MILLENNIUM
EMS Solutions Ltd.

6111 91 Street
Edmonton, AB T6E 6V6
tel: 780.496.9048
fax: 780.496.9049

Suite 325, 1925 18 Avenue NE
Calgary, AB T2E 7T8
tel: 403.592.6180
fax: 403.283.2647

#106, 10920 84 Avenue
Grande Prairie, AB T8X 6H2
tel: 780.357.5500
fax: 780.357.5501

10208 Centennial Drive
Fort McMurray, AB T9H 1Y5
tel: 780.743.4290
fax: 780.715.1164

toll free: 888.722.2563
www.mems.ca

Treatment of Saline Water

Prepared for:
Canadian Association of Petroleum Producers (CAPP)
c/o Petroleum Technology Alliance Canada (PTAC)

Prepared by:
Millennium EMS Solutions Ltd.
Suite 325, 1925 – 18th Avenue NE
Calgary, Alberta
T2E 7T8

April 2013
File # 12-332

Executive Summary

Petroleum Technology Alliance Canada (PTAC) is investigating the feasibility of treating saline water from source water wells to criteria that would allow storage in unlined earthen reservoirs and transportation via overland pipelines. The objective of this study is to develop risk-based guidelines that would dictate the level of treatment required to store saline water in this manner.

The scope of work included a comprehensive regulatory review, development of risk-based criteria for the treatment of saline water, and an evaluation of potential liabilities.

PHASE I: Regulatory Review

Review of Existing Guidelines for Saline Water Storage and Transport

Guidelines related to saline water from regulatory agencies in North America were reviewed and summarized. For the purposes of the review it was assumed that the treated water would retain ion concentrations above natural background levels associated with groundwater and would be considered saline. Alberta defines groundwater with over 4,000 mg/L total dissolved solids (TDS) as saline and non-potable, a definition which has also been adopted by British Columbia, Saskatchewan, and Manitoba.

Groundwater Quality Data in the Pipestone and Gordondale Areas

Groundwater quality data for the Pipestone and Gordondale areas of Alberta were compiled and evaluated. Sufficient data could not be found for the Gordondale area; therefore, data from the Pipestone area was considered to be representative of the entire study region. The waters analysed in the Pipestone area were found to have a mean TDS content less than 1,500 mg/L and were potentially potable.

Development of Risk Based Criteria

Two scenarios were developed: storage of 50,000 m^3 of water with a pre-treatment TDS of 20,000 ppm, and storage of 15,000 m^3 of water with a pre-treatment TDS of 2,000 ppm. These initial conditions were used as a starting point to derive risk based criteria, as the water will be treated before entering storage and will not include any other contaminants related to oil and gas processes.

Both human and ecological receptors were considered, exposed through ingestion and contact with impacted groundwater, respectively. Direct contact with saline water in the storage ponds is not considered a hazard to human or ecological receptors.

No existing models were identified that were directly applicable to the scenarios being modelled, and so existing models were adapted. Preliminary modeling was undertaken using the Subsoil Salinity

Tool (SST v2.5.2) and a modified version of the groundwater model used by Alberta Environment and Sustainable Resources Development (ESRD) to derive the Tier 1 and Tier 2 guidelines. The purpose of this preliminary modelling was to generate an expected range for salinity guidelines that would be applicable for unlined ponds. A sensitivity analysis was conducted by varying model input parameters within potential ranges.

Results

The 5th percentile value of all SST model runs from the sensitivity analysis, 5000 mg/L TDS, was selected as a representative guideline that would be protective of the vast majority of sites; no cases evaluated in the sensitivity analysis resulted in guidelines below this value.

Phase II: Risk and Potential Liability

Methodology

The liability assessment uses a fault tree/event tree approach that considers a number of release scenarios. The total liability associated with transporting and storing saline water would be the expected cost multiplied by the unit probability of failure aggregated over the number of kilometres of pipeline or number of storage facilities.

Scenarios and Probabilities of Failure

The expected costs for remediation of six release scenarios were calculated. These scenarios included both catastrophic and gradual releases from: pipelines, lined ponds, and unlined ponds. For each of the six scenarios, four possible spill types were considered, including: large volume of untreated saline water, small volume of untreated saline water, large volume of treated saline water, and small volume of treated saline water.

It was assumed that only treated water would be stored in unlined ponds, and that untreated water would be transported by pipeline or stored in lined ponds. The treated water would meet the derived criteria for storage, but the risk of impact would arise as a result of a greater rate of release than that assumed in the modelling.

Four common options for remedial action were included in the analysis:

- excavation of small soil volumes (or source excavation);
- excavation of large volumes of soil;
- groundwater remediation (assumed to be by recovery and treatment/disposal); and
- risk management of groundwater plume (in conjunction with source removal).

Results

Liability was similar between unlined and lined ponds, with an expected cost of $1.131M for lined excavations and $1.607M for unlined excavation. Liability for pipelines was lower, at $0.265M per km of pipeline. Additional consideration of site placement, pipeline length, and design lifetime are required in order to accurately compare the expected costs of remediation between these methods.

Table of Contents

List of Tables

Page

List of Appendices

1.0 INTRODUCTION

Petroleum Technology Alliance Canada (PTAC) is investigating the feasibility of treating saline water from source water wells to criteria that would allow storage in unlined earthen reservoirs and transportation via overland pipelines. This would facilitate the use of treated saline water instead of freshwater for hydraulic fracturing operations. The objective of this study is to develop risk-based criteria that would dictate the level of treatment required to store saline water in this manner, as per related regulations. The area of study is within the Pipestone and Gordondale areas in Alberta.

This study has been divided into two phases. The first phase is a comprehensive review of regulations related to the definition, treatment, and storage requirements for saline water. This aspect of the project also includes a review of the existing groundwater quality in the study area and a literature review of related studies. This information has been used to derive preliminary risk-based guidelines for the required level of saline water treatment.

The second phase of the project is a life cycle assessment that examines and compares the use of fresh and saline water for hydraulic fracturing, and makes recommendations for each approach based on the geographical context of the study area and estimated liability from accidental release and remediation.

2.0 PHASE I: REGULATORY REVIEW

Guidelines related to the definition, treatment, and storage of saline water from regulatory agencies in Canada and the United States were reviewed, with specific attention directed towards those agencies regulating oil and gas activities in Alberta and British Columbia. The primary agencies reviewed were: Alberta Environment and Sustainable Resource Development (ESRD), the Alberta Energy Resources Conservation Board (ERCB), BC Environment, and the BC Oil and Gas Commission (BC OGC). For the purposes of the regulatory review it was assumed that the treated saline water would retain ion concentrations above natural background levels associated with groundwater and would be considered saline. If the treated water meets or exceeds background water quality it would be considered fresh water, which is covered by the Alberta *Water Act* (Province of Alberta, 2000) or BC *Water Act* (British Columbia, 1996).

2.1 Review of Existing Guidelines for Saline Water

Alberta defines groundwater with over 4,000 mg/L total dissolved solids (TDS) as saline and non-potable, a definition which has also been adopted by British Columbia (BE MOE, 2005), Saskatchewan (Saskatchewan Watershed Authority, 2005), and Manitoba. In Alberta, ERCB regulates saline water produced through the dewatering process and the subsequent disposal of this water, often in saline aquifers, whereas non-saline water is regulated by ESRD. Production and disposal of saline water is monitored and disposal using injection wells is regulated. Disposal of saline water is not permitted above the base of groundwater protection under the Water Act in Alberta. The BC Ministry of Environment (BC MOE) allows for the discharge of produced water to ground only if TDS concentrations are less than or equal to twice the TDS of the underlying groundwater, up to a maximum TDS of 4,000 mg/L (BC MOE, 2008).

The CCME surface water quality guidelines (1999) include limits for TDS in water used for irrigation purposes and these values have generally been adopted by provincial regulators. The CCME TDS guidelines are species dependant and have values for various berries, vegetables, field crops, and forages tolerant to TDS concentrations of 500, 800, 1,500, 2,500, and 3,500 mg/L. A summary of the general guidelines and definitions for saline water is included as Table 1.

Table 1 General Guidelines and Definitions for Saline Water

Jurisdiction	Regulatory Body	Guideline (mg/L)	Receptor	Notes
Canada	CCME	250 Cl, 200 Na, 500 TDS	Drinking water	Aesthetic objectives
Canada	CCME	3000 TDS	Livestock watering	-
Canada	CCME	100 Cl, 500 TDS	Irrigation	Species dependant
Canada	CCME	120 Cl	Aquatic life	Freshwater
Alberta	ESRD, ERCB	4000 TDS	Drinking water	Water is considered potentially potable
BC	BC MOE	4000 TDS	-	Produced water discharge limit
US EPA	-	10 000 TDS	-	Water is considered potentially potable
Wyoming	-	500 TDS	Drinking water	Based on US EPA
Wyoming	-	2000 TDS	Agricultural use	-
Wyoming	-	5000 TDS	Livestock watering	-
Wyoming	-	500 TDS	Aquatic life	-
North Carolina	-	250 Cl	Drinking water	-
USGS	-	1000 TDS	-	Considered fresh
USGS	-	3000 TDS	-	Slightly saline
USGS	-	10 000 TDS	-	Moderately saline
USGS	-	>10 000 TDS	-	Very saline or brine
Florida	-	3000 TDS	Drinking water	-

2.2 Review of Existing Guidelines for Saline Water Storage

The majority of guidelines related to storage of saline water are related to produced water from oil and gas sources. While these guidelines are not necessarily all applicable based on the proposed sources and uses of water proposed by PTAC, they have all been included for reference. A summary of the existing guidelines for saline water storage is included as Table 2.

2.2.1 Alberta Guidelines

Three agencies were found to regulate saline water in Alberta: ESRD, ERCB, and Alberta Infrastructure and Transportation (AT). Releases of saline water from upstream oil and gas facilities are handled through ERCB and other releases by ESRD through the EPEA Release Reporting Regulations. AT has specific requirements for storage of saline water related to road salt storage and application.

ERCB Directive 050 (2012) deals with drilling waste management and includes soil salinity endpoint requirements, including maximum sodium loading rates to the receiving land. These range from 250-500 kg/ha based on the disposal method, and also include triggers for waste parameters that will require additional soil sampling based on salinity parameters. There are additional requirements for maintaining a 10 m separation between water supply wells and waste disposal area that are not directly applicable to saline water, but could be incorporated into the guideline derivation methodology. Directive 050 also contains requirements for remote waste storage sites, with the following conditions that would be applicable to saline water storage:

- the site must be secured to prevent public access;
- the water must be tied back to the original source; and
- drilling waste may not be disposed of within 100 m of a water body.

ERCB Directive 058 (1996) describes waste management requirements for the upstream petroleum industry, but these requirements are not specific to saline water. A pond may be considered a waste storage facility and therefore may be required to comply with Section 11.0 of the ERCB Guidelines on Oilfield Waste Management Facilities. The following documentation would be required:

- monthly inventory balance; and
- receipts describing the volume, source, generator, and type of all waste received.

Requirements for oilfield landfills prohibit placement within 300 m of any area containing permanent surface water or any water supply, including wells. 30 m of delineated vertical separation from a domestic use aquifer (DUA) must be achieved, or a 10 m separation from fractured bedrock. Placement within a recharge area of an unconfined aquifer is also prohibited. It should be noted that the ERCB definition of a DUA is not consistent with the definition used by the ESRD. ERCB (1996) requirements for a DUA are that the water must meet domestic use quality standards and have a transmissivity of $5x10^{-4}$ m^2/s or greater, while ESRD (2010b) specifies that any geologic unit with a bulk hydraulic conductivity greater than $1x10^{-6}$ m/s of sufficient thickness to support a yield of 0.76 L/min is a potential DUA. Landfill cells are also required to remain at least 1.5 m above the seasonal high water table. Performance requirements for waste disposal facilities that must be monitored include TDS, with a limit of 2,000 mg/L in groundwater.

ERCB Directive 055 (2001) describes storage requirements for the upstream petroleum industry, including lined excavations. There are no guidelines for using unlined excavations for storage. There is a general limit on storage duration of 1 year. Some form of secondary containment is required for lined earthen excavations, as well as monthly monitored leak detection systems. Storage must not be sited within 100 m of the normal high water mark of surface water or wells. Requirements for design, construction and weather protection are not specified and are to be considered based on the facility and the material to be stored. Specific requirements for the leak detection system and parameters to be monitored are outlined in Section 8.0 of the Directive.

The ESRD Salt Contamination Assessment and Remediation Guidelines (SCARG) (2001) include some discussion of saline leachate collection. It contains remediation guidelines for salt releases based on background levels, generic guidelines, or site-specific objectives. Remediation targets are intended to protect the soil rooting zone, and are defined based on background control locations and electrical conductivity (EC) and sodium absorption ration (SAR) levels. They do not specifically consider treatment or storage of saline water, and are more focused on remediation of saline spills.

SCARG does not address the definition or treatment of saline water directly; however, it does discuss regulatory requirements related to releases, reporting, remediation that are based on the Environmental Protection and Enhancement Act (Government of Alberta, 1992). The SCARG references select CCME water quality guideline for drinking water and livestock watering, with TDS guidelines of 500 mg/L for drinking water, and 3,000 mg/L for livestock watering. The most relevant aspects of SCARG are the requirements for prevention and mitigation of effects from saline water releases, and the requirement for reclamation to an equivalent land capability. The use of risk management to address salt impacts is also acceptable with approval from ESRD. While the SCARG allow for leaching of salt to below the root zone to minimize impacts, this is not an allowable disposal or treatment option under the EPEA. As the ERCB directives do not provide limits on salinity for stored water, SCARG values for soil will be used to back calculate guidelines for pond water.

AT (2010) has developed guidelines for storage of saline runoff from roadways. These guidelines prohibit the use of natural drainage courses or sewage systems for saline water, and have some basic requirements for saline water storage ponds. Secondary containment is required for brine storage, along with an environmental management plan. If saline water is stored in a containment pond, the following are required:

- pond design is to be based on annual precipitation, not unusual storm events;
- freeboard should be based on normal storm events with a designated area for additional storage;
- a minimum of one upgradient and two downgradient monitoring wells are to be installed, with one of the downgradient wells immediately adjacent to the pond;
- UV resistant heavy polyethylene liner material is required for the pond;
- a topographical survey of the site is required;
- annual inspections of the liner are required;
- a high water line indicating the maximum storage volume must be visible;
- water cannot be discharged from the containment ponds under any circumstance; and
- disposals and inspections must be logged.

2.2.2 BC Guidelines

The BC OGC (2010) accepts lined earthen excavations as an acceptable method to store produced water, but requires a minimum 1 m freeboard and control measures to prevent runoff from entering the excavation. BC guidelines require a minimum liner thickness of 30 mils and require some form of prior registration that includes providing: coordinates, volume, containment method, and descriptions of the leak detection and liner design. Storage may be limited in some cases to a maximum of 90 days for hydraulic fracturing operations, with the actual limitation based on the water source.

The BC Environment Management Act Code of Practice for the Discharge of Produced Water from Coalbed Gas Operations (2008) includes provisions for the disposal of produced water to ground. This applies only to produced water from coalbed methane exploration or production operations. If TDS concentrations are less than twice that of underlying groundwater and under 4,000 mg/L, produced water may be discharged to ground if the following conditions are met:

- other options for use/disposal are evaluated first;
- sensitive stream habitats are not impacted;
- a ground disposal facility is used;
- the facility is not located within 2km of a downgradient drinking water well;
- ongoing analysis of the discharge is completed;
- characterization of baseline conditions has been completed; and
- there has been an assessment of drinking water and irrigation uses in the area.

Table 2 Guidelines for Saline Water Storage

Regulatory Body or Guideline	Guideline
Alberta Infrastructure and Transportation	Pond lining and secondary containment is required. Storage and freeboard requirements are to be based on normal storm events. Discharge from ponds is not allowed.
ERCB Directive 050	Site must be secure. Water must be tied to original source. Cannot be within 100 m of a water body.
ERCB Directive 058	30 m delineation from DUA, 10 m delineation from fractured bedrock. Cannot be within a recharge area of an unconfined aquifer. Must be Further than 300 m from a surface water body. Must remain 1.5 m above seasonal high water table. TDS must be less than 2,000 mg/L in groundwater.
ERCB Directive 055	Excavation must be lined with secondary containment. Cannot be within 100 m of high water mark for surface water or wells. Some limitations on storage duration.
BC OGC	Excavations used for storage must be lined with material of at least 30 mil. Minimum 1 m freeboard. Registration of storage site with OGC is required.

2.3 Review of Existing Guidelines for Fresh Water Storage

In addition to the requirements for saline water storage outlined in Section 2.2, any stored treated water stored will also have to meet the guidelines for fresh water storage for Alberta and BC outlined below.

2.3.1 Alberta Guidelines

In Alberta, storage is included under the definition of 'diversion of water' in the *Water Act* (Province of Alberta, 2000), and requires a license. Depending on whether an initial licence was granted for the original saline water extraction process, an additional license or amendment to the initial license may be necessary; however, some form of approval from ESRD will be required as storage of large volumes of water is not an activity that is explicitly exempt from regulation. It is expected that an application of this type would include: the volume of water, location of storage pond with scale drawings, dimensions of the storage pond, a reservoir capacity elevation curve, landowner consent, a summary of the expected pumping activities, and any conditions related to the required level of water treatment.

While exemptions for water storage dugouts do exist, these require either agricultural or household use, and that the water is naturally impounded at a capacity under 12,500 m^3 with a maximum annual withdrawal of 6,250 m^3. AT also requires a minimum setback of 40 m from the highway property line on all primary and secondary highways. Setbacks for other roads are set by the local counties or municipalities.

2.3.2 BC Guidelines

Under the BC *Water Act* construction and use of a storage pond is a right acquired under a license, and requires completion of the Schedule 2 Dam& Reservoir Information form along with a water license application. The application will require: a drawing of the proposed storage pond, GPS coordinates, a topographical map of the area, survey plans, proof of land ownership or landowner consent, identification of the water source, and the capacity and dimensions of the pond.

The BC Ministry of Highways also require a minimum setback of 7.6 m from the edge of the road or 45.6 m from the centre of the road.

2.4 Groundwater Quality Data in the Pipestone and Gordondale Areas

2.4.1 Methodology

Groundwater quality data for the Pipestone and Gordondale areas were obtained from two sources; the Alberta Water Well Information Database (with water quality chemistry data), and scientific literature/reports of previous work completed in the area.

Data for the Pipestone were obtained from wells in Townships 69 through 72 and Ranges 7 through 11. Additionally, average water quality data based on analyses of several water wells (sample size range from 79 to 288) in Townships 69 through 76 were also included in the analyses (Table 3). Groundwater quality data were compiled and evaluated statistically based on aquifer material in which wells were completed. Categorization is based on groundwater samples derived from bedrock versus those derived from drift material. Based on data analysed, depth of wells completed in bedrock lithology ranged from approximately 29 meters to 159 meters. Wells completed in drift material were approximately 9 to 61 metres below ground surface. The most important bedrock aquifer in the Pipestone subject area is found in the Wapiti Formation.

Sufficient data could not be found for the Gordondale area. A review of available water well information located only a single deep well drilled to a depth of 468 m, below the base of groundwater protection. Due to the limited information available, groundwater data from the Pipestone area was considered to be representative of the entire study region.

Table 3 Data Sources and Water Quality Parameters of Interest

Well ID/Name/Locality	Type of Aquifer Material	Geology	Well Depth (m)	Source	Location				Salinity Parameters (mg/L)											
					Section	Township	Range	Meridian	TDS	Na	Ca	K	Mg	CO_3^{2-}	HCO_3^-	SO_4^{2-}	Cl^-	EC	Hardness	Alkalinity
420136	Wapiti sandstone/shale	Bedrock	29	WWDR	24	72	9	6	441	150	24	2	5	N/A	499	13	N/A	769	82	409
Farm well	Sand	Bedrock	31.7	Jones 1960	21	72	7	6	960	N/A	N/A	N/A	N/A	N/A	N/A	22	14		160	800
Farm well	Wapiti Sandstone	Bedrock	33.5	Jones 1960	20	72	7	6	930	N/A	N/A	N/A	N/A	N/A	N/A	2	11		140	820
417909		Bedrock?	36.6	WWDR	35	70	11	6	1465	533	13	2	5	N/A	938	450	N/A	2250	53	769
Wembley	Wapiti Sandstone	Bedrock	38.7	Jones 1960	15	71	8	6	1790	N/A	N/A	N/A	N/A	N/A	N/A	586	16	N/A	20	600
376409	sandstone/shale	Bedrock	40.2	WWDR	15	71	10	6	2010	754	7	2	1	39	1190	615	5	299	20	1040
Bedrock		Bedrock	0-46	Hackbarth 1977		69-76			1251	399	33	2	14	7	829	394	10	N/A	164	691
Beaverlodge Well	Wapiti Formation	Bedrock	49.4	Jones 1966	2	72	10	6	1244	N/A	N/A	N/A	N/A	N/A	N/A	75	18		0	925
417820		Bedrock?	61.9	WWDR					828	358	6	1	1	N/A	857	19	38	N/A	20	702
361279	Shale limestone/sandstone	Bedrock	76.8	WWDR	21	70	8	6	1108	361	47	3	22	N/A	902	221	10	1728	206	740
Bedrock		Bedrock	46-91	Hackbarth 1977		69-76			1130	394	21	2	6	7	913	234	15	N/A	93	772
Bedrock		Bedrock	91-137	Hackbarth 1966		69-76			936	359	18	2	4	8	870	87	16	N/A	49	723
420100		Bedrock	153	WWDR	11	72	8	6	532	227	N/A	0	N/A	9	554	42	10	1080	35	471
419424	Wapiti shale/sandstone?	Bedrock	158.5	WWDR	6	71	9	6	1240	360	N/A	N/A	N/A	33		180	10	N/A	230	595
Wembley test well	Wapiti Formation	Bedrock?	no depth info	Jones 1966	12	70	8	6	346	N/A	N/A	N/A	N/A	N/A	N/A	32	3	N/A	230	260
observation well	Gravel	Drift	9.1	Jones 1960	36	71	10	6	2116	N/A	N/A	N/A	N/A	N/A	N/A	616	4	N/A	30	915
Farm well	sand and gravel	Drift	23.8	Jones 1960	28	71	10	6	1554	N/A	N/A	N/A	N/A	N/A	N/A	508	N/A	N/A	425	495
Test Well	sand and Gravel	Drift	34.1	Jones 1960	35	71	10	6	1176	N/A	N/A	N/A	N/A	N/A	N/A	235	1	N/A	180	695
	Glacial Drift	Drift	0-61	Hackbarth 1977		69-76			1227	377	60	3	22	2	836	384	12	N/A	274	627
Test Well	sand and Gravel	Drift	no depth info	Jones 1960	28	71	10	6	1184	N/A	N/A	N/A	N/A	N/A	N/A	370	N/A	N/A	345	600

(red) μS/cm

(green) Parameter not necessarily salinity related.

2.4.2 Water Quality Data

Statistical analyses for both 'bedrock' and 'drift' derived waters were completed for salinity related parameters. In addition, results of alkalinity and total hardness have been included in the analyses. As a general rule water quality summary statistics were computed only for parameters with at least three data points. Summary statistics of salinity related water quality parameters for bedrock and drift derived waters are presented in Tables 4 and 5, respectively.

Results of the salinity related water quality parameters in the Pipestone area are summarized below:

Groundwater chemistry from wells completed in bedrock

- Groundwater is typically of sodium bicarbonate type;
- TDS concentrations ranged from 346 to 2,010 mg/L with a mean value of 1,081 mg/L;
- Sodium concentrations ranged from 150 to 754 mg/L with a mean value of 390 mg/L;
- Potassium concentrations ranged from 0 to 3 mg/L with a mean value of 2 mg/L;
- Calcium concentrations ranged from 6 to 47 mg/L with a mean value of 21 mg/L;
- Bicarbonate concentrations ranged from 499 to 1,190 mg/L and a mean value of 839 mg/L;
- Chloride concentrations ranged from 3 to 38 mg/L with a mean value of 14 mg/L;
- Sulphate concentrations ranged from 2 to 615 mg/L and a mean value of 198 mg/L;
- Carbonate concentrations ranged from 7 to 39 mg/L and a mean value of 17 mg/L;
- Electrical conductivity 299 µS/cm to 2,250 µS/cm with a mean value of 1,225 µS/cm;
- Alkalinity concentrations ranged from 260 to 1,040 mg/L with a mean of 688 mg/L; and
- Total hardness concentrations ranged from 0 to 230 mg/L with a mean value of 100mg/L.

Groundwater chemistry from wells completed in drift material

- TDS values ranged from 1,176 to 2,116 mg/L with a mean value of 1,451 mg/L;
- sulphate concentrations ranged from 235 to 616 mg/L with a mean value of 423 mg/L;
- alkalinity values ranged from 495 to 915 mg/L and a mean of concentration of 666 mg/L; and
- total hardness concentrations ranged from 30 to 425 mg/L with a mean value of 251 mg/L.

The following summary conclusions can be made based on both bedrock derived waters (from approximate depth of 29 to 159 metres) and drift derived waters (at approximate depth of 9 to 61 metres) analysed in the Pipestone area:

- mean TDS content of groundwater in the Pipestone area is generally less than 1,500 mg/L and must be considered potentially potable;

- TDS is generally higher (in comparison to bedrock waters) for drift derived waters and tends to decrease with depth;
- bedrock aquifers are of sodium bicarbonate type; and
- bedrock derived waters tends to be 'softer' in comparison to drift derived waters.

Table 4 Summary Statistics for Bedrock Derived Water (mg/)

Parameters	Mean	Maximum	Minimum	Median	Standard Deviation	95th Percentile	75th Percentile	25th Percentile
TDS	1081	2010	346	1108	461	1856	1248	879
Sodium	390	754	150	361	164	655	398	358
Calcium	21	47	6	20	14	42	26	11
Potassium	2	3	0	2	1	3	2	2
Magnesium	7	22	1	5	7	19	8	3
Carbonate	17	39	7	8	15	38	27	7
Bicarbonate	839	1190	499	870	206	1089	913	829
Sulphate	198	615	2	87	214	595	314	27
Chloride	14	38	3	11	9	26	16	10
EC (µS/cm)	1225	2250	299	1080	773	2146	1728	769
Hardness	100	230	0	82	81	230	162	28
Alkalinity	688	1040	260	723	199	960	786	598

Table 5 Summary Statistics for Drift Derived Water (mg/L)

Parameters	Mean	Maximum	Minimum	Median	Standard Deviation	95th Percentile	75th Percentile	25th Percentile
TDS	1451	2116	1176	1227.00	403.09	2003.60	1554.00	1184.00
Sodium	-	-	-	-	-	-	-	-
Calcium	-	-	-	-	-	-	-	-
Potassium	-	-	-	-	-	-	-	-
Magnesium	-	-	-	-	-	-	-	-
Carbonate	-	-	-	-	-	-	-	-
Bicarbonate	-	-	-	-	-	-	-	-
Sulphate	423	616	235	384.00	145.04	594.40	508.00	370.00
Chloride	-	-	-	-	-	-	-	-
EC (μS/cm)	-	-	-	-	-	-	-	-
Hardness	251	425	30	274.00	152.91	409.00	345.00	180.00
Alkalinity	666	915	495	627.00	156.49	871.00	695.00	600.00

2.5 Review of Related Studies

Searches for peer reviewed journal articles and published studies on the treatment and storage of saline water were completed using academic search engines. Only a few sources were identified, and none were found to be relevant to the approach proposed by PTAC.

2.6 Development of Risk Based Criteria

2.6.1 Conceptual Model

Two scenarios were provided by PTAC, reflecting anticipated storage of treated saline water in the Pipestone and Gordondale areas. For the Gordondale area it was assumed that up to 50,000 m^3 of water could be stored, and for the Pipestone area it was assumed that up to 15,000 m^3 of water could be stored. Untreated TDS values of 20,000 ppm and 2,000 ppm were initially applied to the Gordondale and Pipestone areas, respectively, based on worst-case assumptions. These initial conditions were only used as a starting point to derive risk based criteria, and as the water will be treated before entering the storage ponds actual TDS values will be lower.

It is assumed that treated saline water will be stored in unlined reservoirs with a depth of approximately 5 m for use in hydraulic fracturing operations. The reservoir would be excavated into a fine-grained (clay) formation (hydraulic conductivity 1x10^{-8} m/s or lower) and filled with treated water that would be stored for a period of time before being used. A domestic use aquifer depth of 30 m has been assumed based on the shallowest screened interval identified from water well records in the Pipestone and Gordondale areas. The unlined ponds will act as a contaminant source and gradually release the treated water to the surrounding soils, and water from the pond will flow into the soil surrounding the pond and displace the existing porewater outwards and downwards from the pond walls and base. The soil material surrounding the pond is assumed to be completely saturated and acting as a source area from which salt is transported laterally and vertically towards potential receptors. Table 6 includes the conditions of the pond and surrounding soil material used in the conceptual model and guideline derivation process.

Table 6 Conceptual Site Model Assumptions

Parameter	Value
Pond Volume	50,000 m^3
Pond Length	100 m
Pond Width	100 m
Pond Depth	5 m
Hydraulic Conductivity of Native Material	1 x 10^{-8} m/s
Climate Moisture Index	2 scenarios: moist and dry
Soil porosity, bulk density, moisture	ESRD (2010) fine grained defaults
Water table	2 scenarios: 1.5 m and 10 m
DUA Depth	30 m

The main parameters of potential concern are sodium, chloride, and TDS. Other substances related to salinity impacts may be present, but are considered to be less harmful to human and ecological receptors or present in much lower quantities and have not been included in the conceptual site model. In order to develop a salinity guideline for the treated saline water stored in the pond, the worst case ratio of chloride to TDS from the baseline bedrock water chemistry (1:10) was used to calculate a TDS guideline from the derived chloride guidelines. It is assumed that the stored water has been treated and will not include any other contaminants related to oil and gas processes, such as petroleum hydrocarbons or polycyclic aromatic hydrocarbons.

The conceptual site model considers both human and ecological receptors. Human receptors can potentially be exposed through consumption of impacted groundwater, and ecological receptors can be exposed through contact with impacted groundwater. Therefore, the exposure pathways included in derivation of risk-based guidelines are: protection of the rooting zone, protection of domestic use aquifers (DUA), protection of dugouts for agricultural purposes, and protection of surface water bodies for freshwater aquatic life. Direct contact with saline water in the storage ponds is not considered a hazard to human or ecological receptors.

2.6.2 Preliminary Modelling

No existing models were identified that were directly applicable to the scenarios being modelled. Since the project timeline did not allow for the development of a *de novo* model tailored to the site conceptual model, existing models with previous acceptance by ESRD and other regulators were adapted. By adjusting model inputs to reflect the conceptual model and considering multiple approaches, it is believed that the results conservatively reflect the proposed scenarios.

Preliminary modeling was undertaken using the Subsoil Salinity Tool (SST v2.5.2) and a modified version of the groundwater model used by ESRD to derive the Tier 1 and Tier 2 (2010a,b) guidelines. The purpose of this preliminary modelling was to generate an expected range for salinity guidelines that would be applicable for unlined ponds. It is noted that the models used were not intended for this purpose, and do not take into account the influence of the pond on the surrounding groundwater, and therefore conservative assumptions were required, particularly with respect to water storage duration. The models may better reflect conditions after water is no longer stored in the excavations, with residual impacts remaining in soils.

2.6.2.1 SST Model

The SST was used to calculate soil chloride guidelines for the material surrounding the storage pond, which were used to back calculate an equivalent pore water chloride guideline. The pore water chloride guideline will be used as a preliminary guideline for the stored water. Calculation of pore water concentrations from soil concentrations utilized a dissociation constant of 0.234, which was verified to be consistent with internal calculations of the SST model; however, additional verification of dissociation constants from the study area may be required.

Table 7 includes a list of all the SST inputs used in the preliminary modeling and the justification for their selection. In order to determine which inputs have the greatest influence on the SST guidelines, a limited sensitivity analysis was undertaken using likely input values expected in the site area (Appendix B). The climate moisture index (CMI), depth to groundwater, distance to surface water, impact depth, and domestic use aquifer (DUA) depth were all independently varied to determine which had the greatest influence on the governing guidelines. It was found that the DUA guideline was the lowest guideline in most cases, and that the DUA guideline depends primarily on the following three parameters: CMI category, pond depth, and depth of the DUA.

Table 7 SST Inputs for Base Case Scenarios

Parameter	Value	Reasoning
Tier	2B	No soil data available to complete Tier 2A inputs
Land Use	Agricultural	Most sensitive surrounding land use
CMI	Moist	Scenario 1, 2
	Dry	Scenario 3, 4
Fish farm within 500 m	No	Assumed
Water Table Depth (m)	<2	Scenario 1, 3
	10	Scenario 2, 4
Background TDS in Shallow GW (mg/L)	1470	Average value from background wells
Background Cl- in shallow GW (mg/L)	30	SST Default
Distance to SW (m)	125-250	Minimum distance allowed by model
Source length (m)	100	based on pond size
Shallow GW gradient	0.028	SST Default
Shallow GW hydraulic conductivity (m/s)	1.00E-08	Base case default
Deep GW	SST defaults	No site specific information is available
DUA depth (m)	10	Conservative value based on WWs in the area
DUA chloride (mg/L)	30	SST Default
DUA gradient and conductivity	SST defaults	No site specific information is available
Root zone salinity		
Saturation (%)	100	Assumed
EC	2.5	Used values from background groundwater
Top of impact (m)	1.5	Shallowest option available
Bottom of Impact (m)	5	Pond depth in base case
Soil Type	Fine	Base case default
Type of analysis	Unimpacted	Assumed

Based on classification using the SST, the study area contains natural subregions that are either considered to be moist or dry. Due to lower water infiltration rates, guidelines for soil chloride are generally higher in the dry areas. The depth of the pond directly influences the maximum impact depth, which must be considered in conjunction with the depth of the DUA. The separation distance between the bottom of impacts and the DUA has a linear relationship with the DUA guideline calculated by SST, which increases with increasing separation between the two. While the model only allows for a maximum DUA depth of 20 m, guidelines for a 30 m deep DUA were extrapolated from the model. Areas with deeper depths to shallow groundwater may also increase the lowest guidelines in some cases, but this does not affect the DUA pathway. Preliminary soil guidelines for the four base case scenarios calculated using the SST are included in Table 8.

Table 8 Preliminary SST Guidelines

Scenario	Soil Chloride Guidelines calculated With SST (mg/kg)						Calculated Pond Water Guidelines (mg/L)		
	Root Zone	Livestock Water	Irrigation	Aquatic Life	DUA (calculated 20 m)	DUA (extrapolated 30 m)	Equivalent Chloride Groundwater	Pond TDS Guideline	Pond TDS Guideline with Evaporation Multiplier
1 – Moist CMI, shallow water table	1600	2200	460	1200	440	620	1978	19780	18 000
2 – Moist CMI, deep water table	1600	NGR	NGR	2500	430	610	2623	26230	24 000
3 – Dry CMI, shallow water table	1100	2200	470	1200	1600	2500	2021	20210	18 000
4 – Dry CMI, deep water table	1100	NGR	NGR	3500	1300	2000	4730	47300	43 000

2.6.2.2 Modified ESRD Model

The ESRD model is intended to derive soil quality guidelines from the final water use, and includes four dilution processes:

- partitioning of the contaminant from soil to pore water;
- transport of leachate to the groundwater table;
- mixing of the leachate with groundwater; and
- transport of the substance to a discharge point.

The modified version used to calculate pond TDS guidelines does not include partitioning, as the pore water is acting as the contaminant source. Salinity parameters are conservative solutes and do not biodegrade, and so only dilution through vertical transport to shallow groundwater was considered.

As this model assumes an infinite source mass and does not factor in the time required for the contaminant plume to reach receptors, the effects of dilution through transport processes was minimal. Mixing of the leachate with groundwater is most significant process through which the pond water is diluted before reaching receptors. The modified model does not make any changes to the transport of mixing calculations from ESRD (2010a) and the same inputs and assumptions as the SST model were used in order to compare the results of the two approaches. The inputs for the modified ESRD model are included as Table 9.

Table 9 Modified ESRD Groundwater Model Inputs for Base Case Scenarios

Parameter	Value	Reasoning
Distance to Drinking Water Receptor	0 m	Assumed
Distance to Dugout	0 m	Assumed
Distance to Surface Water	300 m	Base case default value
General Characteristics – Shallow Aquifer		
Source Length	100 m	Based on pond size
Source Width	100 m	Based on pond size
Source Depth	5 m	Based on pond size
Source Depth below Root Zone – Minimum	1.5 m	Assumed based on depth of root zone.
Depth to Groundwater	NA	Does not influence model outcome.
Fraction of Organic Carbon	0.005	Adopted from ESRD (2010b) without change.
Saturated Hydraulic Conductivity	0.32 m/y	Base case default value.
Hydraulic Gradient	0.028	Adopted from ESRD (2010b) without change.
Aquifer Thickness	5 m	Adopted from ESRD (2010b) without change.
Bulk Density	1.4 g/cm^3	Fine-grained value adopted from ESRD (2010b) without change.
Water Content	0.12	Fine-grained value adopted from ESRD (2010b) without change.

Table 9 Modified ESRD Groundwater Model Inputs for Base Case Scenarios

Parameter	Value	Reasoning
Recharge – Downward Movement	0.015	Downward movement value for Fine-grained soil for a Moist Climate Moisture Index as referenced in ESRD (2010c).
	0.006	Downward movement value for Fine-grained soil for a Dry Climate Moisture Index as referenced in ESRD (2010c).
Recharge – Upward Movement	0.001	Upward movement value for Fine-grained soil for a Dry or Moist Climate Moisture Index as referenced in ESRD (2010c).
General Characteristics – DUA		
Depth to Groundwater	30 m	Assumed based on shallowest water well in the area.
Fraction of Organic Carbon	0.005	Adopted from ESRD (2010b) without change.
Saturated Hydraulic Conductivity	32 m/y	Adopted from ESRD (2010b) without change.
Hydraulic Gradient	0.028	Adopted from ESRD (2010b) without change.
Aquifer Thickness	5 m	Adopted from ESRD (2010b) without change.
Bulk Density	1.4 g/cm^3	Fine-grained value adopted from ESRD (2010b) without change.
Water Content	0.12	Fine-grained value adopted from ESRD (2010b) without change.
Water Quality Guidelines (mg/L)		
Water Quality Guideline – Drinking Water	250	For chloride from ESRD (2010b).
Water Quality Guideline – Freshwater Aquatic Life	230	For chloride from ESRD (2010b).
Water Quality Guideline – Wildlife Watering	4788	For TDS estimated from Livestock values in ESRD (2010b,c).
Water Quality Guideline – Livestock Watering	3000	For TDS from ESRD (2010b).
Water Quality Guideline – Irrigation	500	For TDS from ESRD (2010b).

Guidelines derived using the modified ESRD model are considerably lower than the SST guidelines, and are governed by the irrigation pathway. These guidelines could potentially be adjusted to consider the possible crops being irrigated in the study area. The assumptions used in the modified ESRD model are likely overly conservative. Preliminary soil guidelines for the dry and moist natural subregions of the study area calculated using the modified ESRD model and are included in Table 10. These guidelines are included for illustrative/comparison purposes only.

Table 10 Modified ESRD Groundwater Model Guidelines for TDS in the Storage Pond (mg/L)

Scenario	DUA	FAL	Wildlife Watering	Livestock Watering	Irrigation	Lowest Guideline with Evaporation Multiplier
Dry	10 000	3200	6700	3200	540	490
Moist	10 000	3100	6500	3100	520	470

2.6.3 Evaporation Modelling

If treated saline water is stored in ponds for significant periods of time then water would evaporate, particularly in summer months. Since this evaporation would remove water without removing chloride, it would have the effect of increasing chloride concentrations above the concentrations in the saline water being added to the pond.

In order to evaluate the effect of evaporation on chloride concentrations in the treated saline water storage ponds, a mass-balance model was developed. Based on discussions with PTAC, it was assumed that water would be added to the pond over a two month period, and then removed over a period of two weeks. At the end of the water addition, the volume would equal the maximum pond capacity; at the end of water removal, it would be 15% of the pond capacity. The process would be repeated on three different occasions throughout the year.

Water evaporation rates were determined from ESRD data for lakes in the region, and were based on lakes with a depth of approximately 4 m. The evaporation model inputs are shown in Table 11.

Table 11 Evaporation Model Inputs

Parameter	Gordondale	Pipestone
Pond Capacity (m^3)	50000	15000
Pond Depth (m)	5	5
Pond Area (m2)	10000	3000
Source water chloride concentration (mg/L)	11000	54
Evaporation rate (mm)		
January	5	5
February	5	5
March	5	5
April	30	30
May	75	75
June	110	110
July	130	130
August	110	110
September	90	90
October	40	40
November	10	10
December	5	5

The results of the modeling indicated that chloride concentrations in water would stabilize after approximate 3 years of the pond being used as described above. The maximum monthly concentration was predicted to be approximately 1.5 times the chloride concentration in the original water, and the annual average chloride concentration was predicted to be approximately 1.1 times the concentration in the original water. This calculation currently does not factor in precipitation entering the ponds, and therefore is considered to be a conservative estimate. Calculated guidelines for pond storage concentrations adjusted for the maximum expected evaporation multiplier (1.1, since the modelling is based on long-term transport) are included in Tables 8 and 10 for the SST and modified ESRD models, respectively.

2.6.4 Results

Preliminary modelling indicates that the maximum TDS concentration that could be stored in unlined ponds could range from 470 to 43,000 mg/L, depending on the site conditions and the assumptions used in guideline derivation.

TDS guidelines derived with SST model ranged from 18,000 to 43,000 mg/L. The guideline value of 18,000 mg/L was obtained when the water table was assumed to be shallow (<2 m below grade), and higher guideline values of 24,000mg/L and 43,000 mg/L were obtained when a deep water table (10 m below grade) was assumed with a moist or dry climate index, respectively.

In order to determine an appropriate value for the salinity limit for unlined ponds, sensitivity of the SST model to multiple input parameters was reviewed. Climate moisture index, depth to groundwater, distance to surface water, impact depth, DUA depth, and background chloride concentration were varied within the range of values expected within the study area, as shown in Appendix B. The 5th percentile value of all SST model runs from the sensitivity analysis, 5000 mg/L (TDS, after adjusting for evaporation), was selected as a representative guideline that would be protective of the vast majority of sites, and there were no cases where SST model runs resulted in guidelines below this value. The conditions that resulted in the selected guideline value occurred when the pond was within a moist region, the depth of the pond was 9 m below grade, and there was a DUA located 1 m directly beneath the pond. Since no results below this value were predicted in this sensitivity analysis, and the analysis included the full range of conditions expected in the Gordondale and Pipestone areas (including shallow DUA and ponds up to 9 m deep), this value is considered appropriate for screening purposes throughout the Gordondale and Pipestone areas. It may not be suitable in areas with elevated background chloride concentrations in groundwater, however, and it should not be applied outside the Gordondale and Pipestone areas without confirming that the Climate Moisture Index complies with a "dry" or "moist" regime.

Several of the assumptions made in the preliminary modelling are likely to be overly conservative, especially for the modified ESRD model, and could be readily be refined if site specific data on soil properties, site hydrogeology, and pond construction were available. Guidelines could be selected based on the sensitivity analysis (Appendix B) or re-calculated.

3.0 PHASE II: RISK AND POTENTIAL LIABILITY

3.1 Methodology

The liability assessment uses a fault tree/event tree approach that considers a number of possible release scenarios and the likelihood and consequences associated with each. Each release scenario is characterized by the following four components:

- release or failure scenario;
- nature and magnitude of spill;
- extent of impact and media impacted; and
- remedial and/or risk management response.

The components of a release scenario are linked by nodes in the fault tree, and each has a number of possible outcomes; the ultimate outcome would be one of a number of possible remedial responses that have typical costs associated with them. Probabilities are assigned to each of the outcomes at a given node. The probabilities at a given node sum to 1.0, except for the remedial options where the probabilities sum to 1.0 for groundwater and 1.0 for soil.

The expected costs of following a particular branch along the fault tree is the ultimate remedial cost multiplied by the probabilities at each node along that branch. The expected remedial cost associated with the overall failure scenario is the sum of the expected costs for all the branches. The total liability associated with transporting and storing saline water would be the expected cost multiplied by the unit probability of failure aggregated over the number of kilometres of pipeline or number of storage facilities. As this information is not currently available, costs have been estimated based on 1 km sections of pipeline and individual storage ponds.

Aside from the probability of the scenario occurring, which is obtained from the literature or empirical data were available or in some cases from proprietary information, the probabilities at each node are determined using expert judgement. The evaluations of the six release scenarios are described below, and the overall expected liability for the pipeline lined storage pond, and unlined storage pond are included in Table 12. Unit pricing values used in the liability assessment are included in Table 13.

Table 12 Liability Scenario Matrix

Liability Scenario		Failure Scenario			Cost Calculation	
Description	**Overall Probability of Failure**	**Description**	**Probability of Scenario**	**Overall Probability for Scenario**	**By Failure Scenario**	**By Method**
Pipeline	0.25	Catastrophic Failure	0.11	0.03	$29,179.21	$265,265.50
		Gradual Release	0.89	0.22	$236,086.30	
Lined Pond	0.23	Catastrophic Failure	0.85	0.20	$859,916.53	$1,131,607.48
		Gradual Release	0.15	0.03	$271,690.95	
Unlined Pond	1	Catastrophic Failure	0.20	0.20	$198,546.00	$1,606,791.00
		Gradual Release	0.8	0.8	$1,408,245.00	

Table 13 Liability Unit Costs

Impact	Cost
Soil (small)	$500,000.00
Soil (moderate)	$1,000,000.00
Soil (large)	$5,000,000.00
Soil (very large)	$50,000,000.00
Groundwater (small)	$2,000,000.00
Groundwater (large)	$5,000,000.00
Groundwater Risk Management	$500,000.00

3.2 Risk of Leak or Release

Release scenarios included catastrophic and gradual releases from unlined storage ponds, lined storage ponds, and pipelines. A catastrophic release was defined as a single event which resulted in a significant portion of the stored water being released from the contained area, such as a spill. A gradual release was defined as the continuous leaching of saline water from the pond to the surrounding environment. Available data on pond failure, including release volume and associated pond design, are limited. Reliable data on pipeline release volumes and frequency were more available, with the major source for this assessment being ERCB (2007). Overall, data on the various release scenarios were limited and the extent of impact along with associated remedial action and cost was based on combination of professional experience and available data.

Data on pipeline releases in Alberta indicate that pipelines carrying fluids other than gas fail on average 25 times per year per 1,000 km of pipeline (ERCB, 2007); therefore, the overall probability of pipeline failure was estimated to be 0.25. Release types have been qualified in Alberta; total hits and ruptures comprise 11% of releases. These hits and ruptures were considered to be representative of catastrophic failures, with the remaining 89% assumed to be gradual releases.

Trends in the failure scenarios of storage ponds were correlated from reporting on tailing dams related accidents from *The International Commission on Large Dams* (ICOLD, 2007). The overall probability of lined pond failure is relatively low; failures are estimated to occur in less than 1% of ponds per year (Martin and Davies, 2000). Based on this data, it is estimated that over the lifetime of a storage pond, predicted to span 20 years, the failure probability would be 0.23. Release types have been qualified by ICOLD, for this assessment gradual releases were represented by seepage and groundwater incidents. Gradual releases are estimated to comprise 15% of failures, with 85% of the remaining failures thought to be representative of catastrophic failures.

Unlined ponds are assumed to gradually seep substrates from the start of operations and will require some amount of remediation in all cases; therefore, the overall probability of failure assigned to the unlined pond scenario was 1.0. As catastrophic failure of a pond is expected to be related to extreme weather events or other unforeseeable conditions, and the probability of a catastrophic failure scenario was assumed to be similar for lined and unlined ponds. Therefore, the assumed overall catastrophic failure rate for lined ponds of 0.20, based on a failure probability of 0.23 with 85% of those being catastrophic, was applied to unlined ponds as well. As all unlined ponds are assumed to fail, an overall gradual release failure probability of 0.8 was assumed. Conceptually, the type of failure for ponds is not as important; the nature of materials governing transport will be the most important factor in qualifying the failure.

3.2.1 Scenarios and Probabilities of Failure

The expected costs for remediation of six release scenarios were calculated. These scenarios were:

- Pipeline – catastrophic failure;
- Pipeline – gradual release;
- Lined pond – catastrophic failure;
- Lined pond – gradual release;
- Unlined pond – catastrophic failure; and
- Unlined pond – gradual release (in excess of predicted).

Probabilities were assigned to the above failure scenarios based on a combination of literature values and data obtained from proprietary risk assessments of process risk, which, for the purpose of this study, suggest the following:

- pipeline failure occurs at a rate of 25 per 1,000 km per year;
- 15% of pipeline failures are large ruptures (catastrophic), 85% are small leaks (gradual);
- storage pond catastrophic failure rates are 0.0005 per pond per year for large ponds; and
- storage pond gradual release failure rates are 0.0001 per pond per year.

The failure probabilities for pipelines (0.25), lined ponds (0.23), and unlined ponds (1.0) were calculated based on the above data. This assumes that the water is still considered saline but is treated to a level that meets the derived risk based guidelines, which were calculated assuming that the pond exists in unlined clay soils.

However, if the treatment process decreases salinity concentrations below the established background levels, remediation may not be required and the failure probabilities for gradual releases would have to be adjusted accordingly.

3.2.2 Nature of Spill

For each of the six scenarios, four possible spill types were considered:

- untreated saline water, large volume;
- untreated saline water, small volume;
- treated saline water, large volume; and
- treated saline water, small volume.

It is assumed that only treated water would be stored in unlined ponds, and that only untreated water would be transported by pipeline or stored in lined ponds. The treated water would meet the derived criteria for storage, but the risk of impact would arise as a result of a greater rate of release than that assumed in the modelling. Based on professional judgement and Millennium's experience with contaminated sites, it was assumed that the majority (0.8 to 0.996) of releases would be small volumes.

3.2.3 Extent of Impact

For each of the possible spill types, various impact extents were considered to be possible. Impact extents were based on the expected volume of soil and/or groundwater that would likely require remediation from either the large or small spill types.

3.2.4 Remedial Actions

The four most common options for remedial action were included in the analysis:

- excavation of small soil volumes (or source excavation);
- excavation of large volumes of soil;
- groundwater remediation (assumed to be by recovery and treatment/disposal); and
- risk management of groundwater plume (in conjunction with source removal).

Only remedial actions likely to be selected for each extent of impact were included. Small to moderate soil volumes were assumed to be excavated, while options for groundwater remediation or risk management were included for larger extents of impact. Generic costs were assigned to these options; and these can be changed as appropriate based on input from PTAC.

3.3 Summary

Liability was similar between unlined and lined ponds, with an expected cost of $1.131M for lined excavations and $1.607M for unlined excavation. Liability for pipelines was considerably lower, at $0.265M; however, this was calculated based on 1 km of pipeline. Additional consideration of site placement, required pipeline length, and design lifetime are required in order to accurately compare the expected costs of remediation between these methods, but based on the initial results all three options will likely be viable under some conditions. The complete fault tree/event tree calculations for each scenario are included as Appendix A.

4.0 DISCUSSION AND CONCLUSIONS

There are multiple agencies in both British Columbia and Alberta that regulate saline water usage, treatment, and storage. For the purposes of this study, the most relevant are the Alberta ERCB and the BC OGC. The definition of saline water is consistent between most Canadian organizations, including Alberta and BC; however, the storage and treatment requirements do vary between jurisdictions and industries significantly. In most cases, storage of saline water in unlined ponds is prohibited, and comprehensive containment and monitoring is required when excavations are used for saline water storage.

A review of the water quality of the study area indicated that most groundwater in the area would be considered to be potentially potable, and therefore avoiding contamination of domestic use aquifers will in most cases be the most significant requirement. Development of preliminary risk-based salinity limits for unlined ponds indicated that under most of the expected site conditions, TDS concentrations less than 5,000 mg/L can be stored in unlined ponds without adversely impacting the available drinking water in the study area. This value was based on the results of the sensitivity analysis performed on the SST model, using the 5th percentile groundwater guideline value from 59 input scenarios. The SST model runs used to determine this value are included in Appendix B. Refinement of the preliminary calculations using site specific data and potentially more complex groundwater transport models would be required before adopting these guidelines directly.

When the potential liability of pipelines, lined excavations, and unlined excavations were compared using a fault tree/event tree approach, it was found that all unlined ponds had higher expected liability than lined ponds, and the liability of unlined ponds was approximately equivalent to the liability from 6 km of pipeline. The probabilities used in these calculations should be adjusted where possible based on input from PTAC using data from their existing operations and their expected costs.

Based on the results of this study, all three options for procuring saline water for hydraulic fracturing are potentially viable; however, site specific data is needed to refine the existing models and calculations. Additionally, the use of unlined storage ponds will also have to address regulatory concerns that this strategy involves knowingly introducing salinity contamination into the environment, and alternative guidelines based on representative background soil concentrations may have to be used instead.

Storage of saline water in unlined ponds may violate existing guidelines, policies and regulations and an appropriate level of treatment must be discussed with regulators before proceeding. Due to the value currently placed on freshwater, there may be a willingness on the part of regulators to explore options which will replace the use of freshwater with treated saline water for hydraulic fracturing without compromising the surrounding environment. If this type of storage is contemplated, then regulators should be engaged and provided with a case demonstrating the net benefit to the province for this activity.

5.0 LIMITATIONS AND CLOSURE

This report has been prepared in accordance with generally accepted environmental engineering practices, based on an agreed scope of work. Outcomes presented herein were prepared for the Canadian Association of Petroleum Producers (CAPP). This report references information collected by others and provided to Millennium EMS Solutions Ltd. by Petroleum Technology Alliance Canada. While this information is believed to be complete and accurate, unless specifically indicated otherwise, Millennium EMS Solutions Ltd. has not independently verified the information provided.

We thank you for the opportunity to be of assistance to PTAC. Should you have any questions, please contact Ian Mitchell at 403.270.4724.

Yours truly,

Millennium EMS Solutions Ltd.

Prepared by:

Dan Stein, B.Sc.
Risk Assessment Specialist

Prepared by:

Lindsey Mooney, M.Sc., P.Biol.
Risk Assessment Specialist

Prepared by:

Geneva Robins, M.Sc., P. Biol.
Risk Assessment Specialist

Reviewed by:

David Williams, P.Eng.
Senior Risk Assessment Engineer

Reviewed by:

PROFESSIONAL ENGINEER ALBERTA

Ian Mitchell, P.Biol., P.Eng.
Risk Assessment Discipline Lead

6.0 REFERENCES

Alberta Infrastructure and Transportation (AT). 2010. Contract Administration Manual – Appendix 6. January 2010.

British Columbia. 1996. Water Act. RSBC 1996 Chapter 483. Current to January 23, 2013.

British Columbia Ministry of Environment (BC MOE). 2008. Code of Practice for Produced Water from Coalbed Gas Operations.

BC MOE. 2005.EnvironmentalManagement Act – Code of Practice for the Discharge of Produced Water from Coalbed Gas Operations. BC Reg 156/2005.

British Columbia Oil and Gas Commission (BC OGC). 2010. Oil and Gas Water Use in British Columbia. August 2010. Available online at: http://www.bcogc.ca/document.aspx?documentID=856&type=.pdf

BC OGC. 2009. Information Letter # OGC 09-07 – Storage of Fluid Returns from Hydraulic Fracturing Operations.

Canadian Council of Ministers of the Environment. 1999. Canadian Water Quality Guidelines for the Protection of Aquatic Life.

Chambers, D. M., and B. Higman. 2001. Long term Risks of Tailings Dam Failure. Available online at: http://www.csp2.org/reports/Long%20Term%20Risks%20of%20Tailings%20Dam%20Failure%20-%20Chambers%20&%20Higman%20Oct11.pdf

Energy Resources Conservation Board (ERCB). 2012. Directive 050 – Drilling Waste Management.

ERCB. 2007. Pipeline Performance in Alberta, 1990 – 2005. Report 2007-A. Available online at: www.ercb.ca/reports/r**2007**-A.pdf

ERCB. 2001. Directive 055 – Storage Requirements for the Upstream Petroleum Industry. December 2001.

ERCB. 1996. ERCB Directive 058 – Oilfield Waste Management Requirements for the Upstream Petroleum Industry. November 1996.

Environment and Sustainable Resource Development (ESRD). 2010a. Tier 1 Soil and Groundwater Remediation Guidelines. December 2010.

ESRD. 2010b. Tier 2 Soil and Groundwater Remediation Guidelines. December 2010.

ESRD. 2001. Salt Contamination Assessment & Remediation Guidelines. May 2001.

Government of Alberta. 1992. Environmental Protection and Enhancement Act.

Henselwood, F. and G. Phillips. 2004. A matrix-based risk assessment approach for addressing linear hazards such as pipelines. Available online at: http://www.chemistry.ca/index.php?ci_id=3122&la_id=1

International Commission on Large Dams (ICOLD) Bulletin 121. 2001. Tailings dams risk of dangerous occurrences – lessons learnt from practical experience. Presented in part at: http://www.tailings.info/knowledge/accidents.htm#

Martin, T.E., and M.P. Davies. 2000. Trends in the stewardship of tailings dams. Available online at: http://www.infomine.com/library/publications/docs/Martin2000.pdf

Province of Alberta. 2000. Water Act. Revised Statutes of Alberta 2000 Chapter W-3. Current as od March 15, 2012.

Saskatchewan Watershed Authority. 2005. The Saskatchewan Watershed Authority Regulations.