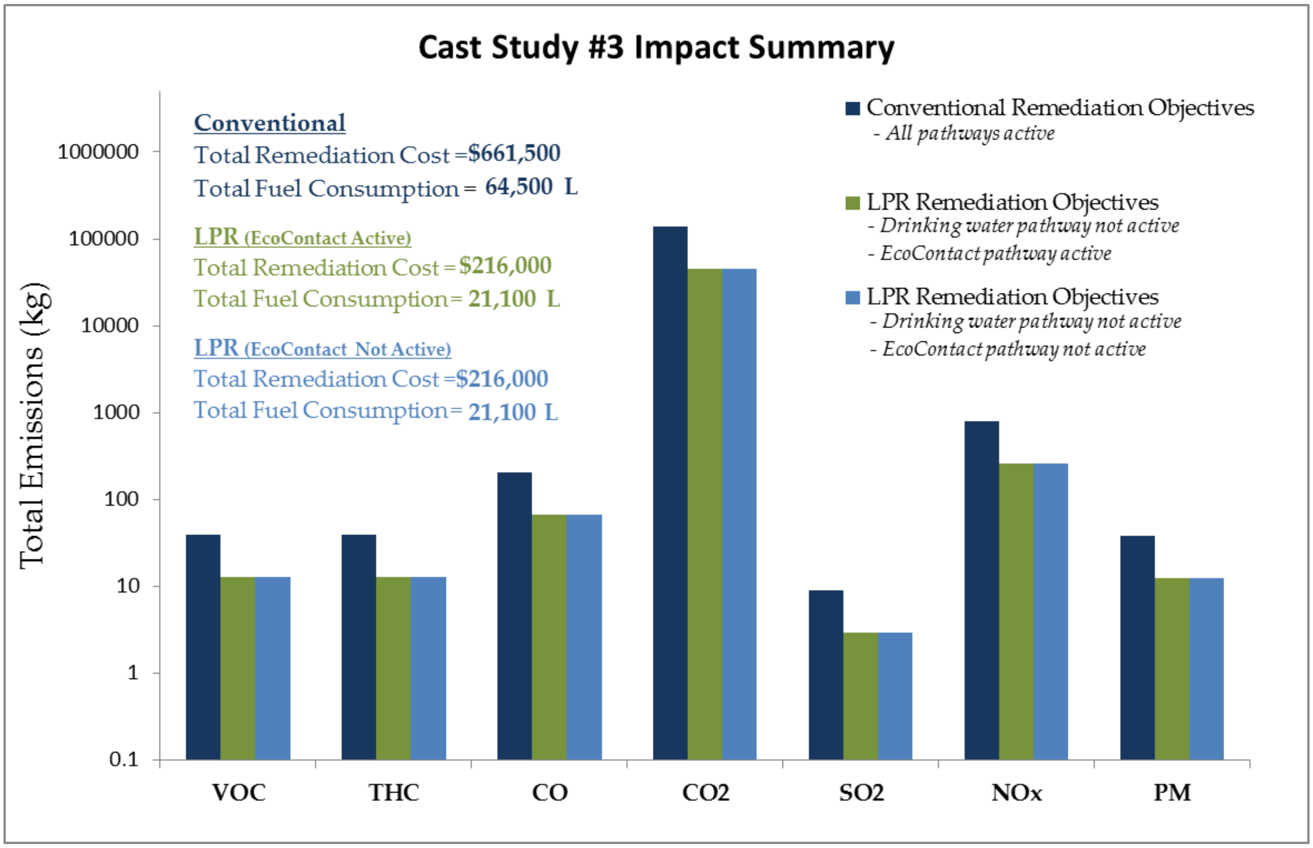

Figure 4 **Comparative fuel consumption and total GHG emissions for conventional remediation versus MEMS LPR approach.**

4.4 Case Study Summary

Low probability receptors, including drinking water (DW) and ecological soil contact, were assessed using three case studies. These case studies were primarily located in remote areas of northeastern BC and were associated with various oil and gas activities. The predominant LPR identified for all three BC cases was DW; however, ecological soil contact was also identified as a key LPR influencing remedial objectives for PCOC.

Review of the site assessments assuming conventional remediation, indicated that future DW could not be excluded (in accordance with Protocol 21) as hydrogeological data requirements pertaining to geological units and potential aquifers were not sufficient. However, the application of LPR assessment methods provides a supportable argument to allow for the elimination of the DW pathway as an LPR given their remote locations, lack of current use and/or low density of wells, and the low likelihood of future occurrence. The work to date was based on information contained in the BC Water Well Database and the BC Water Resources Atlas. Further assessment aimed at confirming DW as a LPR could include searching additional sources to project temporal trends, and expanding the assessment to case study sites in more populated areas, then applying methods such as those developed in the Alberta research (see Section 5).

The ecological soil contact (EcoContact) pathway was found to be a useful LPR in reducing remedial volumes and costs as well as greenhouse gas emissions for Case Study #2. Consideration of the ecological soil contact as a LPR is contaminant specific and would require further consideration of rooting depth and specific plant species present in the region and/or site vicinity.

Based on the preliminary assessment of the three case studies the average remedial volume was approximately 15,300 m^3 using conventional methodology and approximately 7,300 m^3 using the LPR approach. The 52% reduction in remedial volume accounted for an average savings of approximately $1,439,000. Average GHG emissions and fuel consumption were also reduced by approximately 61%. A summary of the case studies is provided in Table 5 below.

Table 5 Comparative Results of Conventional versus LPR Approaches to Remedial Objectives

Case Study	Predominant LPR	Remediation Volume (m^3)		Fuel Consumption (L)		Remediation Costs ($)		Savings ($)
		Conv.*	LPR	Conv.*	LPR	Conv.*	LPR	
BC 1	DW	225	77	3,900	1,400	62,200	35,500	26,700
BC 2	DW & EcoContact	42,000	20,500	735,200	360,000	7,535,800	3,690,000	3,845,800
BC 3	DW	3,700	1,200	64,500	21,100	661,500	216,000	445,500
Average	-	15,300	7,300	267,900	127,500	2,753,200	1,313,800	1,439,300

* Conv. (Conventional Remediation Objective Approach)

5.0 SUMMARY OF ALBERTA LPR STUDIES

In addition to the BC research, MEMS is currently assessing the applicability of LPR assessment for contaminated sites in Alberta. In most cases, assessment, remediation and subsequent reclamation of contaminated sites in Alberta are driven by the regulatory requirement that contaminated sites meet guidelines that are protective of all receptors and exposure pathways which are linked, by definition, to a given land use. Unless receptors and exposure pathways can be excluded on a site-specific basis, where permitted under the Alberta Environment and Parks (AEP) Tier 2 process, the guidance requires that all receptors associated with the respective land use be considered as being present (AEP 2016). There is no ability to adjust the remediation process to account for sites where the receptor or pathway does not exist, and is unlikely to occur in the future (*i.e.*, LPRs). Some examples of potential LPRs MEMS is currently investigating in Alberta include: dugouts, domestic water wells, residences, market gardens, cultivated land replacing pastures, rooting depths, and non-present ecological species. Key potential impacts at sites subjected to remediation in the absence of a governing receptor include: production of GHGs, inflated remediation costs, damage to Alberta's infrastructure, increased traffic accidents and unnecessary use of resources such as landfill capacity.

Thus, for a certain number of sites in Alberta, remediation criteria are driven by non-existent receptors or pathways (LPRs) which may occur in the future without consideration of the impacts associated with remedial activities. MEMS hypothesised that under LPR conditions, remediation of a site will cause adverse effects to the environment, inflate remediation costs, and negatively impact Alberta's infrastructure and financial resources without any socio-environmental benefits in return.

The results of two Alberta case studies are discussed below to further support the applicability of potential LPR assessment in B.C.

5.1 Alberta Case Studies

The Alberta case studies identified for LPR assessment included a site located in an agricultural White Area northeast of Calgary and a site located in a Green Area northeast of Edmonton (White and Green Management Areas are defined as per Government of Alberta 2012). For each site, Phase 2 environmental assessments were reviewed to identify concentrations of contaminants and receptor pathways affected. An overview of the two AB Case Studies is provided in Table 6. Receptor pathways associated with dugouts, domestic water wells, and ecological direct contact were identified for further analysis using an LPR approach. Potential impacts from GHGs and differences in the consumption of diesel fuel and financial costs between conventional remediation and LPR approaches were also evaluated for each site.

Table 6 Alberta Case Study Overview

Alberta (AB) Case Study	Land Use	Contaminants	Remediation Volume (m^3)	Estimated Cost of remediation	AEP* Soil and Groundwater Remediation Standards Exceeded for Pathway? Eco Soil Direct Contact	Domestic Use Aquifer (DUA)	Fresh Water Aquatic Life (FWAL)	Livestock Dugout
AB 1	Agricultural	Salts and Hydrocarbons	19,400	$1,428,600	Yes	Yes	No	Yes
AB 2	Natural/Grazing	Hydrocarbons	500	$98,400	Yes	Yes	No	No

**AEP Tier 1 and 2 Remediation Guidelines (AEP 2016)*

5.1.1 AB Case Study 1 Summary

The AB Case Study 1 is located within cultivated agricultural land near Stettler, Alberta. The site is a former tank battery and wellsite. The closest permanent residence is approximately 800 m northeast of the site. The nearest surface water body is a dugout, measuring approximately 20 m x 40 m, located approximately 200 m east-northeast of the eastern site boundary. Other dugouts are present at a distance of approximately 500 m to 800 m in a generally downgradient direction from the Site (south through southeast).

Historical site assessments identified the following PCOC were elevated compared to Tier 1 guidelines:

- elevated hydrocarbon concentrations consistent with weathered crude oil were present at high concentrations (>100,000 mg/kg total PHCs) to the north and within the former flare pit and were generally limited to the top 1.5 m of the soil profile;
- elevated boron concentrations were identified at multiple locations of the site; and
- elevated salt concentrations were identified in the southern portion of the site and in the temporary work spaces to the southeast and south of the site.

Of the approximately 19,400 m^3 of affected soil, approximately 1,500 m^3 of hydrocarbon and associated boron exceedances (that co-localize with the hydrocarbons) are expected to be excavated and disposed at an approved landfill. The remaining affected area, consisting primarily of elevated salt concentrations, is assessed in subsequent sections of this report. Tier 1 guideline exceedances for salinity have been noted for the DUA, livestock watering (dugout) and ecological direct soil contact pathways. Current impacts to dugouts or a DUA have not been identified at the site. Additionally, current and future impacts to the ecological direct contact pathway are not expected. The rationale for these conclusions is summarized below.

DUA pathway:

- Currently, there are no domestic use water wells at the site.
- A previous assessment showed that the shallow geological unit does not qualify to be a DUA.
- Based on the MEMS Tier 2C salt model, chloride concentration in a potential DUA (assumed to be directly below 17.1 m bgs, the depth of the deepest borehole drilled at the site) was predicted to reach a maximum of 282 mg/L in 250 years.
- A concentration of 282 mg/L exceeds the drinking water guideline of 250 mg/L, which is not a health based guideline but an aesthetic objective.

Dugout:

- The nearest surface water bodies to the site are dugouts (no natural water bodies were identified in vicinity of the site), with the closest dugout located approximately 200 m east-northeast of the eastern site boundary.
- Based on the MEMS Tier 2C salt model, chloride concentrations at the groundwater-surface water interface of the nearest existing dugout downgradient of the site will not exceed the guidelines protective of freshwater aquatic life (120 mg/L) during a 1,000-year time frame.

Ecological direct contact pathway:

- The majority of chloride mass is located between 2 and 4 m below ground surface. Previous work (PTAC 2013) confirmed that the vast majority of soil invertebrates are present in the top 1.5 m of the soil profile and would not be affected by deeper salt concentrations.
- Soil salinity below the rooting zone (below 1.5 m) is not expected to directly affect plant growth.
- Available data indicate that deeper salinity is not likely to migrate into the rooting zone at the site due to the following reasons:
  - a detailed daily water balance model, using Hydrus 1-D (MEMS 2014), predicted a net downward water flow through the vadose zone; and

- an indicator parameter (sulphate) examined within background boreholes showed there was no evidence of sulphate accumulation in surface soil which would be expected from long term movement of moisture upwards through the vadose zone.

5.1.2 AB Case Study 2 Summary

The AB Case Study 2 is located within a forested area northeast of Edmonton, Alberta. The site includes a former decommissioned Steam Plant and multiple associated well sites. A small creek runs through the southwest corner of the Site to an unnamed surface water body approximately 400 m northwest of the Site. A potential dugout is located approximately 350 m west of the site. The nearest surface water body is a potential dugout in the southwest corner of the site. The nearest residence is 320 m northwest of the site. Land uses surrounding the Site include both agricultural and natural area. The site is primarily being used as a grazing lease.

Historical site assessments identified elevated hydrocarbon concentrations, compared to Tier 1 guidelines, for F2 and F3 fractions within the top 3 m of ground surface. Natural land use guidelines (with livestock grazing) would apply to the site since a more sensitive land use (*i.e.* agricultural land use) is not located within 30 m of impacted wellsites. Additionally, surface water bodies were not located within 300 m of any identified guideline exceedances.

Total volume of hydrocarbon impacted soil at site 2 is estimated to be approximately 500 m^3. Tier 1 guideline exceedances for hydrocarbons have been noted for the DUA (F2 only) and ecological direct soil contact pathways. Based on vegetation assessments completed since 2000, vegetation on-site has slowly re-established on the sandy soil and withstood livestock grazing pressure. Disturbed areas with and without elevated hydrocarbon parameters appear comparably vegetated. This suggests that the elevated hydrocarbon concentrations are not limiting vegetation establishment on-site. Regulators have previously indicated to MEMS that they favour minimal surface disturbance remediation methods due to the difficulty of re-vegetation in the sandy soil present at the site.

5.2 Overview and Methodology

The overall objectives of the Alberta LPR analysis were to predict the probability analysis of future relevant receptors (specifically, dugouts, domestic water wells, and ecological direct contact) within the extent of contamination at each site, and to assess the costs and benefits of remediating the sites for the protection of the potential LPRs (*i.e.*, receptors not currently present). An overview of the methods MEMS has developed for assessment of dugout and domestic water wells are provided below; the methods for assessment of ecological direct contact as a potential LPR are still under development, and therefore can not yet be presented.

5.2.1 Dugout Assessment

The data used for dugout assessment was based on the recently released land use footprint datasets by the Alberta Biodiversity Monitoring Institute (ABMI 2016). The ABMI site level human footprint dataset contains anthropogenic disturbance features, including dugouts and other surface features, collected from 3 km x 7 km tiles distributed evenly across the province. The datasets are available from 1999 to 2014.

The cumulative number of future dugouts present in a tile at any given time was predicted using the ABMI data. Initially, this prediction was made by fitting the trend from the ABMI dugout data to a linear function. This approach was expected to be a conservative overestimation of the probability of future dugouts since the maximum number of dugouts will be dependent on the capacity of the area to sufficiently support farm water requirements. A second non-linear approach, which considered the maximum theoretical limit (*i.e.* maximum dugout capacity), was also used to provide a more realistic prediction of the cumulative number of dugouts in the tile at a given time (Figure 5).

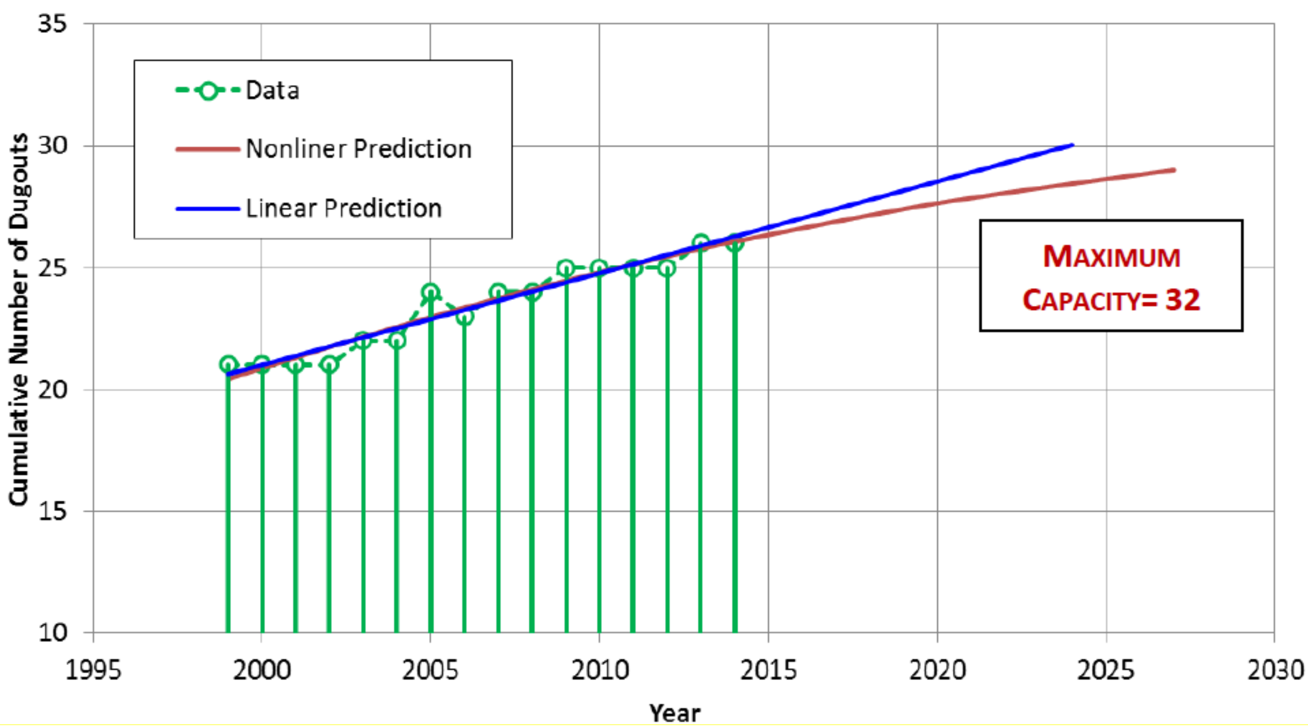

Figure 5 Prediction of future dugouts using data from an ABMI Tile Dataset.

The cumulative number of dugouts calculated using the linear prediction model was higher than the number calculated using the non-linear model. Additionally, the values calculated using the linear model exceeded the maximum theoretical limit for the number of possible dugouts in the given area, which is based on the maximum capacity of the area to sufficiently support farm water requirements.

The probability of at least one future dugout occurring within the area of impact was estimated using a cumulative binomial distribution function applied to the cumulative record of dugouts occurring in each ABMI tile. The probabilities of at least one dugout occurring in the area of impact for the AB Case Study 1 are presented in Table 7 below. The probabilities were calculated using both linear and non-linear prediction models. As expected, the probabilities calculated using the linear prediction model were much higher than those calculated using the non-linear model.

Table 7 Calculated Probability of a Future Dugout at AB Case Study 1

Data Source	Prediction Model	20 Years	50 Years
ABMI Tile Data	Linear	0.49%	1.23%
	Non-Linear	0.13%	0.33%

Future dugout probability was also expressed as a unit probability in percent/annum/hectare using the linear model. The unit probability was considered to appropriately demonstrate regional variation of future dugout probability and does not require site-specific data for the area of impact or a time period (Table 8).

Table 8 Future Dugout Unit Probability (%/Annum/Hectare) – AB Case Study 1

Data Source	Prediction Model	%/Annum/Hectare
ABMI Tile Data	Linear	0.018%

Note: The calculation is based on the 50-year predictions

For each AB Case Study, the calculated unit probabilities were plotted on a map for the township surrounding the site. The results from AB Case Study 1 are presented in Figure 6. The unit probabilities for the tile were extrapolated to the township. A unit probability of 0.018%/annum/hectare was calculated for the area of impact on for AB Case Study 1; this probability is within the mid-range calculated for the region.

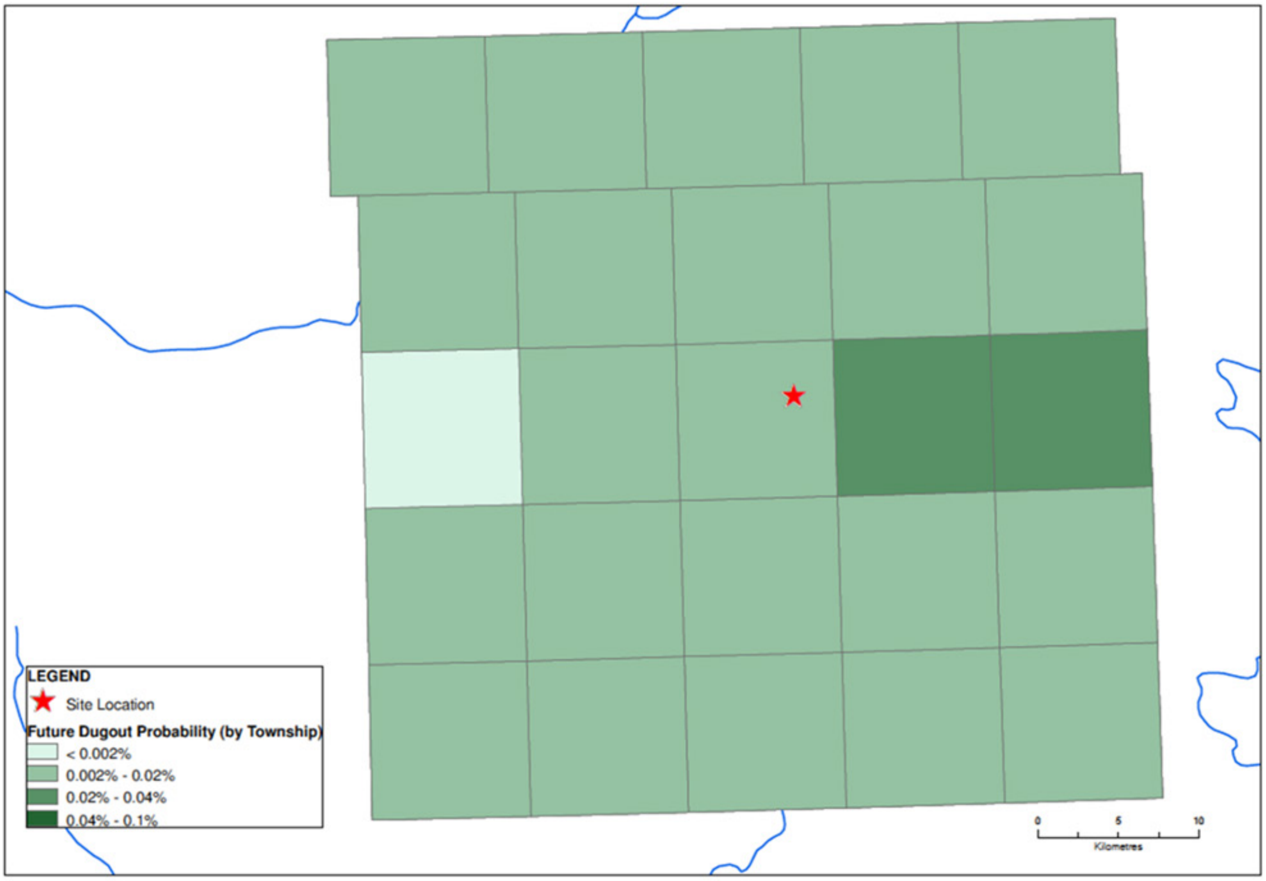

Figure 6 **Probability of future dugouts (% Probability/Annum/Hectare) for 25 townships surrounding AB Case Study 1.**

5.2.2 Domestic Water Well Assessment

The data used for the domestic water well assessment were from the AEP Water Well Information Database (October 2016) and the AEP Baseline Water Well Testing (BWWT) Database (October 2016). These data sources included well installation dates, information on water well locations, completion depths, and proposed use of the water wells.

The AEP Water Well Information Database contains records for water wells drilled in the province of Alberta. It has only been mandatory since the mid-1970s for water well drillers to submit drilling reports to the AEP Water Well Information Database and, as a result, the water well dataset available from this data source may not be complete prior to the mid-1970s. Based on this knowledge, only water wells reported from 1980 to present were used in the assessment. In addition, data from the AEP Water Well Information Database was supplemented with information from the AEP BWWT database. The BWWT Database contains the data collected during the testing of water wells in relation to Coal Bed Methane (CBM) development in the province. This testing became a requirement in 2006. The data includes GPS coordinates for the wells tested and documentation of additional water wells, if the tested well was not present in the AEP Water Well Information Database.

All the geographical locations and dates of installation of water wells drilled at varying depths were identified in vicinity of each case study. Prediction of the cumulative number of future water wells was made using the two data sources for historical water wells. The predictive models used were generally the same as those used for future dugouts; however, water well probabilities were also subdivided by completion depth. The cumulative number of water wells in the townships surrounding each AB case study were calculated for different depth intervals (0-10 m, 10-20 m., 20-30 m and depths greater than 30 m). As an example, Figure 7 presents the AB Case Study 1 results for the 0 - > 30m interval and Table 9 shows the cumulative number of new water wells predicted for the township containing AB Case Study 1 over the next 20 and 50 years for varying depth intervals.

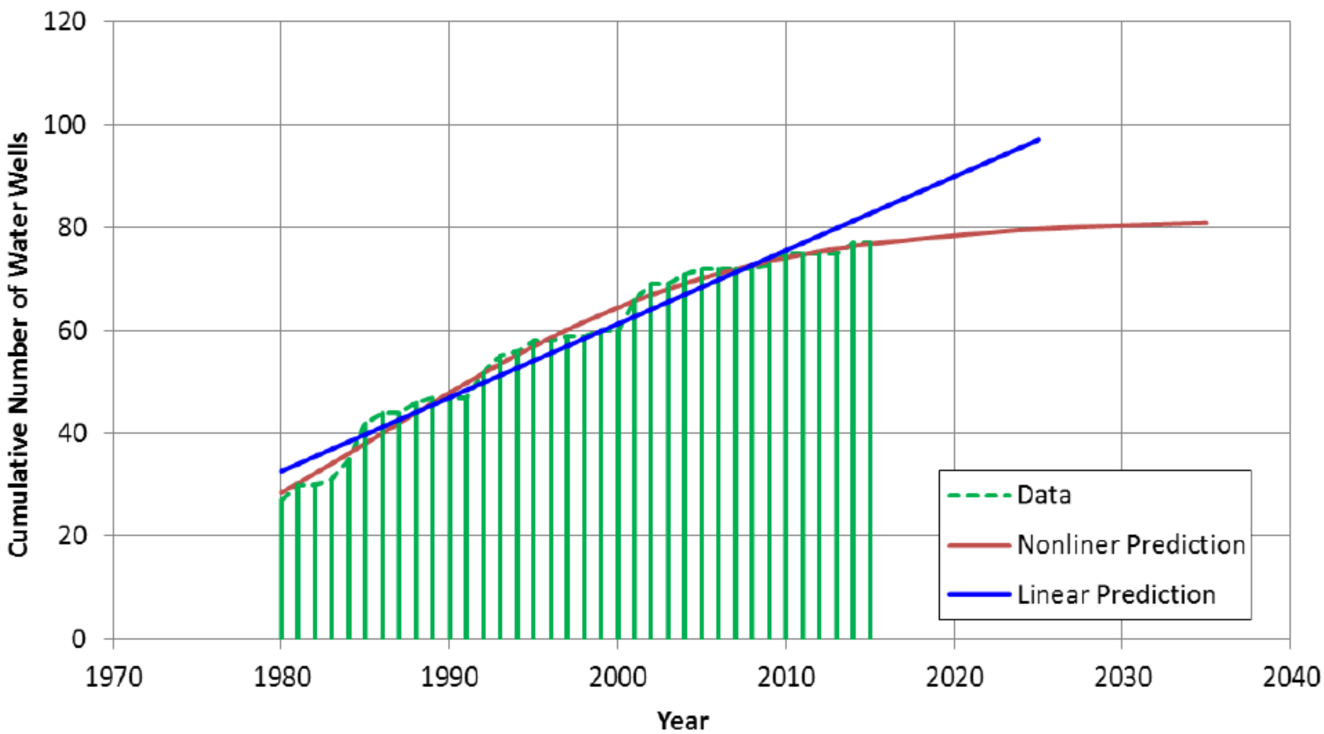

Figure 7 **AB Case Study 1 - Cumulative number of water wells and predictions >30 m depth interval.**

Table 9	**Cumulative Number of New Water Wells in the Township of AB Case Study 1**		
Depth Interval	**Prediction Model**	**20-Year Prediction**	**50-Year Prediction**
0-10 m	Linear	2	5
	Non-Linear	1	1
10-20 m	Linear	9	22
	Non-Linear	1	1
20-30 m	Linear	7	18
	Non-Linear	1	1
>30 m	Linear	29	72
	Non-Linear	3	4

The probability of at least one future water well occurring within the area of impact was estimated using a similar cumulative binomial distribution function as used for the prediction of dugouts a LPR. For AB Case Study 1 the estimated probabilities for at least one water well occurring in the area of impact are presented in Table 10 below. The probabilities were calculated using both linear and non-linear prediction models. As expected, the probabilities calculated using the more conservative linear prediction model were much higher than those calculated using the non-linear model.

Table 10	**Calculated Probability of a Future Water Well at the Site**		
Depth Interval	**Prediction Model**	**20-Year Prediction**	**50-Year Prediction**
20-30 m	Linear	0.04%	0.09%
	Non-Linear	0.005%	0.005%
>30 m	Linear	0.08%	0.2%
	Non-Linear	0.01%	0.01%

Future water well probability was also expressed as a unit probability in percent/annum/hectare using the linear model. The unit probability was considered to appropriately demonstrate regional variation of future well probability and does not require site-specific data for the area of impact or a time period. Table 11 below summarizes the calculated unit probabilities for the two depth intervals assessed for AB Case Study 1.

Table 11 **AB Case Study 1 - Future Water Well Unit Probability (%/Annum/Hectare)**		
Data Source	**Prediction Model**	**%/Annum/Hectare**
20-30 m	Linear	0.002
>30 m	Linear	0.0062

The calculated unit probabilities for 25 townships surrounding the AB Case Study 1 are shown in Figure 8 for >30 m depth intervals. In the Alberta assessment, MEMS performed the same calculations for all depth intervals, for both AB Case Studies.

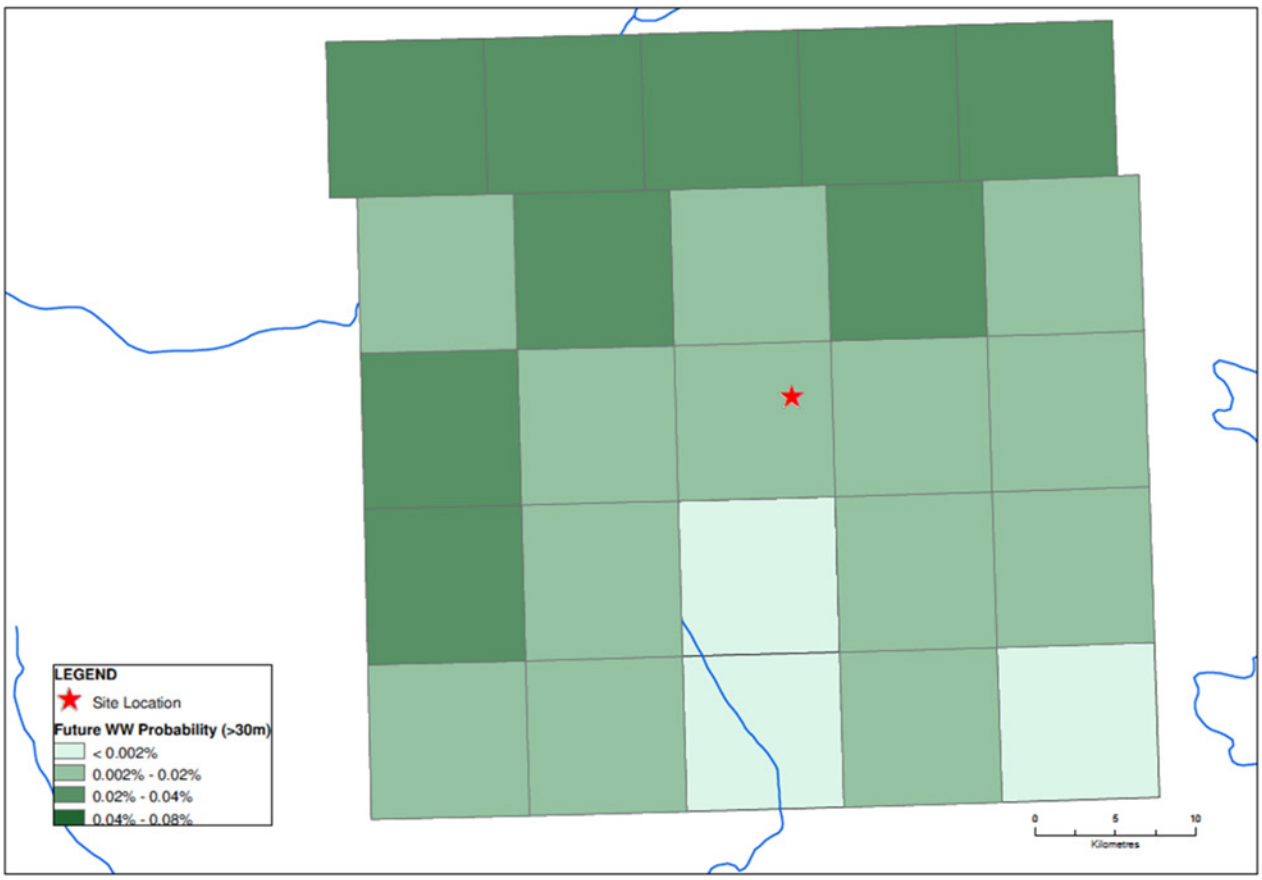

Figure 8 **AB Case Study 1 - Probability of future water wells (%probability/annum/hectare) for wells completed at a depth of >30 m.**

5.2.3 Remediation Costs, Fuel Consumption and GHG emissions

The same methods described in Section 4.0 were applied to the AB Case Studies 1 and 2 to determine costs associated with conventional remediation and remediation with LPR assessment, estimate fuel consumption, and GHS emissions. The results of which are illustrated in Figures 9 and 10.

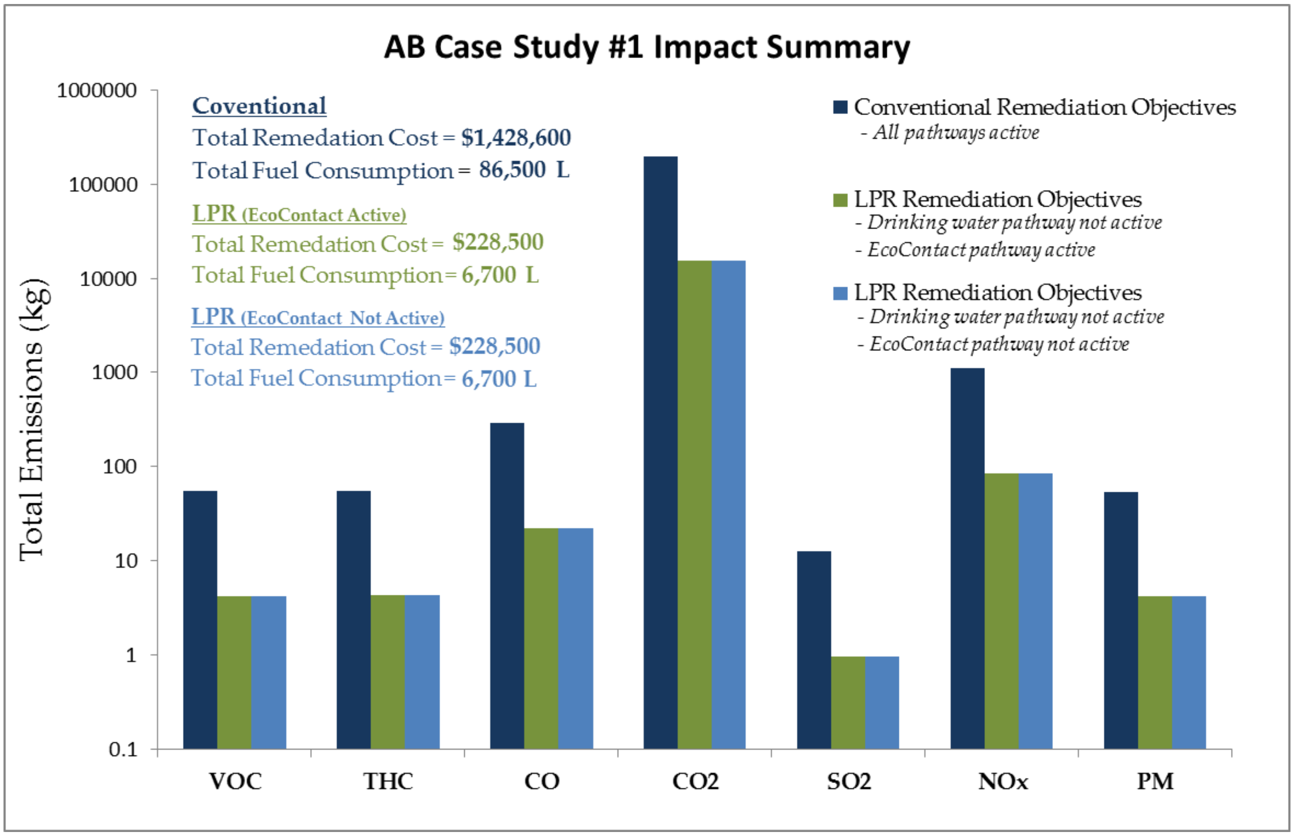

Figure 9 AB Case Study 1 - Comparative fuel consumption and total GHG emissions for conventional remediation versus MEMS LPR approach.

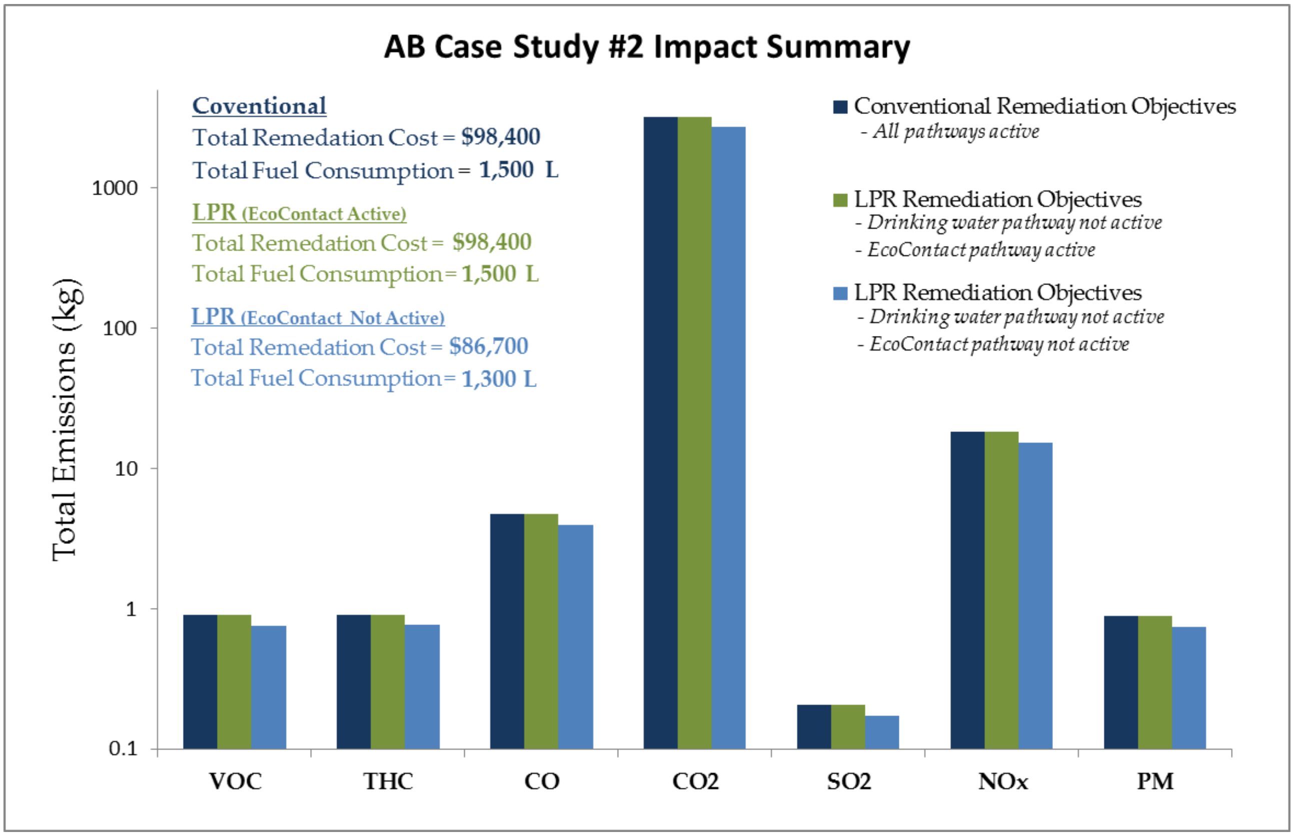

Figure 10 AB Case Study 2 - Comparative fuel consumption and total GHG emissions for conventional remediation versus MEMS LPR approach (assuming elimination of eco direct contact pathway).

The results demonstrate difference between the two cases with respect to remediation costs and the type of LPR. Assessment of dugout and water wells drive the differences in remediation volumes and remediation costs for Case Study 1. Whereas for AB Case Study 2, these parameters only change substantially when ecological direct contact is identified as an LPR and the potential accordance of a dugout or domestic water wells does not reduce remediation costs or potential GHG emissions.

Additional assessment of the cost associated with each LPR assessment and standards achieved was conducted for AB Case Study 1 to determine the sensitivity of each parameter with respect to changes in cost (Figure 11).

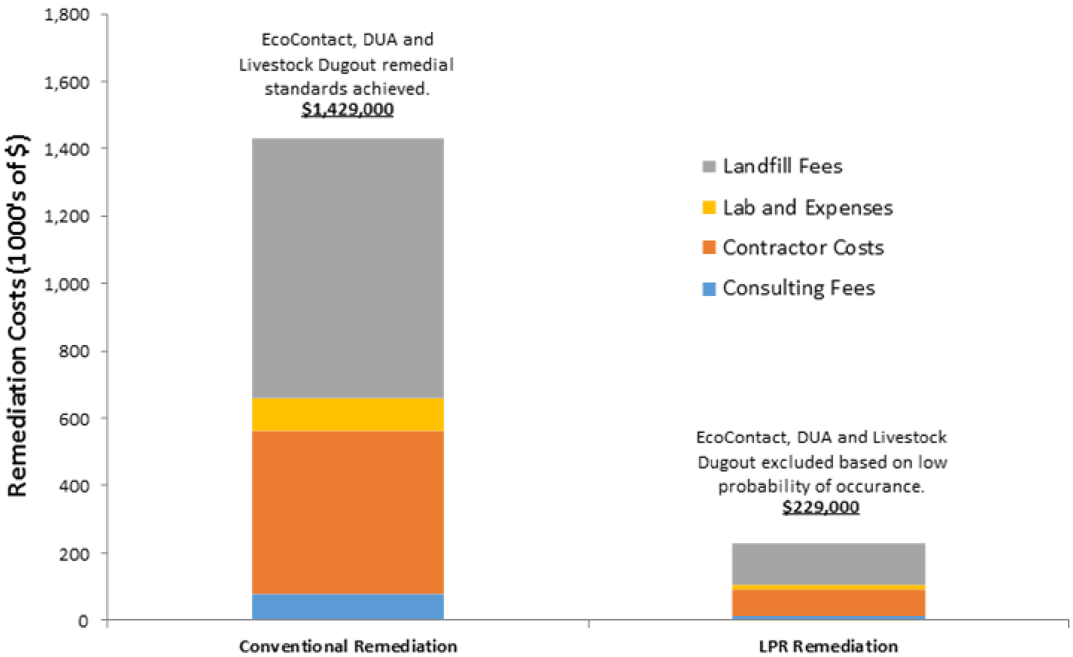

Figure 11 Projected cost estimates for various remedial options for AB Case Study 1.

5.3 Key findings

The overall objective of the LPR analysis was to calculate the probability of future occurrence of dugouts and water wells in the vicinity of two AB Case Studies and to assess financial and environmental costs associated with remediating each site for the protection of receptors that are not currently present. When compared to an LPR approach, the use of conventional remediation at each site to protect potential impacts to future LPRs was demonstrated to result in potential increased expenditures (Table 12), increased fuel consumption and increased GHG emissions (Table 13).

Table 12 Comparison of Impacts of Conventional Versus LPR Remediation

Case Study	Remediation Volume (m^3)		Fuel Consumption (L)		Remediation Costs ($)		Savings ($)
	Conv.†	LPR	Conv.†	LPR	Conv.†	LPR	
AB 1*	19,400	1,500	86,500	6,700	1,428,600	228,500	1,200,100
AB 2**	500	388	1,500	1,300	98,400	86,700	11,700

* Reduction in in remediation volumes and costs demonstrated with dugout and domestic water wells identified as LPR.
** Reduction in remediation volumes and costs demonstrated with ecological direct contact identified as an LPR.
† Conv. (Conventional Remediation Objective Approach)

Table 13 Change in Fuel Consumption and GHG Emissions of Conventional Remediation Versus LPR Remediation

Case Study	Emissions	Remedial Volume	Fuel Consumption	Remediation Costs
	Percent Reduction (%)			
AB 1*	92%	92%	92%	84%
AB 2**	16%	16%	16%	12%

* Reduction in in remediation volumes, fuel consumption, and remediation costs demonstrated with dugout and domestic water wells identified as LPR.
** Reduction in remediation volumes fuel consumption, and remediation costs demonstrated with ecological direct contact identified as an LPR.

Currently, there are no domestic use water wells at either Alberta site nor are there any dugouts likely to be impacted by existing contamination. Therefore, impacts to these receptors do not currently exist and there is no current risk. Application of conventional remediation will result in 100% chance of increased expenditures and GHS emissions, with a low likelihood of risk reduction due to the low probability of future LPRs being present in impacted areas of the site.

5.4 Applicability to BC

Although in BC, the irrigation and livestock watering water uses are not as relevant due to the ability to exclude future use for these purposes under Protocol 21, the results of the dugout LPR assessment in Alberta serves to demonstrate that the LPR assessment methods can reduce remediation costs and environmental impacts associated with conventional remediation if LPR assessment is include in contaminated sites assessment. Currently, the focus of the Albertan research has been on the estimation of probability of dugouts and water wells as LPR both of which are influential as LPRs under the Alberta framework. Application of LPR assessment methods has demonstrated that there can be a substantial reduction in remediation volumes and GHG emissions without impacting the potential risk of adverse health effects associated with exposure to contamination.

The AB study developed mapping methods and statistical approaches to assess the likelihood of future groundwater wells as a basis to support drinking water use as a potential LPR. Given that DW use has been demonstrated in the BC case studies to be influential on remedial costs and impacts, the mapping and analysis tools developed and applied in Alberta could be extended to BC, particularly in more populated areas, to support consideration of DW use as an LPR in areas where it may not be possible to exclude it under Protocol 21.

Although only briefly discussed herein, ecological soil contact was considered as a potential LPR in the Alberta case studies and work is currently ongoing as part of a separate research initiative to determine whether it can be supported. Given ecological soil contact was also identified as an influential pathway in one of the BC cases, this additional work may also be applicable to BC.

6.0 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS FOR NEXT STEPS

The application of LPR assessment methods developed by MEMS to three BC case studies, as well as parallel work conducted in Alberta, has demonstrated the potential for the costs and environmental impacts of remediation to be reduced without increasing the potential risk of adverse effects associated with the residual contamination.

Existing regulatory guidance and protocols in effect in BC, particularly Protocol 13 (SLRA) and Protocol 21 (Water Use Determination), allow for limited consideration of LPRs on a site specific basis. In addition, site-specific remediation to risk-based standards, which can in principle allow for the inclusion of other probabilistic considerations, is also a regulatory option. However, one of the objectives of the present study, and the ongoing LPR initiative, is to explore the potential for the LPR concept to be “systematized” such that LPRs can be considered more broadly, for example on a local regional basis under the application of numerical standards.

In this regard, and in the BC regulatory context, the results demonstrate that DW use is a potential “high value” LPR in terms of remedial cost and impact reduction, whereas considering irrigation (IW), livestock watering (LW) and aquatic life (AW) water uses as LPRs is already somewhat accommodated under Protocol and does not offer substantial incremental benefits in BC. Given that Protocol 21 requires future DW use to be considered, further research into the ability and data requirements to justify DW as an LPR, where appropriate, should be considered. This work could include water well mapping and temporal statistical analysis of the probability of future wells on a regional basis in BC, similar to the research completed in Alberta.

Additionally, ecological direct contact (toxicity to soil invertebrates and plants) appears to offer potential benefits as an LPR in BC depending on the contaminants of concern. For both Alberta and BC, assessment of ecological direct contact could be a significant parameter for LPR research, and there is a potential for the combination, or harmonization, of assessment methods under future stages. It is expected that incorporation of ecological direct contact in the LPR approach would focus on regional species and rooting depths, but additional work in this area is required.

Parallels can be drawn between the results of the Alberta LPR assessment and potential assessment of LPRs in BC. Methods developed through the Alberta research also have potential benefits in BC when considering DW and ecological direct contact as LPR. In particular, development of water well mapping methods and statistical analysis methods based on BC data sources is identified as having potential benefits in BC site management, especially when extended to sites occurring in more populated areas of the Province.

Based on the results of the current assessment, the following next steps are recommended:

- identify additional BC case study sites in more populated areas with DW as potential LPR. This would allow for region-specific probability mapping of DW similar to that conducted in MEMS' Alberta research;
- further investigate the influence of the ecological direct contact pathway at additional BC sites to confirm the potential benefit application of LPR assessment could make on contaminated site assessment. This will require more detailed assessment of this pathway as an LPR to define plant rooting depth and species types, to allow for the subsequent development of probability mapping methods. As similar research is ongoing in Alberta, where possible, the combination of resources to evaluate this as a potential LPR could provide a beneficial outcome; and
- identify additional case study sites in agricultural land use (or other areas with greater human use) to assess whether other potential human pathways could be considered LPRs (e.g. vapours). Depending on the availability of BC and Federal data sources, potential LPR surrogates representative of the vapour inhalation pathway could be land use itself, or the occurrence of buildings. The probability of exposure occurring *via* vapour inhalation could be mapped based on the likelihood the LPR occurs.

7.0 LIMITATIONS OF LIABILITY AND CLOSURE

This report pertains solely to the low probability receptor analysis for the BC Oil and Gas Research and Innovation Society. Information obtained by site investigation or provided by third parties is believed to be accurate and reflective of site conditions, but is not guaranteed. The assessment was conducted using industry accepted hydrogeological practices to satisfy the requirements of the applicable regulations, approvals and/or directives. Millennium EMS Solutions Ltd. has exercised reasonable skill, care, and due diligence in assessing the information acquired during the preparation of this report.

The BC Oil and Gas Research and Innovation Society and their working interest partners may rely on this report for specific application to this research. The report may not be relied upon by any other person or entity without Millennium EMS Solutions Ltd.'s written consent and that of the BC Oil and Gas Research and Innovation Society. Any uses of this report by a third party, or any reliance on decisions made based on it, are the responsibility of that party. Millennium EMS Solutions Ltd. is not responsible for damages or injuries incurred by any third party, as a result of decisions made or actions taken based on this report.

Yours truly,

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