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Native Prairie Protocol for Salt-Affected Wellsites Scientific Rationale Document

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Table of Contents

List of Tables

1.0 INTRODUCTION

There are a large number of oil and gas sites with salts in soil that exceed one or more generic guideline values. The nature of generic guidelines is that, by definition, they do not uniquely consider site-specific conditions and therefore may indicate the potential for an adverse effect when in actuality there is no such potential. Undertaking remedial activities where no potential for adverse effect exists will result in a negative net environmental benefit. Resources (equipment, consultants, money, landfill space, time, *etc.*) allocated to remediation with no benefit to environmental protection could be used to address more significant environmental problems or to increase the number of sites reclaimed. The benefit of generic guidelines is that they are easily administered with clear remedial endpoints.

Given the concerns noted above with applying generic guidelines to salt sites, there is a need for an alternative method of managing these sites. The alternative method should be efficient (cost, timely) and science-based. A method meeting these objectives will enable timely, economic regulatory closure and will significantly reduce the net negative environmental benefit that can occur when unnecessary intrusive remediation occurs. This would be beneficial to landowners, regulators, the public and industry. Petroleum Technology Alliance Canada has initiated a project to look for a solution to these issues. The current document provides a proposed solution.

1.1 Objective

The objective of this project is to develop a scientifically-defensible protocol for closure of salt-affected sites in native prairie settings where there are no current, and no likely future adverse effects from the salts.

1.2 Funding Acknowledgements

This work was made possible by funding from Petroleum Technology Alliance Canada (PTAC) under project number #18-RRRC-04 and previously under PTAC Project #15-SGRC-08. Thanks to Sonia Glubish the CAPP project sponsor for technical input and support to the project.

1.3 Native Prairie Protocol Technical Steering Committee

A technical steering committee (TSC) guided the development of the 2016 Scientific Rationale Document and the work of the TSC is carried forward into the current Scientific Rationale Document. The 2016 TSC included the following individuals, whose valuable contributions are appreciated and acknowledged.

- Glenn Ball - ConocoPhillips Canada.
- Kevin Ball - Alberta Energy Regulator.

- Gordon Dinwoodie - Alberta Environment and Parks.
- Tracy Kupchenko - Alberta Energy Regulator.
- Brian Lambert - Alberta Environment and Parks.
- Debbie Tainton – Canadian Natural Resources Limited.
- Miles Tindal - Millennium EMS Solutions Ltd.
- Shawn Willetts - ConocoPhillips Canada.

The 2018 Scientific Rationale Document was guided by the following TSC:

- Gordon Dinwoodie - Alberta Environment and Parks.
- Sonia Glubish – Canadian Natural Resources.
- Daniel Pollard - Alberta Energy Regulator.
- Miles Tindal - Millennium EMS Solutions Ltd.

2.0 RATIONALE

There are a large number of wellsites with salt concentrations exceeding generic guidelines in the subsurface in native grassland ecosystems in Alberta. Reclamation criteria applicable to these sites (ESRD, 2013) include requirements that the native grassland ecosystem established on these sites must match the ecosystem in surrounding, undisturbed areas within a specified tolerance. Many sites have been successfully reclaimed in the past, or have reverted back to natural vegetation since abandonment, but salt concentrations remain in the subsurface that exceed current Tier 1 guideline values. Intrusive remediation of such sites will destroy the existing native grassland ecosystem and re-establishing such an ecosystem can take many decades. Indeed, research summarized in Section 3.2 below indicates that in some cases, there were still differences between the grassland communities on undisturbed and previously-disturbed land even after 90 years. In cases where the salt in the subsurface has no current, and no likely future, adverse effects, any gain from removing salt from the subsurface will not justify the ecosystem damage that would be caused.

The rationale for the current work is therefore to avoid additional damage to established native grassland ecosystems where possible. The current document develops criteria to identify sites where residual salts are not expected to cause current or future adverse effects, and reclaimed native grassland sites can safely be left undisturbed.

3.0 PLANT ROOTING ZONES IN SOUTHERN ALBERTA NATIVE PRAIRIE ECOSYSTEMS

The objective of this project (Section 1.1) involves identifying salt-affected sites in native prairie settings that have no current, and no likely future adverse effects on plant communities. Adverse effects on plant communities from salts in the subsurface can only occur if the salts are present (now or in the future) within the rooting zone of the plant. Consequently, an understanding of typical rooting depths of prairie grassland ecosystems and the time required to achieve these rooting depths is helpful in achieving the project objectives. Available relevant information is summarized in the following sections.

3.1 Rooting Depth

Grassland ecosystems occur to varying degrees in the Grassland, Parkland, Foothills and Rocky Mountain Natural Regions of Alberta (ESRD, 2013). These natural regions are characterized by hot, dry growing conditions, and a low precipitation to evaporation ratio. Low levels of precipitation lead to an allocation of plant resources to below ground production in the form of roots and crown production in grasses. Sims and Singh (1978) found that in mixed grass and short grass prairie, below-ground production accounted for between 52 and 86% of total net production. This suggests that for prairie ecosystems the majority of plant production is focused on root biomass.

Information on maximum rooting depth was available for four grass species, five forb species and two shrub species relevant to the Natural Regions considered. Many of these data are sourced from Coupland and Johnson (1965) who looked at rooting depths in mixed prairie in Saskatchewan. Data are summarized in Table 1, and discussed in the following sections. Supporting information in the AEP (2016) Range Plant Community Guide was also considered.

Table 1 Rooting Depths for Selected Alberta Grassland Species

Common Name	Scientific Name	Rooting Depth (m)		Source
		Majority of Roots	Maximum Observed	
Grasses				
Needle and Thread Bunchgrass	*Stipa comata*	0.6	1.1	Coupland and Johnson (1965)
Blue grama	*Bouteloua gracilis*	0.3	0.9	Weaver and Darland (1949); Coupland and Johnson (1965)
Western wheatgrass	*Elymus smithii*	0.3	1.5	Coupland and Johnson (1965)
June grass	*Koeleria macrantha*	0.3	0.75	
Forbs				
Pasture sage	*Artemisia frigida*	nd	1.6	Coupland and Johnson (1965)
Moss phlox	*Phlox hoodii*	0.3	0.96 (without pasture sage) 0.61 (with pasture sage)	
Spiny iron plant	*Haplopappus spinulosus*	0.3	1.8	
Hairy golden aster	*Heterotheca villosa*	0.3	1.3 (solonetzic soils) 2.4 (sandy soils)	
Horsetail	*Equisetum arvense*	0.5	3	
Shrubs				
Scarlet mallow	*Sphaeralcea coccinea*	nd	1.2	Coupland and Johnson (1965)
Silver sagebrush	*Artemisia cana*	nd	2.4	

Stipa comata

Needle and thread is a late successional perennial bunchgrass that grows in association with a number of species. It is a component of climax grassland communities. Coupland and Johnson (1965) found that the roots were concentrated in the top 60 cm, but were able to reach a depth of 110 cm depending on subsoil texture. *Stipa Comata* is considered a tall grass with respect to plant community structure and requires a stable/balanced soil environment.

Bouteloua gracilis

Blue grama is a tufted perennial grass, but typically forms short rhizomes as well. It is characterized as a sod forming grass that is one of Alberta's warm season (C4) native grasses. Weaver and Darland (1949) found that 93% of the roots were found in within 30 cm of the soil surface. Coupland and Johnson (1965) found that the rooting depths ranged from 35-90 cm. Blue grama is considered a short grass with respect to plant community structure. It is considered very drought resilient and it is considered an "increaser" in that it increases in percent cover with increased disturbance. Blue grama is a ground coverer.

Elymus smithii

Western wheatgrass is a perennial grass that forms extensive creeping rhizomes. It occurs on a wide variety of sites, and increases in percent cover with increased soil water and decreases in percent cover in dry conditions. Coupland and Johnson (1965) found that the rhizomes don't often exceed 30 cm and occur in the top 15 cm of soil. The fibrous roots can reach a maximum depth of 150 cm in upland sites. Western wheatgrass is salt tolerant and an early colonizer of disturbed sites.

Koeleria macrantha

June grass is perennial bunch grass and grows in a variety of plant community types across a number of subregions. Coupland and Johnson (1965) found that majority of the roots were within the top 30 cm of soil, with the maximum rooting depth ranging from 33 to 75 cm depending on site and soil conditions. June grass is generally found in loam soils and is considered an easy species to source seed for reclamation purposes.

Artemisia frigida

Pasture sage is a perennial herbaceous species that has both a tap root and a fibrous root system. It acts as an increaser with disturbance and is an indicator of disturbances such as fire or heavy grazing. Coupland and Johnson (1965) found that the taproot was able to reach depths of greater than 1.6 m. It was also noted that with growing in association with blue grama, that the roots of pasture sage typically were 3 cm deeper than blue grama. Following heavy grazing it will spread to cover and protect the soils.

Phlox hoodii

Moss phlox and little club moss and lichens are often described as the "under layer" of native grass systems. They cover the ground and protect the soil and seed bank from the elements. Moss phlox is a perennial herbaceous species that has both a tap root and a fibrous root system. It acts as an increaser under disturbance. The natural/normal percent cover moss/lichen layer ranges from 1-42% depending on the plant communities. If there is severe disturbance such as fire it is often the last means of protecting the soil from erosion. Coupland and Johnson (1965) found that the maximum depth of the taproot was 96 cm, but in areas where it was found with pasture sage, the phlox had roots that were 35 cm shallower. The moss/lichen layer requires 20+ years to re-establish. Protection of this "prairie sod" is critical to ensure a full recovery to "pre-disturbance" plant community. Once it is disturbed it is gone; there is no means of "re-seeding" this layer.

Haplopappus spinulosus

Spiny iron plant is a perennial herbaceous species that has both fibrous roots and a tap root, it acts as an increaser with disturbance. Coupland and Johnson (1965) found that the fibrous roots were located within the top 30 cm of the soil surface, while the tap root could extend as deep as 1.8 m.

Heterotheca villosa

Hairy golden aster is a common perennial herbaceous species that has both a tap root and a fibrous root system. Coupland and Johnson (1965) found that the majority of the fibrous roots were located in the top 30 cm, but the maximum extent of the tap root ranged from 1.3 m in solonetzic soils and 2.4 m in sandy textured soils.

Equisetum arvense

Horsetail is a herbaceous perennial that forms extensive creeping rhizomes and has deep tap roots. Although not a large component of plant communities within grassland Natural Regions, it can be found on disturbed sites and areas of elevated soil water levels. Williams (1979) found that 50% of the rhizomes were within the top 50 cm of soil, while Coupland and Johnson (1969) found that the vertical root system could reach depths greater than 3 m. Horsetail is indicative of wetlands (temporary, ephemeral, permanent) and sandy soils with high water table.

Sphaeralcea coccinea

Scarlet mallow is a low perennial herbaceous forb species that has a dominant tap root with very little branching or fibrous roots. It is an increaser that is typically found in areas of disturbance or areas that are overgrazed. Coupland and Johnson (1965) found the tap root extending to a depth of 120 cm with limited lateral branching of the tap root.

Artemisia cana

Silver sagebrush is a woody perennial deciduous shrub that forms a tap root. It acts as an increaser but is an importance source of forage for various wildlife species. Although it acts as an increaser, it is typically not found on areas that have had any soil disturbance as it is slow to establish from seed. Coupland and Johnson (1965) found that silver sagebrush had the deepest roots of any species examined, extending below a depth of 2.4 m. Silver sagebrush is indicative of overflow or seasonal flooding/water flow conditions. Silver sagebrush is a very important species with respect to wildlife habitat and food source, including sage grouse and pronghorn antelope.

3.1.1 Ecology of Relevant Deep Rooted Species

Deeper rooted species within native grassland communities are of particular concern since they may be able to access salts in deeper areas than other species. Two grassland shrub species, silver sage (*Artemesia cana*), and winterfat (*Eurotia lanata*) are considered to be deep rooting, as are some grass species, including needle and thread grass (*Stipa comata*), and western wheatgrass (*Elymus smithii*). Information on silver sagebrush and other deep rooted species is summarized below. These deep rooted species are also common in overflow and blowout community types (discharge/recharge areas) and solonetzic soils.

Disturbance and bare soils on reclaimed energy footprints appear to create favorable conditions for silver sagebrush, and cover of silver sagebrush was found to have doubled on disturbed sample points in blowout sites in southeastern Alberta (Gates *et al*., 2010). However, blowout sites may be less resilient to disturbance due to changes in physical, chemical and hydrologic characteristics of the soils and the absence of soil crust and the absence of the moss and lichen layer due to disturbance (Gates *et al*., 2010). Disturbance and bare soils related to energy footprints often have higher percent cover of *Chenopodiaceae* species such as Kochia (Salsola), Flixweed and Russian thistle. These forbs are salt loving or salt tolerant species.

The seed production of sagebrush is high; however, few seeds survive the germination and seedling stage, with drought being the primary cause. They require moist soil for establishment and growth, with pulses of growth observed in years of above average precipitation (Howard, 2002). Cloning is silver sagebrush's most common method of reproduction, sprouting from its roots, rhizomes and crown, though sprouting from the root crown is reported less frequently in literature than sprouting from roots or rhizomes. In a study on response of native shrubs to pruning silver sagebrush over three years, the mean heights of the plants was unchanged between the pruned and unpruned plants, though crown area was significantly less in the pruned plant (Howard, 2002).

Romo and Young (2012) suggested that rhizomatous sprouting of *A. cana* might enhance reclamation of disturbed sites where plant material and appropriate moisture is available. Winterfat (*Eurotia lanata*) is another deep-rooted shrub that is utilized by antelope for food, and nesting cover for birds. Germination of winterfat decreases with salinity. Winterfat is an indicator of healthy, stable soils often associated with minimal bare soils.

3.2 Time to Maturity for Grasslands Ecosystems

The time taken to achieve maturity following disturbance is relevant to the current study since at maturity, no further penetration of deeper soils with potentially different salt concentrations will occur. It was not possible to identify a single threshold time for grasslands ecosystems to reach maturity, but relevant information is summarized below.

A number of studies have looked at the plant community development following abandonment from different types of disturbances. Key points from these studies are summarized in Table 2, and discussed below.

Table 2 Expected Time to a Climax Grassland Community Following Disturbance

Author	Study Location	Conclusions
Morris *et al.*, (2011)	Utah, USA – Abandoned farmland	Following 90 years of recovery measurable differences between the previously disturbed and undisturbed areas remained
Dormaar and Smoliak (1985)	Manyberries, Alberta – Abandoned farmland	Suggest 55 years of recovery with moderate grazing levels was needed before the community would reach similar composition to the undisturbed community
Whitman *et al.*, (1943)	North Dakota, USA - Abandoned farmland	Suggests 60 years of recovery was needed to reach a climax vegetation community
Samuel and Hart (1994)	Wyoming, USA – Disturbed rangelands	After 61 years, secondary succession had not returned plant communities to the climax state.
Elsinger (2009)	Central Alberta – Former Pipeline and Wellsite Disturbances	Reclamation success of 17 pipelines and 36 well sites was assessed by reference to undisturbed prairie and determining the influences of age, construction and revegetation methods and cattle grazing. Reclamation success was more closely related to methods of construction and revegetation and grazing pressure than to age.
Desserud (2006)	Southwestern Alberta – Former Pipeline Disturbance	Concluded age was a less important factor than construction and revegetation methods in determining reclamation success.

Most prairie plants are long lived and do not invest much of their energy into seed production (Government of Saskatchewan, 2012).

In a study looking at the recovery of sagebrush ecosystems after abandonment from farming in Utah, Morris *et al.*, (2011) found that even after 90 years of recovery there were still measurable differences between the previously disturbed and undisturbed areas.

Dormaar and Smoliak (1985) looked at abandoned farmland of three ages: 60, 58 and 35 years. In each case the abandoned plant community had still not recovered to match the undisturbed community. In each case the percent cover of blue grama was significantly greater in the abandoned lands than in the undisturbed. As blue grama acts as an increaser in response to disturbance, this is an indicator that the sites had not recovered to match the control sites at the time of assessment. Although above-ground biomass was greater on the abandoned sites, below ground biomass was greater on the undisturbed sites. The conclusion from this research was that more than 60 years of recovery with moderate grazing levels was needed before the community would reach similar composition to the undisturbed community.

This conclusion supported the work of Whitman *et al.*, (1943) who concluded that more than 60 years of recovery was needed to reach a climax vegetation community. In a study looking at similar species but within a different plant community type, Samuel and Hart (1994) concluded that on mixed grass prairie in Wyoming, more than 61 years was needed for disturbed rangeland to return to pre-disturbance conditions.

Taken together, the above studies show that re-establishing a grassland ecosystem on previously farmed land can take many decades. In fact, none of these studies was able to demonstrate a re-established grassland ecosystem which matched adjacent undisturbed areas, and it is therefore not known whether these sites would in fact eventually return to pre-disturbance conditions.

Elsinger (2009) examined a number of wellsites and pipelines to examine the factors that affect reclamation success. This study was conducted in the Rumsey Natural Area which is located in the northern fescue natural subregion and examined pipelines constructed from 1976 to 2000 and wellsites constructed from 1967 to 2004. The pipelines showed no significant correlation between time since reclamation and the plant community relationship to the undisturbed control areas. The wellsites showed a similar response with no correlation between specific years and reclamation success. When put into groups of similar construction date and reclamation/revegetation strategy, the only group that was not significantly different from the undisturbed were wellsites constructed from 2001-2004. The conclusion from this research was that construction method and not time was the significant factor influencing plant community development. Construction methods that limited or had no topsoil disturbance led to sites that most closely resembled the undisturbed prairie. These results confirmed those of Desserud (2006) who examined pipeline reclamation success in the foothills fescue ecoregion and found that age was a less important factor that construction and revegetation method in determining success.

These two studies show the value of minimum disturbance wellsite construction practices, and indicate that time since abandonment, considered in isolation, is not a useful indicator of likely reclamation progress.

There was no information available in the literature that provided usable information on the time to maturity for individual grassland plant species relevant to Southern Alberta.

4.0 OVERALL APPROACH

The overall approach adopted to achieve the project objective involved two major steps in relation to the ecological direct contact exposure pathway:

1. Demonstrate no current adverse effect on the grassland ecosystem.
2. Demonstrate no likely future adverse effect on the grassland ecosystem.

There is already a detailed and carefully thought-out protocol for demonstrating no current adverse effect on prairie grassland ecosystems. This is the *Reclamation Criteria for Wellsites and Associated Facilities for Native Grasslands* (ESRD, 2013) document. The requirements of this document are adopted here without change for achieving Step 1 above.

The approach adopted to demonstrate no likely future adverse effect in Step 2 is based on showing that future migration of salts from beneath the root zone upwards into the root zone is unlikely, and therefore the salinity profile within the rooting zone is not expected to become worse over time. Techniques to demonstrate this are discussed in detail in Section 5 below.

Other relevant exposure pathways also require assessment using existing tools, as indicated in Section 6.

5.0 VERTICAL MIGRATION OF SALTS

5.1 Rationale

Closure of salt-affected wellsites requires consideration of a range of exposure pathways including the ecological direct contact pathway which protects plants and soil invertebrates from adverse effects based on direct contact of roots with salts. The default approach to assessing this exposure pathway for salts is to compare soil electrical conductivity and sodium adsorption ratio to Alberta Tier 1 guideline values (AEP, 2019a).

An alternative approach is explored in this project, whereby the growth and diversity of a plant community is used as a more direct indicator of lack of adverse effect. A strong plant community is a good indicator of no adverse effect under current conditions. However, additional information is required to provide confidence that adverse effects would not be expected in future. If subsurface conditions are such that future upwards migration of salts is a significant risk, then there is the concern that deeper salts could potentially move up into the rooting zone and impact future plant health and growth. Accordingly, it is important to develop a methodology for identifying conditions where future upwards migration of salts may or may not be expected.

The following sections explore a number of aspects of this issue, including:

- Using the distribution of naturally-occurring salts to predict long-term water and salt migration (Section 5.2), including:
  - The dynamics of salt migration and accumulation;
  - The use of naturally occurring salts as pedogenic tracers; and
  - A comparison of chloride and sulphate as natural tracers.
- Investigating the linkage between water table depth and risk of salt accumulation at surface (Section 5.3):
  - Alberta-based field studies reported in the literature; and
  - Field studies from other areas reported in the literature.

5.2 Natural Salt Distribution as an Indicator of Future Salt/Moisture Movement

If a net upward water flux has persisted over time in a given location, it would be expected that naturally-occurring salts in the soil profile would have moved upward and have accumulated within the root zone or at the surface. Conversely, the absence of such an accumulation of naturally-occurring salts within the root zone or at surface would indicate that future upwards migration of salts, including anthropogenic salts, was not expected. The term "pedogenic tracer" is used herein to describe the use of the naturally-occurring salt distribution to draw inferences about the long-term water movement in the vadose zone. Literature relevant to various aspects of the use of naturally occurring salts as pedogenic tracers is summarized in the following sections.

5.2.1 Relationship Between Moisture Flux and Salt Migration

Given the solubility of many naturally-occurring salts, it seems intuitive that long-term net salt movement would be in the same direction (up or down) as long term moisture migration. However, since this is such a key assumption of the overall project, literature information supporting this assumption, together with general information on salt migration and accumulation, was compiled and is summarized below.

The movement and distribution of soluble salts is a function of water movement in the subsurface. Salts can be leached from the soil and transported downwards *via* infiltrating water as a result of precipitation, snowmelt or surface runoff. Water is also taken up by plants and evaporated and salts may be concentrated at the evapotranspiration front. Salt concentrations in the surface and shallow subsurface are dynamic and seasonal. However, the net accumulation of salts at the surface over long periods occurs where there is an overall upwards water flux. The accumulation of salts at or close to the surface is referred to by Nachshon *et al.*, 2013 as the "Surface Salt Belt". The depth of the shallow salt accumulation depends on the depth of the rooting zone, water table and soil type (Nachshon *et al.*, 2013) but may also be influenced by freezing of the soil in winter (Gray and Granger 1985).

The most important factor resulting in upwards water flux and surface salt accumulation is net evapotranspiration exceeding precipitation rates. The climate across the prairies of Canada and the United States is typically semi-arid with net potential evaporation exceeding precipitation (Nachshon *et al.*, 2013). However, surface salt accumulation is far from ubiquitous. Other critical factors that increase the risk of surface salt accumulation include groundwater table depth, topography, geology and hydrology (Weibe *et al.*, 2006). These are discussed in more detailed below.

A groundwater table close to (but not above) the ground surface has been identified as a key factor in surface salt accumulation (*e.g.*, Weibe *et al.*, 2006, Hendry and Buckland, 1990, Hendry *et al.*, 1990). Capillary forces cause water to rise from the water table into the unsaturated zone, bringing dissolved salts with it. Where the water table is shallow, this increases the likelihood of capillary rise carrying salts to a depth where they can be concentrated by evaporation, or into the root zone where they may be concentrated by transpiration. Removal of the water by evapotranspiration results in further water being drawn up into the capillary fringe and a net upward flux of water and salt. Where the water table is below a certain critical depth water rising by capillarity would not cause salinitzation of arable soil horizons (Li *et al.*, 2014). The height of capillary rise is dependent on the soil texture and layering.

Surface topography is also a very important factor. In the prairies, wetlands, ponds and other low areas result in "depression-focussed recharge". Even small depressions concentrate the run-off generated by rain and snowmelt in small areas, leading to large infiltration rates. This effect is particularly pronounced where flow from snowmelt is overland due to the frozen ground (Berthold *et al.*, 2004). Low salt concentrations are found directly under areas of depression-focussed recharge due to the leaching of salts by the infiltrating water and downward hydraulic gradients over extended periods of time (Berthold *et al.*, 2004).

Conversely, salt accumulation is often found in the areas around wetlands and ponds and is referred to as the "Saline Ring" (Nachshon 2013) or "Slough Ring Salinity" (Weibe *et al.*, 2006). The high lateral influx of water to the area around the depression results in an increase in the water table and soil moisture content. Despite the influx of water, where there is net evapotranspiration, the overall upwards flux leads to salt accumulation.

High sulphate, chloride and EC values have been recorded within approximately 20 m of recharge areas. The salt accumulations can extend to about 2 m depth, due to the deep and developed root system of the vegetation in these wetter areas (Nachshon *et al.*, 2013). Sulphate concentrations of more than 5,000 mg/L were reported at some locations in a Saline Ring compared with around 400 mg/L in groundwater below areas directly below the depression-focussed recharge (Berthold *et al.*, 2004).

A Saline Ring is also present where groundwater discharges to low lying areas. Salt concentrations around discharge ponds are higher than around recharge ponds (Nachshon *et al.*, 2013). Also, the water in discharge ponds is saline and high salt concentrations are found in the soil below the pond. The high concentrations are a result of the upward hydraulic gradient (Heagle *et al.*, 2013). Weibe *et al.*, (2006) state that the lateral movement of salts *via* groundwater from upland to low lying areas where the water table is closer to the surface is a major cause of salt accumulation in the low lying areas.

Nachshon *et al.*, (2013) developed a conceptual model of prairie salt dynamics, based on observations from a literature review of a wide range of previous field studies on sulphate dynamics in the prairies of North America. Sulphate is the primary salt considered in the model based on its relative abundance in the prairies. The conceptual site model describes the lateral and vertical distribution of sulphate in relation to areas of recharge and discharge. The conceptual model includes areas of sulphate accumulation at surface in areas where the groundwater table is closest to the surface -typically around the margins of recharge or discharge ponds. Sulphate depletion at surface is seen in areas where the water table is deepest – in upland areas between ponds.

Allison and Hughes (1983) noted that recharge rate and drainage flux can be significantly altered by changes in land use such as site clearance or cropping.

Startsev (2009) conducted growth experiments with alfalfa grown in 2 m deep tubes in an indoor environment. A strong upward moisture gradient was applied by supplying water continuously to the bottom of the tubes, and not allowing any moisture to enter the tubes from the top. Salt accumulation was measured at and close to the soil surface after two seasons of growth. The conditions in this experiment are artificial and not representative of grassland conditions in Southern Alberta, however this experiment does confirm that naturally-occurring salts in a soil profile will move upwards over time under the influence of an upward moisture gradient.

Van Schaik and Stevenson (1967) collected data that allowed a direct link to be made between the direction of net annual moisture flux and salt accumulation at surface. The authors installed a total of 12 non-weighing lysimeters that were filled with a uniform clay loam soil. Water tables were maintained at 91, 122, and 152 cm below ground surface (four repetitions each). Net annual moisture flux data are summarized in Table 3, and salt accumulation data are summarized in Table 4.

Table 3 Net Annual Moisture Flux as a Function of Water Table Depth

	Depth to Water Table		
Period	**91 cm**	**122 cm**	**152 cm**
	(cm^3/cm^2)	**(cm^3/cm^2)**	**(cm^3/cm^2)**
June 1 – November 1, 1964	-0.13	-0.74	-1.83
November 1 – June 1, 1965	+0.94	-2.44	-1.50
June 1 1964 to June 1 1965	+0.81	-3.18	-3.33

Notes:

Data from Van Schaik and Stevenson (1967), June 1, 1964 to June 1 1965

Moisture flux is defined as the volume of water per unit area which moves through a horizontal plane over the specified period.

Upward moisture flux is positive, downward movement is negative

Soil is clay loam

Data are average of 4 repetitions

The data in Table 3 show that the net annual water movement from the water table was always downwards when the water table was at 122 cm or 152 cm, but was mostly upwards when the water table was shallower (91 cm). These data provide an important experimental verification of the concept of a critical water table depth below which upwards moisture flux is unlikely.

Table 4 Soil Salinity *vs*. Depth

	Depth to Water Table		
Depth (cm)	**91 cm**	**122 cm**	**152 cm**
	Salinity (mmho/cm)	**Salinity (mmho/cm)**	**Salinity (mmho/cm)**
0 – 2.5	5.23	1.58	1.50
2.5 - 5	2.68	1.39	1.26
5 – 10	2.79	1.56	1.44
10 – 15	1.86	1.45	1.69
15 - 25	1.98	1.82	1.64

Notes:
Data from Van Schaik and Stevenson (1967), June 1, 1964 to June 1 1965
Soil is clay loam
Soil salinity was uniform prior to the 1964 growing season.
Data are average of 4 repetitions

The data in Table 4 show the soil salinity profiles for the same three experimental designs as Table 3 with the water table held at 91 cm, 122 cm, and 152 cm. The salinity profile for the experiment with the water table held at 91 cm shows soil salinity that increases at shallower depths, indicating salt accumulation at the soil surface. This corresponds with the data from Table 4 indicating mostly upwards moisture flux with the water table at this depth. The two experiments with deeper water tables (122 cm and 152 cm) show no such surface accumulation of salt (Table 4) corresponding to a downwards net water flux.

Taken together, the Van Schaik and Stevenson (1967) data presented in Tables 3 and 4 confirm two important points relevant to the current project:

1. Net moisture flux in these experiments was upwards when the water table was shallow, but with the water table below a certain critical depth the net moisture flux was downwards. These data support the concept of the net moisture flux being downwards when the water table is deeper than a critical threshold depth.

2. Net upwards moisture flux in these experiments corresponded to a net accumulation of salinity at surface, while net downwards moisture flux corresponded to no net accumulation of salinity at surface. These data support the concept that the direction of net movement of salt ions is the same as the direction of net moisture movement.

5.2.2 Use of Natural Tracer Compounds to Determine Drainage Rates and Direction

Allison *et al.*, (1994) reviewed physical and chemical methods to estimate recharge in the vadose zone in arid and semiarid areas of Australia (*i.e.*, precipitation less than around 700 mm/yr) . The Allison *et al.*, (1994) review found that physical measurements, such as water balance and Darcy flux methods were the least successful, while methods using naturally-occurring tracers were the most successful. The authors indicated that tracer methods have a very significant advantage over many other methods in that they integrate all the processes that combine to affect water flow in the unsaturated zone. Physical direct methods were found to be problematic due to small fluxes and the high temporal and spatial variability of drainage. Lysimeters were found to be useful to directly measure root zone drainage (especially for coarse soils), but are very expensive to construct and operate. Allison *et al.*, (1994) focussed on chloride, tritium and other naturally-occurring isotopes as tracers.

Berthold *et al.*, (2004) also concluded that environmental tracer methods (*e.g.*, using tritium or chloride) were superior to groundwater recharge measurements based on Darcy's law. This conclusion was based on the fact that environmental tracer methods integrate recharge processes over a long period of time, particularly in clay-rich tills where the groundwater velocities are very low. They observed that the subsurface distribution of solutes represents the spatial variability of recharge flux averaged over a long time period.

Allison *et al.*, (1994) noted that significant spatial variability in the distribution of environmental tracers could be found over a small area, implying a corresponding spatial variability in recharge patterns.

Woods *et al.*, (2013) investigated the field-scale spatial variability of the transport of applied (Cl) and pedogenic (SO_4) tracers, and compared and interpreted these within a soil landscape. Chloride was applied to the ground surface as a tracer in 1966 and 1971, and thus the distribution of chloride represented recharge patterns averaged over approximately 35 years. Sulphate was assumed to have been formed by oxidization of sulphide minerals following the last glaciation, and thus represents recharge patterns over a timescale of the order of 10,000 years.

The distribution of salts over the study areas was complex, resulting in part from the differing timescales for different salts, and also from varying recharge patterns across the site. However, it was clear that both chloride and sulphate had been flushed downwards from the surface over time, and had accumulated in bands below the surface. Over the slightly more "upland" parts of the study area, the chloride was depleted in the top metre, and concentrated in the 1-2 m depth range. Sulphate was typically concentrated in the 2.5 to 3.5 m depth range, reflecting the longer migration timescale for this salt. Both chloride and sulphate were typically depleted to greater depths beneath the slight depressional areas of the site, reflecting the greater recharge in these areas.

Keller *et al.*, (1991) studied hydrogeochemical processes in an 18 m thick till unit below a flat prairie landscape. Once again, significant spatial variability in salt concentrations was found and attributed to depression focussed recharge. The results of the study indicate that the hydrogeochemical variability in the till and water quality in the underlying aquifer are persistent over a ~100 year period.

Taken together, the four studies discussed above confirm that using salts as tracers in the subsurface is a viable method for determining long-term moisture flux patterns in the vadose zone.

5.2.3 Use of Chloride as a Tracer

Several studies using chloride profiles to estimate recharge were reviewed in Allison *et al.*, (1994). Chloride inputs to the surface were assumed to be from rainfall and dry fall out rather than lithological or anthropogenic sources. Vertical chloride concentration profiles correlated well with known changes in recharge rates based on known variations in rainfall and fluctuating lake levels. The author also noted that the depth profiles of chloride concentrations were complex, often with peaks below the root zone that may be attributed to preferential flow, diffusion of chloride to the water table and paleoclimatic induced changes in recharge.

Scanlon *et al.*, (2008) studied the mobilisation of solutes including chloride in the unsaturated zone in semiarid regions of the United States. The study found variable chloride profiles with depth. In one region, peaks in the chloride concentration in the deeper root zone (around 1.6 m depth) were found. In other areas peaks were found at greater depth. This was attributed to differing paleoclimatic conditions. Shallow or surface salt accumulations were not apparent in any of the profiles.

5.2.4 Use of Sulphate as a Tracer

Heagle *et al.*, (2013) used a 19 year mass balance of a wetland pond to demonstrate that sulphate is transferred from surface water to the underlying sediments during dry periods and back to the pond during wetter periods. This shows that the current distribution of sulphate can be used to infer recent patterns of recharge and discharge, and therefore that sulphate can act as an effective pedogenic tracer. This work was supported by groundwater gradients measured over several years. It was suggested by the authors that the repetition of this cycle over long periods has allowed subsurface sulphate to accumulate.

The work of Woods *et al.*, (2013) shows that the sulphate distribution confirms the downward moisture flow direction indicated by the chloride profile, even though the timescales are different.

The distribution of sulphate salts in groundwater and soils was documented at two sites where clayey tills overlie regional aquifers (Keller *et al.*, 1988). Once again, the variability in the distribution of salts was interpreted to be related to the variation in recharge across the site controlled by micro-topography. Sulphate was analysed in soil at depths up to approximately 14 m at locations with horizontal spacing of tens of metres at two different sites. Electrical conductivity measurements were also collected using a non-contacting earth conductivity meter. The authors suggested that soil samples from the boreholes could not adequately characterise the sulphate results. However, electrical conductivity measurements used a larger averaging volume and were able to show a spatially intricate pattern of sulphate abundance and depletion through the oxidised and un-oxidised zone to the underlying aquifer. Sulphate distribution was found to be consistent with groundwater flow patterns.

5.2.5 Comparison of Sulphate and Chloride as Pedogenic Tracers

Research reported in PTAC (2012) demonstrated that chloride and sulphates leached from experimental columns at generally similar rates. Leaching experiments were completed using a range of soil types and compactions and various chloride and sulphate concentrations. Chloride and sulphate were shown to leach at the same rate and clear signs of sulphate retardation was only measured at very high concentrations (5,000 to 10,000 mg/L). Batch adsorption and extraction experiments also indicated that no significant sorption was occurring, and that precipitation is a key process for sulphate transport.

Hayashi *et al.*, (1998) suggest that sulphate is not an ideal tracer because of complicated reduction-oxidation and acid-base reactions. They selected chloride as a tracer in their study as it is conservative. Most plant species do not take up significant quantities of chloride from soil water (Allison *et al.*, 1994).

Sulphate is identified as being susceptible to plant uptake, immobilisation, mineralization and precipitation by Woods *et al.*, (2013), who state that sulphate can still be used to assess relative spatial differences in deep drainage fluxes below the root zone.

Scanlon *et al.*, (2008) studied the mobilisation of sulphate, fluoride and chloride in the unsaturated zone in semiarid regions. The report notes that sulphate, unlike chloride, has multiple sources and sinks including biochemical reactions that alter valence states. Soil samples were analysed for sulphate, fluoride and chloride and sulphur isotopes were measured to evaluate likely sulphate sources. The vertical profiles of sulphate and chloride were very similar in some of the study areas, with peaks occurring at the same depths. However, at other sites, a lag of up to 4 m was found for sulphate. In agricultural areas growing crops, the concentrations of sulphate in areas where chloride has been flushed out were higher than anticipated. The residual sulphate was attributed to incomplete flushing of pre-cultivation sulphate. The potential contribution from anthropogenic sources (*e.g.*, atmospheric deposition and fertilizers) was identified. The reduced mobilisation of sulphate relative to chloride may be related to plant uptake, gypsum precipitation and dissolution, or sorption. Also the cycling of sulphur in organic matter can delay downward sulphate movement.

Varallyay (2006) provides vertical profiles of chloride, sulphate and other ions in soil from three sites. Sulphate concentrations are higher than chloride, but show a similar distribution, with peak concentrations at the same depths.

5.2.6 Pedogenic Tracer Summary

Overall, chloride appears to be a very good pedogenic tracer in areas with significant concentrations of naturally-occurring chloride. Several authors pointed out the advantages of using chloride over sulphate based on very limited interaction with soil minerals and limited uptake by plants. However, in the grasslands of Southern Alberta, the utility of chloride as a pedogenic tracer is limited by the low concentrations of naturally-occurring chloride, and the widespread presence of anthropogenic chloride from oilfield and other activities.

Sulphate can act as an effective pedogenic tracer, particularly in regions with higher natural sulphate concentrations, such as the prairies of Southern Alberta. As pointed out by a range of authors, quantitative interpretation is made more challenging by the larger range of potential interactions in which sulphate ions can engage, including mineral interactions, precipitation, and uptake by plants. These interactions could affect the *rate* at which sulphate ions were flushed relative to moisture flow, but will not affect the *direction* in which sulphate ions will move. Thus, sulphate accumulation at surface will still be an effective indicator of long term upward movement of moisture. Sulphate is selected as the most appropriate pedogenic tracer for the purposes of this project.

5.3 Water Table Depth as an Indicator of the Vertical Migration Potential of Salt

Areas with shallow groundwater can experience a net annual loss of water from the water table due to capillary flow and evaporation or evapotranspiration at the surface. This net upward movement of water will tend to result in an accumulation of salinity at the ground surface. The critical value of water table depth for this to occur is a function of soil type and climatic conditions, and therefore will vary from region to region. For Southern Alberta, this process is generally considered to be a concern when the water table is shallower than approximately 1 to 1.5 m (Bennett, 1990; Van Schaik and Milne 1962, 1963; Van Schaik and Stevenson, 1967). Alberta Agriculture and Forestry (2013) suggest that in general, the water table must be within 2 m (6 ft) of the soil surface for this occur, but that the critical depth varies with soil texture. Specific studies investigating the critical depth are discussed below.

5.3.1 Southern Alberta Field Studies

Van Schaik and Milne (1962) noted that the standard practice in arid areas of the United States at that time was to install tile drains at 5 ft depth (1.5 m) to reverse soil salinization due to shallow water tables. The authors investigated whether tile drains at 30" (0.75 m) depth would be sufficient to reverse soil salinization due to shallow water tables in a study near Vauxhall, Alberta. They found that dropping the water table to 0.75 m was not sufficient to resolve the soil salinity issue unless 1.8 m of irrigation water was applied. The implication of this study is that the critical water table depth for these soils in this climate lies somewhere between 0.75 m and 1.5 m depth.

Van Schaik and Milne (1963) undertook a follow-up study at the same site where the water table was maintained at approximately 3 ft (0.9 m). They found that this water table was not sufficiently deep to prevent soil salinization beneath a surface cover of grass. The implication of this study is that the critical water table depth for these soils in this climate lies somewhere between 0.9 m and 1.5 m depth.

In a field study at the Lethbridge Research Station in Southern Alberta, Van Schaik and Stevenson (1967) set up a range of studies to determine the minimum depth at which the water table can be maintained without causing harmful accumulation of salts at the surface. The authors installed a total of 12 non-weighing lysimeters that were filed with a uniform clay loam soil. Water tables were maintained at 91, 122, and 152 cm (four repetitions each) and observations were made over two seasons. The soil surface was kept bare. After the first year of data, net upward annual water movement and salt accumulation at surface was measured in lysimeters with the water table at 91 cm, but not when the water table was 122 cm or 152 cm (Tables 3 and 4). Based on their results, the authors concluded that net downward movement of water was expected if the rainfall between June 1 and November 1 equals or exceeds 15 cm, and the water table depth is greater than 1 m. Conversely they point out that surface salt accumulation is a concern where the water table is shallower than 1 m. The authors also note that the low evaporation of groundwater at the soil surface that they measured may help explain the lack of salt accumulation at the soil surface at Lethbridge compared with that in many areas of the western United States.

Bennett (1990) conducted a three year observational study on plots of cropped soils (clay loam to clay) adjacent to rehabilitated irrigation canals in Southern Alberta. Previously, 70% of salinized soils in the irrigated areas of Southern Alberta had been attributed to leakage from irrigation canals resulting in shallow water tables and associated soil surface salinization. Rehabilitation efforts in the 1970s and 1980s included relining many of the irrigation canals and thus greatly reducing the leakage of irrigation water. Bennett (1990) set up three study plots at each of 8 locations adjacent to a rehabilitated canal section to look for improvements in the salinity status of the soils as a result of the expected falling water tables. Water table depths were quite variable throughout the year. A general decrease in the level of the water table was observed in only about half of the affected areas. Little improvement in soil salinity was seen when the water table depth was as shallow as 1 to 1.5 m. However, the author was able to conclude that an improvement in the salt status of some soils was detected when water table levels were maintained at depths greater than 1 – 1.5 m through most of the growing season.

In a wide ranging survey of soil salinity with more than 500 samples of soil salinity in three irrigation districts in Southern Alberta, Chang *et al.*, (1985) correlated soil salinity with water table depth. In the Taber Irrigation District they found a statistically significant decrease in soil salinity with increasing water table depth, with a mean soil EC of 2.51 dS/m for a water table depth of 1.2 m, and an EC of 1.52 dS/m for a water table depth of 1.5 m. In the Western Division of the St Mary River Irrigation District they found a statistically significant decrease in soil salinity with increasing water table depth, with a mean soil EC of 1.77 dS/m for a water table depth of 1.2 m, and an EC of 0.24 dS/m for a water table depth of 1.5 m. In the Lethbridge Northern Irrigation District they also found a decrease in soil salinity with increasing water table depth, however the decrease was not statistically significant.

5.3.2 Field Studies from Other Locations

Studies from other regions are less relevant to the current project than Southern Alberta studies, since key climate parameters can be very different. However, the two following studies are included for completeness.

In a southeast Australia study, where on the average potential evapotranspiration exceeds rainfall over the whole of the year, (Talsma, 1963) determined the salinity hazard of fine-textured soils is markedly reduced if the water table is kept about 1.2 m below the surface of a bare soil or 1.2 m below the rooting zone of a cropped soil.

In a Western Australia study Nulsen (1981) illustrated that the critical depth of a saline water table (loamy sand to sandy clay textures) for agricultural production (wheat and barley) is 1.5 to 1.8 m.

5.3.3 Water Table Depth - Summary

A range of field studies providing information on the critical groundwater depth for soil salinization were summarized in the preceding section. For grasslands in Southern Alberta, most of the field studies agree that a water table greater than 1.5 m carries minimal risk of soil salinization. Alberta Agriculture and Forestry (2013) are slightly more conservative indicating that soil salinization is unlikely where the water table is deeper than 2 m. The more conservative value of 2 m is adopted herein as an indicator depth for the water table, below which there will be little risk of soil salinization. This does not imply that a water table depth shallower than 2 m will result in future soil salinization at a given site.

6.0 OTHER EXPOSURE PATHWAYS

A closure strategy for any salt-affected site must ensure no current, and no likely future adverse effects for all relevant exposure pathways and receptors. The primary relevant exposure pathways for salt sites are the following:

- ecological direct contact;
- protection of potable drinking water;
- protection of freshwater aquatic life and wildlife watering in natural surface water bodies; and
- protection of livestock watering in dugouts.

The ecological direct contact pathway has been addressed in this report. Existing tools are available and should be used to assess the other exposure pathways indicated above. These existing tools include the Subsoil Salinity Tool (ESRD, 2014), available options within the Alberta Tier 1/ 2 guideline document (AEP, 2019a,b) and other approaches that generate Tier 1or Tier 2 equivalent guidelines.

7.0 CLOSURE

This report was prepared by Millennium EMS Solutions Ltd. ("MEMS") for the Petroleum Technology Alliance of Canada ("PTAC") and has been completed in accordance with the PTAC Technical Steering Committee's ("TSC") terms of reference. This report does not necessarily represent the views or opinions of PTAC or the PTAC members.

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