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Salt-Affected Wellsite Closure Project
Scientific Rationale Document

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Introduction

There are a large number of oil & 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. Given these concerns, an alternative method of managing such sites is needed. Petroleum Technology Alliance Canada (PTAC) has initiated a project to look for solutions to these issues for all relevant exposure pathways and land uses. The current document is focussed specifically on issues relating to the ecological direct contact exposure pathway (growth and reproduction of plants and soil invertebrates) in native grasslands areas of Alberta, and develops an Alternate Closure Protocol to identify sites which have no current, and no likely future adverse effects on native grassland ecosystems.

Relevant background data on native grassland ecosystems and on the factors controlling the movement of moisture and salts in prairie soils was compiled and summarized. A regional moisture flux modelling study was completed for south eastern Alberta to identify the predicted variation of water table indicator depth across the region. The term water table indicator depth is used in this document to reflect a water table depth below which salt accumulation at surface is considered unlikely.

Alternative Closure Protocol

An alternative closure protocol was developed in this document for salt-affected wellsites in native grassland habitats in south eastern Alberta.

The Alternate Closure Protocol has three main steps:

Step #1) Demonstrate that the site conditions are having no current adverse effect on the grassland plant community.
Step #2) Demonstrate that the site conditions are not likely to have an adverse effect on the grassland plant community in the future.
Step #3) Demonstrate that the site conditions are not likely to have an adverse effect on any other receptors via relevant exposure pathways.

Successful completion of Step #2 requires a favourable outcome from all three of the following tasks:

Step #2a) use a modelling approach to demonstrate that long-term net upward migration of moisture in the vadose zone is unlikely;

Step #2b) demonstrate that there is no long term tendency for natural salts to accumulate at the soil surface by using the vertical profile of sulphate concentrations in soil; and

Step #2c) demonstrate that there is no long-term tendency for salts to accumulate within the root zone even in cases where there is no salt accumulation at surface.

If all the above steps are successfully completed then the site can proceed to regulatory closure via the Alternate Closure Protocol. Further details on each of the three steps are provided in the document.

1.0 INTRODUCTION

There are a large number of oil & 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, an alternative method of managing these sites needs to be found. The alternative method should be efficient (cost, timely) and science-based. Such a process for characterizing and risk assessing salt sites would enable timely, economic regulatory closure and would significantly reduce "net negative" environmental benefit. This would be beneficial to landowners, regulators, the public and industry. Petroleum Technology Alliance Canada has initiated a project to look for solutions to these issues for all relevant exposure pathways and land uses. The current document reports specifically on issues relating to the ecological direct contact exposure pathway (growth and reproduction of plants and soil invertebrates) in native grasslands areas of Alberta.

1.1 Project Structure and Scope

This project was initiated in Fall 2014 as a collaborative initiative between select industry partners and the regulatory community. The title of the original project was "Native Prairie SSRA Guidance at Southern Alberta Sites". In September 2015, the project was absorbed into a wider, PTAC-funded project entitled "Salt-Affected Wellsite Closure Project". The objectives and scope of these two projects are related, but not identical, and are indicated below.

1.1.1 Native Prairie SSRA Guidance at Southern Alberta Sites – Objective and Scope

The objective of the original project was to develop scientifically-based guidance supporting site-specific risk assessment (SSRA) at native grassland sites in Southern Alberta.

At this stage the main thrust of the project was focussed towards gaining a better understanding of the depth profile of the rooting zone in native grassland communities, and how this depth profile was likely to change over time as disturbed areas progressed along a trajectory towards a mature grassland community.

The scope of the original project was specified in a letter to the participants dated November 12, 2014, and included the following tasks:

1. Identify the relevant plant receptors for a native prairie setting in Southern Alberta.
2. Compile available information on the time required for these relevant plant receptors to reach maturity, both as individual species and as a community.
3. Compile available information on representative maximum rooting depth values for relevant plant receptor species.
4. Initiate literature-based research to determine whether net downward flow of water in the vadose zone is a sufficient condition to preclude the upwards migration of salts and other contaminants.
5. If feasible, develop soil guideline management limits for salts and petroleum hydrocarbons specific to native grassland settings in Southern Alberta.
6. Generate a scientific rationale document summarizing the information collected in the above tasks.
7. In collaboration with industry members and the regulatory community, develop a protocol document to facilitate closure of wellsites on native grassland.

1.1.2 Salt-Affected Wellsite Closure Project – Objective and Scope

The overall objective of the PTAC project is to develop scientifically-defensible protocols to identify salt-affected sites that have no current, and no likely future, adverse effects and provide a viable path to regulatory closure for these sites. This will be accomplished by developing protocols tailored to different exposure pathways, land classes and regions.

The current phase of the PTAC project reported in this document is directed towards understanding the conditions required to have confidence that deeper salts will not migrate back up into the rooting zone in the future. If the existing development of native vegetation indicates that the grassland community is progressing satisfactorily along a pathway towards no current adverse effect, then the lack of future upward salt migration will provide confidence that no future adverse effect will be expected either.

The scope of the current phase of the PTAC project includes the following tasks:

1. Develop and revise the protocol document; participate in regulatory discussions, meetings, and TSC communications.
2. Investigate the use of the natural sulphate soil profile to determine the long-term tendency for vertical salt movement in the subsurface.

3. Conduct a regional unsaturated zone modelling study to attempt to identify specific eco-zones within the native grasslands area of Alberta with and without the potential for upward salt migration.
4. Investigation of the effect of water table depth on potential for upward salt migration.

Note that the current phase of the PTAC project focusses on issues related to demonstrating no current or likely future adverse effect in relation to the ecological direct contact exposure pathway for sites within the native grassland areas of Alberta. Other initiatives will consider other exposure pathways and other land uses/regions.

1.2 Related Documents

This scientific rationale document summarizes the background information and research collected to meet the scope of both the original "Native Prairie SSRA Guidance at Southern Alberta Sites" project and the PTAC "Salt-Affected Wellsite Closure" project. Other related reports and initiatives include the following:

- A literature study has been initiated at the University of Alberta compiling existing information on soil salinity effects on vegetation found in Alberta. Results of this work will be reported under separate cover.
- A "Protocol Document" (Scope item #7 of the original project and #1 of the PTAC project) is being developed under separate cover that will provide a streamlined path to site closure for salt-affected sites on native grassland.
- Other related documents specific to other different land classes and regions may be developed as the project evolves.

1.3 Funding Acknowledgements

This work was made possible by an initial commitment to funding from the following organizations:

- Canadian Natural Resources Limited;
- Cenovus Energy; and
- ConocoPhillips Canada Limited;
- Husky Energy;
- Millennium EMS Solutions Ltd.

However, it was later decided to roll the original initiative into a PTAC project, and the project was funded under PTAC Project #15-SGRC-08.

1.4 Native Grassland Protocol Technical Steering Committee

A technical steering committee (TSC) was assembled to guide the development of a protocol specifically directed at streamlining the closure of salt-affected sites on native grassland. The TSC included the following individuals, whose valuable contributions are 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.

2.0 BACKGROUND TO NATIVE GRASSLAND INITIATIVE

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, 2013a) 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 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 may not justify the ecosystem damage that would be caused. 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 SOUTHERN ALBERTA NATIVE GRASSLAND PLANT COMMUNITY INFORMATION

Section 3 summarizes available information on Southern Alberta native grassland plant communities, focussing on the rooting depth of native grassland species and how that evolves over time. This information is relevant to the overall initiative since salts can only affect plant communities if the salts are currently within the rooting zone, or move into the rooting zone over time.

3.1 Ecoregions

Grassland ecosystems occur to varying degrees in the Grassland, Parkland, Foothills and Rocky Mountain Natural Regions of Alberta (ESRD, 2013a). Four Natural Subregions are defined for the Grassland Natural Region: Dry Mixedgrass, Foothills Fescue, Mixedgrass, and Northern Fescue.

The Dry Mixedgrass Natural Subregion was selected as an example (due to the aridity of the region and the difficulty in re-establishing the climax plant community on disturbed wellsites) to see whether sufficient information might be available to define the relationship between rooting depth and time since reclamation. This relationship is relevant to the question of how much time is required before rooting depth is essentially stable. A stable rooting depth would be a characteristic of a climax or reference plant community. The reference plant community is determined by many factors including but not limited to climate, soils and aspect. Salts are found naturally in the subsoil of prairie plant communities. If the soils are unstable or inhospitable than it would be evident in the results of a range health assessment. A "Poor" or "Healthy with Problems" rating would indicate issues with species composition, plant vigor and percent cover.

While rooting depth is still increasing, it is possible that roots may access deeper soils with higher salt concentrations and result in possible future growth impact.

3.1.1 Dry Mixedgrass Natural Subregion

The dry mixed grass natural subregion is one of four grassland subregions in Alberta. It occurs at the southern extent from the Alberta-Montana border to north of Oyen, and the western extent to Hanna. This subregion is characterized by dominantly level landscapes with intermittent hummocky and low relief terrain in the form of coulees. Generally speaking the dominant soils are Brown Chernozemic and dominant vegetation is needle and thread grass (*Stipa comate*) and blue grama grass (*Bouteloua gracilis*).

Soil correlation guidelines to link soils to range site types for the Dry Mixedgrass subregion can be found in the Range Plant Communities and Range Health Assessment Guidelines of the Dry Mixedgrass Natural Subregion of Alberta (Adams *et al*, 2013).

Within the Dry Mixedgrass subregion are numerous documented ecological range sites and related reference plant communities based on 40+ years of research by public lands (ESRD). These have all been mapped by the Grassland Vegetation Inventory (GVI) which was completed for the entire grasslands and parkland region of Alberta. The GVI can assist in determining which plant community a site is located (ESRD, 2011). Plant communities are surface expression of the soils and climate of the ecosite. Certain plant communities include species that are more salt tolerant than others, regardless of their rooting depth.

The most common reference plant community in the Dry Mixedgrass subregion is DMGA3 which is dominantly blue grama grass (*Bouteloua gracilis*), needle and thread grass (*Stipa comata*), and Junegrass (*Koeleria macrantha*) ,with a number of other grasses and forbs. A common shrub species is silver sagebrush (Artemisia cana) which is often indicative of overflow or more mesic sites.

3.2 Rooting Depth Information

Dry mixed grass prairie is characterized by hot, dry growing conditions, and a precipitation to evaporation ratio of 0.3-0.4:1. This low level of precipitation leads to an allocation of 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 Dry Mixedgrass subregion. 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.

See also information in the AEP (2016) Range Plant Community Guide.

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 communities, and is indicative of reference plant communities in the Dry Mixedgrass subregion. 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. Needle and Thread grass is common throughout the DMGA, except for clayey sites on soils (DMGA8) and more most of the overflow sites since they have higher moisture. *Stipa Comata* is considered a tall grass with respect to plant community structure in the DMGA 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. Western wheatgrass is considered to have excellent forage quality. It is recommend that Western wheatgrass is not be seeded at more than 10% of seed mix as it will recolonize on its own naturally and is aggressive. Western wheatgrass is susceptible to ergot.

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.

Table 1 Selected Alberta Grassland Species and Rooting Depths

		Rooting Depth (m)		
Common Name	**Scientific Name**	**Majority of Roots**	**Maximum Observed**	**Source**
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	

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 extended down to 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 the dry mixed grass subregion, 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 reached 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. Scarlet mallow is a common forb throughout DMGA.

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 a present throughout DMGA with varying percent cover ranging from 1-30%. Indicative of overflow or seasonal flooding/water flow. Silver sagebrush is a very important species with respect to wildlife habitat and food source, including sage grouse and pronghorn antelope.

3.3 Time to Maturity for Grasslands Ecosystems

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.

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.

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.

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.

3.4 Time to Maturity for Individual Grassland Species

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.

3.5 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.

Gates *et al*., (2010) found that sagebrush cover was reduced on disturbances where additional reclamation seed mix had been applied. She concluded that natural recovery, coupled with minimal disturbance techniques is the preferred reclamation approach for the Dry Mixedgrass region.

3.6 Approach to Identifying Sites with Rooting Zones Approaching Stability

One of the goals of this section was to provide a methodology to help identify sites where the rooting zone of grassland species was approaching stability, thus mitigating any concern about roots accessing salts in deeper soils in the future. Available information in the literature was compiled with the objective of determining a threshold time after which the rooting zone of reclaimed native grasslands could be assumed to be approaching stability. However, existing literature are not available to support a specific threshold time. An alternative approach was adopted, whereby it is assumed that a site which meets the appropriate native grassland reclamation criteria specified in ESRD (2013a) will be approaching or will have achieved stability of the depth of the rooting zone.

4.0 MANAGEMENT LIMITS FOR GRASSLANDS SITES

Developing region-specific management limits, if feasible, for petroleum hydrocarbons and salts on grassland sites was part of the scope of work for the original native grassland SSRA project.

Management limits are an important part of the Alberta Framework for the Management of Contaminated Sites (see ESRD, 2016a). They effectively provide upset limits for guideline values regardless of which exposure pathways have been excluded or which guidelines have been modified. Currently ESRD (2016a) has published management limits only for a very limited selection of chemicals, including petroleum hydrocarbon fractions and methanol.

Existing management limits consider issues other than the toxicological endpoints which are the basis of the guidelines for other exposure pathways.

4.1 Petroleum Hydrocarbon Management Limits for Grasslands

Generic management limits for petroleum hydrocarbons in ESRD (2016a) were adopted from the values developed in the Petroleum Hydrocarbon Canada-Wide standard (CCME, 2008), and were based on the following series of six considerations:

- mobile free phase formation;
- exposure of workers in trenches to PHC vapours;
- fire and explosive hazards;
- effects on buried infrastructure;
- aesthetic considerations; and
- technological factors.

The six considerations noted above are not all relevant to a grassland setting. In addition, the data on which some of the six considerations were quantified in CCME (2008) were rather limited. Accordingly, there is a concern that the existing management limits adopted in the Alberta Tier 1 guidelines may not be particularly appropriate for application at a grassland site. The six existing considerations were assessed for applicability at grassland sites, and the findings are summarized below.

Free Phase Formation. This was retained as a valid consideration due to the potential for a plume of mobile free phase hydrocarbon to move off site. However, the data used to quantify this consideration in CCME (2008) were limited and only semi-quantitative. Much more defensible data for petroleum hydrocarbon fractions F2 and F3 based on commissioned lab data are available in PTAC (2013). The threshold values developed in that work, below which formation of free phase was not expected, were as follows:

- F2 Fine Soil: 10,000 mg/kg;
- F2 Coarse Soil: 9,000 mg/kg;
- F3 Fine Soil: 14,000 mg/kg; and
- F3 Coarse Soil: 34,000 mg/kg.

These values were adopted for the current initiative.

Trench Inhalation Exposure for Workers. This consideration was based on a scenario of a worker in an urban utility trench being exposed to vapours. This consideration was not considered relevant to a grassland setting since, in general, utility trenches will not be installed in this setting, and the issue can be managed using appropriate personal protective equipment should it arise.

Fire and Explosion. This was retained as a valid consideration. However, the approach adopted in CCME (2008) was an indirect modelling approach. More robust data for F2 and F3 are available in PTAC (2013) based on actual flammability tests with F2 and F3 spiked into two different standard soils. None of the soils (or the pure F2 or F3 cuts themselves) were flammable at room temperature, and these data are adopted here.

Buried Infrastructure. It was felt that this was primarily an urban issue and not expected to be a limiting consideration for most sites in a grassland setting. In addition, attempts to quantify threshold hydrocarbon concentrations in relation to this issue have been unsuccessful to date.

Aesthetics. This issue is difficult to quantify and is expected to be of little relevance in a grassland setting where the soil profile is not expected to be disturbed. Overall, it is considered unlikely that this issue will be a limiting consideration.

Technological Factors. This issue was poorly defined in CCME (2008) and it is felt that there is limited value in retaining it.

Two other issues are added that could be potentially relevant to setting management limits for grassland sites. These issues were not considered by CCME (2008) or AENV (2014a), and are:

Hydrophobicity. High concentrations of hydrocarbons can cause soils to become hydrophobic under certain circumstances. This phenomenon was investigated in PTAC (2013), and the thresholds below which no hydrophobicity was seen were as follows:

- F2 Fine Soil: >64,000 mg/kg;
- F2 Coarse Soil: >64,000 mg/kg;
- F3 Fine Soil: 40,000 mg/kg; and
- F3 Coarse Soil: 4,000 mg/kg.

Upwards Migration into Root Zone. There was a concern that higher concentrations of hydrocarbons in subsoil could potentially migrate back up into the rooting zone. This phenomenon was considered in PTAC (2013), but deemed not to be a limiting consideration of the basis of experimental work by Startsev (2009) with alfalfa grown for two seasons in 30 cm diameter 2 m tall tubes with 1.5 m of clean soil over 0.5 m of soil contaminated with hydrocarbons. A strong upward moisture gradient was created by providing water only from below. The author found that after two seasons growth there was negligible hydrocarbon detectable in the 1.5 m clean soil zone.

Overall, therefore, the four considerations that are identified as a basis for developing Green Zone management limits for petroleum hydrocarbon fractions are as follows:

- mobile free phase formation;
- fire and explosion;
- hydrophobicity; and
- upwards migration into root zone.

All four of these issues were investigated in detail in PTAC 2013, and the findings of that report for each consideration listed were deemed to be applicable to a grassland setting and are adopted here. No attempt was made to adjust the generic management limits for petroleum hydrocarbon fractions F1 and F4, for reasons provided in PTAC (2013). The petroleum hydrocarbon management limits developed for grassland are summarized in Table 3.

Table 3 Grassland Management Limits for Petroleum Hydrocarbon Fractions (mg/kg)

Fraction	Fine Soil	Coarse Soil
F1	800	700
F2	10,000	9,000
F3	14,000	4,000
F4	10,000	10,000

Note: Full details regarding the source of these values are available in PTAC (2013)

4.2 Salts

A brief assessment of the eight total management limit considerations was made for salts, and summarized below.

- Mobile free phase formation: not relevant – salts do not form a free phase.
- Exposure of workers in trenches to vapours: not relevant – salts are not volatile.
- Fire and explosive hazards: not relevant – salts are not flammable.
- Effects on buried infrastructure: not relevant in a native grassland setting.
- Aesthetic considerations: not relevant - no particular aesthetic considerations related to salts.
- Technological factors: not relevant.
- Hydrophobicity: not relevant – salts do not cause hydrophobicity.

- Upwards migration back into root zone: potentially relevant, but dealt with elsewhere.

The only other potential consideration that is apparent for salts is the potential for changes in soil physical properties due to the presence of salts. However, since this consideration is managed through the application of guidelines for sodium adsorption ratio (SAR) it is not necessary to include this consideration in a management limit.

None of the potential considerations for setting management limits are relevant for salts, and accordingly, management limits are neither relevant nor needed for salts.

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 (AENV, 2014a).

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):
  - linkage between water migration and salt migration; and
  - use of naturally occurring salts as pedogenic tracers.
- Investigating the linkage between water table depth and risk of salt accumulation at surface (Section 5.3):
  - field studies reported in the literature;
  - theoretical studies reported in the literature; and

- a regional modelling study conducted for the grasslands region of south-eastern Alberta.

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 at the surface. Conversely, the absence of such an accumulation of naturally-occurring salts 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 Dynamics of Salt Migration and Accumulation

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 are 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 shallow 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 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 are 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 depth water rising by capillarity would not cause salinization 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 these 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 the 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 *et al.*, (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 filed 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 4, and salt accumulation data are summarized in Table 5.

Table 4 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 4 show that the net annual water movement from the water table was upwards only when the water table was at 91 cm, and downwards for both the cases with deeper water tables. The data in Table 5 show increasing soil salinity at the surface for the case with the water table at 91 cm, and no corresponding surface accumulation for the two cases with deeper water tables.

Overall, the data summarized in this section provide a convincing body of evidence confirming that net upward water movement results in accumulation of salts at surface, while net downward water movement results in no accumulation of salts at the surface.

Table 5 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

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.

5.2.3 Use of Chloride as a Tracer

Several studies where chloride profiles were used 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 a,b). 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 Relationship between sulphate and chloride concentrations

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, and sulphate can be used as a pedogenic tracer for the purposes of this project.

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

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 trains 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 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 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 4 and 5). 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 the1970s 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 Theoretical Studies

In a modelling study on the risk of soil salinization from groundwater influenced by seawater intrusion in coastal Queensland, Werner and Lockington (2004) calculated critical water table depths for soil salinization for three soil types (sand, sandy clay loam, and sandy clay). These authors predicted minimal soil surface salinization when the water table was at 3 m or 2 m, but significant soil surface salinization when the water table was at 1 m.

Shah *et al.*, (2007) used variable saturation flow theory to simulate groundwater evapotranspiration for three land covers and a range of soil properties under continuous drying soil conditions. Using computer modelling the authors simulated an initial ground surface water table under consistent diurnal evapotranspiration. Over successive time steps they were able to separate contributions to evapotranspiration between water within the vadose zone and water from the groundwater table as the water table decreased. They were thus able to attempt to predict the extinction depth (water table depth below which the contribution of groundwater to total evapotranspiration is less than 0.5%) for three surface cover types and twelve soils. The authors determined that under grass cover (assumed rooting depth = 1 m) the extinction depth ranged between 1.45 m in the most coarse soil (sand) to 7.15 m in the finest soil (clay).

It should be noted that:

- Potential evapotranspiration (PET) under both vegetated and bare soil conditions was applied at a consistent diurnal time step and did not account for times where PET may be negligible (under frozen soil conditions).
- The PET rate was deemed to be reflective of large parts of the United States.
- The simulations did not feature precipitation events which the author conveys would increase the contribution to evapotranspiration from vadose zone held water versus groundwater.

Overall, the results of this study are more applicable to arid regions with little irrigation or precipitation input. The parameters used mean that the results of this study have little relevance to conditions in Southern Alberta.

5.3.4 Southern Alberta Modelling Study

A modelling study was set up using the model code Hydrus 1-D to determine an indicator depth for the water table for three representative soil types and for seven representative locations distributed around the grasslands region of Southern Alberta. In this context, an indicator depth for the water table is defined as the shallowest water table depth that is not predicted to result in the potential for long-term upward movement of moisture and corresponding upward movement of salts.

Full details of the study are provided in Appendix A. Key elements are summarized below.

Three soil types were used in the model:

- silty clay;
- clay loam; and
- sandy loam.

Climate data for seven different Southern Alberta grasslands locations were used in the model, based on towns for which climate data were available (see Appendix A for details):

- Brooks;
- Calgary;
- Coronation;
- Lethbridge;
- Medicine Hat;
- Suffield; and
- Vauxhall.

Daily precipitation data were taken from the Environment Canada 1981 to 2010 climate normals (Environment Canada, 2015) for the station in question. All available data were considered, and the daily precipitation data for the year with total precipitation closest to the 30 year mean total precipitation were selected.

Monthly evapotranspiration data for each station were taken from ESRD (2013b).

A 1-dimensional unsaturated zone model was set up for each location and soil type. Climate parameters for each location were selected as indicated above. Each model was run for up to 100 years until the net moisture flux values were not changing from year to year, and the stable, long-term water flux and direction (up or down) could be determined. This was repeated for a range of different assumed water table depths, and the moisture flux was plotted against water table depth to determine an indicator depth for the water table below which there was no risk of net upwards moisture and salt movement.

The estimated indicator water table depths for the seven locations and three soil types are summarized in Table 6.

Table 6 Estimated Indicator Water Table Depth

	Depth to Water Table (m)		
Location	**Silty Clay**	**Clay Loam**	**Sandy Loam**
Brooks	0.49	0.55	0.54
Calgary	0.13	0.66	0.56
Coronation	0.35	0.58	0.56
Lethbridge	0.38	0.81	0.64
Medicine Hat	0.19	0.78	0.63
Suffield	0.20	0.51	0.52
Vauxhall	0.24	0.67	0.57

Overall, these model results give estimated indicator water table depth values that in most cases only have a minor variation between the seven locations, suggesting that a single conservative value for indicator water table depth may be appropriate for all native grasslands areas of Southern Alberta. The values of indicator depth estimated for the clay loam soil are in the range of 0.55 m to 0.81 m

(Table 6). This is a little shallower than the indicator depth identified by the Van Schaik and Stevenson (1967) field study of between 0.91 m and 1.22 m. The coarser sandy loam soil had slightly shallower estimated indicator water table depths than the clay loam (Table 6).

The important conclusion to be drawn from these results is that for three different representative soil types and seven climate regimes relevant to the native grasslands of south eastern Alberta, upwards migration of soil moisture and salts to the surface is not a concern whenever the water table is at a depth of 1.0 m or greater.

5.3.5 Water Table Depth Issue - Summary

Various field and modelling studies and other sources of information relating to 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 little risk of soil salinization. The southern Alberta modelling study conducted for the current project (Section 5.3.4 and Appendix A) confirms that no net upwards water or salt migration is predicted for Southern Alberta grasslands for three representative soil types when the water table is at 1.5 m or deeper. Accordingly, 1.5 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 above 1.5 m is an indicator depth that future soil salinization will occur.

6.0 ALTERNATE CLOSURE PROTOCOL FOR SALT-AFFECTED WELLSITES ON NATIVE GRASSLAND

6.1 Introduction and Context

The default approach to managing soil salinity at Alberta sites is via Tier 1 guidelines for electrical conductivity (EC) and sodium adsorption ratio (SAR). The Alternate Closure Protocol provides a parallel, but separate methodology to ensure that valued receptors do not experience adverse effects, and accordingly, sites successfully meeting the criteria of the Alternate Closure Protocol do not need to meet the default Tier 1 guideline values for EC and SAR.

This Alternate Closure Protocol applies to sites on native grassland in Alberta with salt contamination exceeding the generic Tier 1 guidelines. Generic guidelines are a useful component of the Alberta regulatory framework because they are easily administered and have clear remedial endpoints. However, 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. In the case of native grassland, disturbing a site which is on a trajectory to recovery is undesirable due to the length of time required for a stable grassland ecosystem to re-establish and also due to the danger of the incursion of weed species.

This protocol is a tool to help identify sites where leaving existing concentrations of salts in place in soil will not result in adverse effects on any valued receptor, and provides an alternative route to regulatory closure for such sites.

6.2 Overview

The Alternate Closure Protocol has three main steps:

Step #1) Demonstrate that the site conditions are having no current adverse effect on the grassland plant community.

Step #2) Demonstrate that the site conditions are not likely to have an adverse effect on the grassland plant community in the future.

Step #3) Demonstrate that the site conditions are not likely to have an adverse effect on any other receptors via relevant exposure pathways.

If all three steps are successfully completed then the site can proceed to regulatory closure via the Alternate Closure Protocol. Details of how to implement each of the three steps are provided in the following sections.

6.3 Step #1: Demonstrate No Current Adverse Effects (Plant Community)

Step #1 is based on showing that a healthy native grassland community, equivalent to the pre-disturbance community, has been re-established on the site. The current parameters for demonstrating that an equivalent grassland community has been re-established are provided in the Reclamation Criteria for Wellsites and Associated Facilities for Native Grasslands (ESRD, 2013a). The proponent is referred to that document for detailed procedures and protocols.

In order to proceed with the Alternate Closure Protocol, sites must meet all requirements of the most recent version of the Reclamation Criteria for Wellsites and Associated Facilities applicable to Native Grasslands (currently ESRD, 2013a), with the following change:

- A site proceeding with the Alternate Closure Protocol must meet the reclamation criteria applicable to sites constructed on or after January 1, 1993 and abandoned/reclaimed after 2010 regardless of the actual dates of construction, abandonment and reclamation.

Sites that meet the above criteria will be deemed to have successfully demonstrated no current adverse effects with respect to the ecological direct contact exposure pathway. The next step is to demonstrate no likely future adverse effect, as described in the next section.

6.4 Step #2: Demonstrate No Likely Future Adverse Effects (Plant Community)

Meeting the criteria in Step #1 implies that a healthy native grassland community has been re-established on the site, and is on a satisfactory successional trajectory. This demonstrates that there is no current adverse effect with respect to the ecological direct contact pathway. However, long term moisture movement patterns in the subsurface can redistribute salts over time, and therefore could potentially move salts into the rooting zone and result in future adverse effects.

Step #2 provides a methodology for demonstrating that root zone salinity is unlikely to increase over time, and therefore that future adverse effects are unlikely if Step #1 conditions are met.

Successful completion of Step #2 requires a favourable outcome from all three of the following tasks:

Step #2a) Use a modelling approach to demonstrate that long-term net upward migration of moisture in the vadose zone is unlikely; AND,

Step #2b) Demonstrate that there is no long term tendency for natural salts to accumulate at the soil surface by using the vertical profile of sulphate concentrations in soil; AND,

Step #2c) Demonstrate that there is no long-term tendency for salts to accumulate within the root zone even in cases where there is no salt accumulation at surface.

If all three of the above conditions can be met, this is considered sufficient to demonstrate no likely future adverse effects. Further details of what is needed to demonstrate each of the above requirements successfully are provided in the following three sections.

6.4.1 Step #2a: Vadose Zone Soil Moisture Modelling

Several authors have demonstrated that long-term net upward moisture migration can result in upwards salt movement towards the root zone and soil surface while long term net downwards moisture movement tends to flush salts down away from the soil surface and out of the root zone. Accordingly, using a modelling approach to demonstrate the direction of net long term moisture movement in the vadose zone is an important step in determining whether upwards salt migration is a concern at a particular site.

The requirements to demonstrate Step #2a are as follows. A site-specific soil moisture model to determine the direction (upwards or downwards) of the long-term net moisture flux in the vadose (unsaturated) soil zone is required. The HYDRUS-1D software program (Simunek *et al.*, 2013) is one such commercially available model, though other models would be acceptable with suitable justification. Detailed instructions on running unsaturated zone models are not included here, but as a minimum, the model would have to use appropriate local daily precipitation information, appropriate local monthly evaporation/evapotranspiration data, and soil properties and ground cover representative of the site. The model needs to be run for a sufficient length of time so that stability in vertical moisture flux can be demonstrated, and the model must clearly demonstrate the direction (upwards or downwards) of moisture flux under stable conditions.

6.4.2 Step #2b: No Surface Accumulation of Natural Salinity

Many authors have investigated the use of naturally-occurring salts as pedogenic tracers. That is to say they use the current distribution of naturally-occurring salts as an indicator of net long-term moisture flux. Sulphate can make an effective pedogenic tracer particularly in regions with higher natural sulphate concentrations, such as the prairies of Southern Alberta. Additionally, anthropogenic salts from produced water are typically chloride-based, rather than sulphate based, and so using sulphate as a pedogenic tracer is less likely than chloride to be compromised by anthropogenic salts.

An accumulation of sulphate at the soil surface can be used as an indicator of long-term net upwards migration of moisture, and therefore also an indication of the potential for future upwards migration of anthropogenic salts. Conversely a lack of sulphate accumulation at the soil surface can be used as an indicator of no net long-term upwards migration of moisture, and therefore also an indication that the future upwards migration of anthropogenic salts is unlikely.

Many studies have shown that the distribution of salts in the subsurface at a prairie site can be complex, and controlled by quite subtle micro-topographic features. It is possible for one part of a site to have the potential for upward migration of salts and another part to exhibit downward migration. For this reason, it is important to investigate the natural salt profile at a range of locations across a site.

The requirements to demonstrate Step #2b are as follows:

- A sufficient number of boreholes with natural salt profiles are required across the site to be able to represent the range of different micro-topographic settings at the site. This number of boreholes would typically be in the range 3 to 6 for most sites, with the lower number being appropriate for an essentially planar site, and a higher number of boreholes being needed for a site with more micro-topography (local lower and higher areas).
- Salinity analysis including sulphate is required at a sufficient range of depths in each borehole to characterize the way that sulphate concentration changes with depth. A typical set of

sample depths would be surface, 0.3 m, 0.6 m, 1 m, 2 m, 3 m, and 4 m., though other sets of sampling depths which achieve the objective of characterizing the profile of sulphate with depth would also be acceptable. Note that it is important to have the sulphate concentration at the ground surface well characterized.

- With the two requirements noted above, the onus remains with the professional making the application to justify why the dataset provided meets the objectives in the two previous points.
- Sulphate concentration are plotted against depth for each of the boreholes with salinity profile data. It is recommended that data for all boreholes are superimposed on a single plot to illustrate the variability in the sulphate profile across the site.
- Qualitative demonstration: determine whether the shape of the sulphate profiles is consistent with sulphate being leached down from surface rather than accumulating at surface. If this is so, then the qualitative demonstration is successful.
- Quantitative demonstration: calculate the average sulphate concentration from all samples in the 0 to 0.3 m range [A] and the average sulphate concentration from all samples in the 2 m to 4 m range [B]. If [A] is less and [B], then the quantitative demonstration is successful.

Successful completion of Step #2b requires either i) meeting the requirements noted above for qualitative and quantitative demonstrations, or ii) a carefully explained rationale from the professional making the application as to why the distribution of sulphate at the site in question demonstrates no surface accumulation of sulphate.

6.4.3 Step #2c: Salt Accumulation Zone and Water Table Depth

Even in cases where there is no potential for salt accumulation at surface, there can still be the potential for deeper salts to be transported up and accumulate in the root zone. Step #2c addresses this concern.

The presence of a zone of salt accumulation will be apparent as a "bulge" on the profile(s) of sulphate against depth generated to assess Step #2b indicating sulphate concentrations that are higher than the concentrations in overlying and underlying samples. Such a zone of salt accumulation can be generated by salts being flushed down from surface, transported upwards from deeper layers, or both. If a zone of salt accumulation is present, and if it extends partially into the root zone (assumed for the purposes of this Step to be the top 1.0 m of the soil profile), then upwards migration of salts into the root zone is a concern unless the water table is sufficiently deep to make this improbable. For the purposes of this Step, it is assumed that a water table at 2.5 m depth or greater is sufficiently deep that upward migration of moisture and salts into the root zone is unlikely.

Successfully completing any one of the following three points is sufficient to demonstrate Step #2c:

- Determine the depth of the water table in the vicinity of any areas of anthropogenic salts at the site. The water table can be determined by i) careful borehole observations of gleying, mottling and soil moisture or ii) from monitoring wells. If there are multiple measurements at a given monitoring well, the average value of the most recent three measurements should be used. If the water table depth is 2.5 m or deeper below ground surface in the vicinity of any anthropogenic salts, then Step #2c has been completed.
- If the water table cannot be shown to be deeper than 2.5 m, then the next step is to determine whether a zone of salt accumulation is present within the rooting zone (assumed for the purposes of this protocol to be within the top 1.0 m of the soil). A zone of salt accumulation would be identified as a depth range with higher sulphate concentration than either the overlying or the underlying strata. If there is no zone of salt accumulation, or the zone of salt accumulation does not extend into the top 1.0 m of the soil column, then Step #2c has been completed.
- If the water table is shallower than 2.5 m and there is a zone of salt accumulation present within the root zone, then the proponent has the option of utilizing a modelling approach to determine whether accumulation of salts within the rooting zone is a concern or not. The modelling approach would typically build on the model generated in Step #2a, but additionally would need to take into consideration that the moisture lost to evapotranspiration by the plants would be extracted from the soil system throughout the rooting depth (assumed to be the top 1.0 m of the soil column). If the model showed no salt accumulation in the root zone, then Step #2c would be deemed complete.

6.5 Step #3: Other Relevant Receptors and 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. 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 Steps #1 and #2. Step #3 considers the other exposure pathways indicated above.

Existing tools are available to assess whether any risk of adverse effects to receptors exists for these other exposure pathways. These options include the Subsoil Salinity Tool (ESRD, 2016c), available options within the Alberta Tier 1/2 guideline document (ESRD, 2016b), and other approaches that generate Tier 1 equivalent guidelines. Use these existing tool(s) to determine whether the existing concentrations of salts at the site in question could cause an adverse effect to any receptors via any of these other exposure pathways. If not, then Step #3 has been successfully completed.

6.6 Summary

To use the Alternate Closure Protocol for salt-affected wellsites on native grassland it is necessary to complete Steps #1, #2a, #2b, #2c, and #3 successfully. If this is achieved to the satisfaction of the regulator, then the Alternate Closure Protocol is an available alternative to the Tier 1 salinity guideline for salt and it is no longer necessary to compare site measured values of EC and SAR against Tier 1 guideline values for these parameters.

6.7 Final Decision and Residual Liability

It should be noted that the final decision on whether it is appropriate to use the Alternate Closure Protocol at a particular site rests with the regulator.

It should also be noted that the protocol indicated in this document is intended to identify situations where no current or future adverse effects are anticipated at salt-affected wellsites, and to allow a more streamlined process for closing such sites. In the unlikely event that a wellsite closed using the Alternate Closure Protocol did result in future adverse effects, the responsibility to rectify the adverse effects would remain with the proponent.

7.0 CLOSURE

We trust that the information presented herein meets your requirements. Should you have any questions, please call the undersigned at (403) 592-6180.

Yours truly,

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